European Commission

Study on ‘Geothermal plants’ and applications’ emissions: overview and analysis’

Final Report

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Research and Innovation

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EUROPEAN COMMISSION

Study on 'Geothermal plants' and applications' emissions: overview and analysis'

Final Report

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT (ENGLISH)

The study 'Geothermal plants' and applications' emissions: overview and analysis' aims at providing consistent and harmonized life cycle based assessment on the release of air pollutant emissions in the deep geothermal sector in Europe, in response to existing fragmented information and debate. The full analysis is developed at scale of clusters (representative groups of different plants), identified based on geological and technological parameters, through the application of Life Cycle Assessment methodology. Results show that most existing geothermal applications report relatively limited values of greenhouse gas emissions, as well as negligible impacts on the local areas where they are located. However, in rare cases it appears that, especially depending on geothermal fluid properties, specific impacts arise, requiring tailored mitigation measures to avoid risks on environment and human health. In conclusion, a set of recommendations is presented to support future decision-making and at addressing a fair and sustainable development of the deep geothermal sector in Europe.

ABSTRACT (FRENCH)

L'étude 'Émissions des centrales et des applications géothermiques : vue d'ensemble et analyse' vise à fournir une évaluation cohérente et harmonisée, basée sur le cycle de vie des émissions de polluants atmosphériques dans le secteur de la géothermie profonde en Europe, en réponse aux informations contradictoires et aux débats existants. L'analyse complète est développée à l'échelle de clusters (groupes représentatifs de centrales), identifiés sur la base de paramètres géologiques et technologiques, en appliquant la méthodologie d'Analyse du Cycle de Vie. Les résultats montrent que la plupart des applications géothermiques existantes font état d'émissions de gaz à effet de serre à des valeurs relativement limitées et d'impacts négligeables localement au niveau des zones où elles sont situées. Cependant, dans de rares cas, il apparaît qu'en fonction notamment des propriétés des fluides géothermiques des impacts spécifiques se présentent, nécessitant des mesures d'atténuation adaptées pour éviter les risques sur l'environnement et la santé humaine. En conclusion de cette étude, une série de recommandations est présentée afin de soutenir la prise de décision future et d'aborder un développement équitable et durable du secteur de la géothermie profonde en Europe.

EXECUTIVE SUMMARY (ENGLISH)

*The present study on **"Geothermal plants' and applications' emissions: overview and analysis"** is the main output of the technical assistance requested by the European Commission to gain a consistent, harmonized and exhaustive assessment about the possible release of greenhouse gases and other air pollutant emissions in the geothermal sector in Europe. In particular, this study is focused on deep geothermal energy, producing electricity and/or heat, and does not deal with shallow geothermal heat pumps systems.*

*The **need for a clear and comprehensive assessment of the emissions from geothermal plants and applications** is indeed founded on a growing debate in some areas of Europe on the topic. The controversy results from not-harmonized positions of the various stakeholders involved, the fragmented scientific panorama for the representation of the state-of-art, and the lack of a shared regulatory framework at European policy level. The limited number of studies currently available provide only a partial analysis of geothermal plants and applications' emissions throughout their entire life cycle.*

*The **methodological approach** purposely created to respond to this need consists of the following main tasks:*

- *definition of a shared methodology for the collection of data on geothermal emissions, based on the clusterisation of geothermal applications by geological and by technological parameters;*
- *data collection and definition of proxies to calculate input values for a set of Life Cycle Assessment analyses, performed for selected representative plants at cluster-basis with available data, addressing both power and heating production;*
- *elaboration of a set of guidelines to implement the principles of Life Cycle Assessment coherently and transparently to the case of the deep geothermal sector;*
- *analysis and interpretation of Life Cycle Assessment's results, providing an understanding of the impact of geothermal emissions from energy production on environment and human health.*

*Along the duration of the 14 months study, the process has included a **validation** step by inviting a panel of sectoral stakeholders to evaluate the proposed strategy and by the consultation of plant operators.*

*Owing to the uniqueness of each geothermal reservoir and the numerous technological options to produce and utilize geothermal energy, the clusterisation of installations by considering geographical and technological representativeness is chosen as facilitator of data collection and results representation. As a first assessment of the clusterisation, the **mapping and classification of reservoirs** includes the analysis at European level of those parameters considered as strongly influencing for the analysis of air emissions of geothermal applications. Such parameters are local geology (e.g.: volcanic setting vs. sedimentary basin), the type of geothermal play (i.e.: steam vs. water dominated) and the characteristics of the geothermal resource (e.g.: fluid composition, gas content and composition, temperature, pressure). In parallel, an **inventory of technologies** used in different stages of the life cycle is performed. It provides a clear overview of the state-of-art technologies for exploration, stimulation, drilling operations and well abandonment.*

*Specific focus is dedicated to the analysis of production technology, covering fluids production, energy conversion, cooling systems, heat/cold generation, gas control systems and reinjection. Along the inventory, general effects of each components on emissions and potential opportunities for the improvement of environmental performance are also presented. As a combination of the aspects previously introduced, a set of **typical clusters** for geothermal plants in Europe is developed for power (13 clusters) and district heating (6 clusters) applications respectively. As a general indication, almost 100% of geothermal power plants in Europe are represented within the clusterisation, whereas the coverage is of about 85% for district heating.*

*Based on the general findings of the overview of reservoirs and technologies, a list of **key parameters** (e.g.: drilled depth, gas content, efficiency of abatement system, etc.) is defined, in order to identify all the inputs to be collected for the calculation of the impacts. Each parameter may account for multiple emissions. These parameters represent the numerical and qualitative data collected for the purpose of the study. Then, in order to determine the specific material, energy and air inputs/outputs of each geothermal system, a number of mathematical formulations and equations, **proxies**, is developed, based on statistical correlations and on thermodynamic principles for the estimation of air emissions during operation from physical properties of the geothermal fluid and based on technology. The proxies can be cluster-specific or can be applicable to all the clusters.*

*As an additional methodological input for the study, the "**Sector Category Rules for Life Cycle Assessment**" (SCR) are drafted. The aim of these rules is to draft a methodological guidance to be followed when performing a Life Cycle Assessment (LCA) study related to the geothermal sector. The existence of a shared methodology in defining the cluster and in performing the LCA assessment ensures that the results of the study is representative of plants/applications of the single cluster and to address the need of introducing coherent simplifications, assumptions and schemes for the performing LCA studies referred to a whole cluster, rather than common plant-specific studies. The guidelines address also a number of key methodological choices: exergy is used as allocation method in case of combined heat and power generation, and Environmental Footprint 3.0 is selected as impact assessment method, with specific reference to climate change, ozone depletion, human toxicity (cancer and non-cancer), respiratory inorganics, photochemical ozone formation, acidification, eutrophication (terrestrial, freshwater, marine), ecotoxicity freshwater.*

The results of the study enclose the application of the methodology developed during the first progress of the study, as well as the derivation of the actual results of the LCA analyses, complemented by adequate interpretation to support decision making process.

*The **goal of LCA** analyses is to evaluate direct (i.e.: emissions occurring in the geothermal site from fuel combustion during drilling or as releases during testing and operation) and indirect (i.e.: emissions not occurring locally, associated with materials manufaturing) emissions associated with the production of electricity and/or heating and cooling through the exploitation of geothermal energy for each cluster's reference plant (i.e.: a theoretical plant representative of all the plants within a cluster), covering the life cycle from cradle to gate (i.e.: exploration; stimulation; testing; drilling, casing and cementing; construction of surface components; operation; maintenance).*

***Life Cycle Inventories** (LCIs) are derived through the application of proxies relying on key parameters as input data, featuring each representative plant as well as through the* *collection of primary data. It shall be outlined that important principles underlying the definition of LCIs are the consistency and homogeneity of data gathering and use across all the clusters, conditioned on data availability. According to the provisions of the SCR, particular effort is thus dedicated for the estimation of direct emissions to air during the operation of the plants as an industrial application, in line with the goal of the study and with the peculiar characteristics of the geothermal sector with respect to other energy systems, as well as characterisation of the drilling phase, including testing and stimulation of geothermal wells. The selection of air emissions to be included within the boundaries of the study is based on two main criteria for industry; i.e.: typical emissions encountered and more specific emissions of high concern for environment and health. As a result, carbon dioxide, methane, hydrogen sulphide, nitrogen, ammonia, mercury, arsenic and sulfur dioxide are considered as air emissions included in LCIs and characterizing the main findings of the study.*

In the data collection process, the level of ***data quality*** *accomplished is high in some clusters (where plant-specific data are collected for all the plants within the cluster) to medium (where plant-specific data are collected for some plants within the cluster and average estimations are made for remaining plants) for most of the clusters. However, data collection and results calculation are necessarily affected by the lack of knowledge of certain emissions in some geographical areas (e.g.: natural emissions, lacking of measurements/data), the selection of a cluster-based approach and intrinsic uncertainties of impacts modelling. All these factors impact differently on each cluster's analysis.*

Thus, the interpretation of the final results shall take into account their methodological and analytical ***uncertainty.***

Life Cycle Impact Assessment *(LCIA) results show, in general terms, a great variability, either within the same cluster, either when considering variations across all the clusters. While variability within a cluster mainly derives from intrinsic uncertainties embedded in LCIs definition, the differences across clusters depends on the geological resource and on the properties of the geothermal fluid as well as the technological solutions implemented to exploit it. When occurring, the presence of direct air emissions during operation represents the most influencing factor on the environmental performance of geothermal applications. In this case, depending on the nature of the emissions generated, which is in turn dependent on the composition of geothermal fluid, characteristics of the reservoir and the technological system, different impact categories are affected. Conversely, impacts of plants without direct emissions to the atmosphere are clearly minor and contained in the amount. In terms of* ***global warming potential****, which is one of the most robust outcomes of the analyses and also a well recognized indicator in LCA, the impacts of geothermal power generation calculated presents an average value – weighted on productivity - of 238 gCO_2e/kWh_e, ranging from 5 gCO_2e/kWh_e (no emissions to air during operation) to 898 gCO_2e/kWh_e (emissions to air during operation); 32% of the plants (corresponding to 45% of installed power capacity) have emissions lower than 100 gCO_2e/kWh_e, while 58% of the plants (corresponding to 48% of installed power capacity) have emissions between 100 gCO_2e/kWh_e and 500 gCO_2e/kWh_e. Thermal energy production presents an average value – weighted on productivity – of 38 gCO_2e/kWh_{th}, ranging from 8 gCO_2e/kWh_{th} (no emissions to air during operation) to 220 gCO_2e/kWh_{th} (emissions to air during operation, thermal production only); 60% of the plants analyzed (corresponding to 74% of installed thermal capacity among the plants analyzed) have emissions lower than 100 gCO_2e/kWh_{th}, while 39% of the plants (corresponding to 25% of installed thermal capacity) have emissions between 100 gCO_{2e}/kWh_{th} and 500 gCO_2e/kWh_{th}. The remaining 1%*

(corresponding to 1% of installed thermal capacity) has emissions higher than 500 gCO_2e/kWh_{th}.

*The **contribution analysis** performed on the LCIA results highlights that the share of impact generated by occurring air emissions exceeds 80% in the affected impact categories. In case of power generation without direct air emissions, drilling, being the main industrial activity of the project development, is the most impacting phase. This is due primarily to diesel combustion for electricity generation to supply the engines, but also to the use and disposal of drilling fluids. In the case of geothermal heating, the grid electricity consumption to ensure regular operation is equally relevant. In addition, it emerges that the use of chemicals for fluid treatment and to tackle scaling and corrosion may introduce non-negligible impacts, especially for ecotoxicity freshwater impact category. The construction of surface components, including impacts associated with material manufacturing, is significant for human toxicity impact categories, as for all industrial activities. Finally, in the clusters considered, exploration, stimulation and testing lead to negligible or minor impact on a life-cycle basis. An investigation of the share between **direct and indirect emissions** is also performed, with the aim of understanding also the extents of the local effects, related to direct emissions only. For the case of power generation, this share is highly dependent on the specific cluster and impact category. On the other hand, for the case of thermal energy generation, indirect emissions are usually predominant. As a complementary exercise to understand the influence of the assumptions to provide inputs for future studies, a set of **sensitivity analyses** is included, covering technological as well as methodological issues (i.e.: electricity supply for drilling operation, allocation method, well abandonment, natural emissions, characterisation method for hydrogen sulphide emissions to air).*

*After having elaborated and analyzed in depth the final quantitative results, their **interpretation** allows to derive conclusions and recommendations and to provide comprehensive and understandable information to policy makers. These conclusions can give guidance for the indentification of priorities to ensure a sustanaible development of the deep geothermal sector in Europe. Correlated also with information available from non-LCA studies (e.g.: epidemiological, dispersion analyses, air quality monitoring, etc.), such indications will provide a robust direction for policy making and identification of best practices.*

*The **extent and validity of the conclusions** that can be drawn from this study are determined by the intrinsic features of the LCA analysis and of the LCIA method selected, in terms of applicability, validity and robustness, as well as on the boundaries and the level of detail set within the study itself to meet the time-schedule and scale foreseen for the activity, against the ambitious target of the study.*

*Considering that existing main concerns about the exploitation of geothermal energy are associated with potential impacts arising from direct emissions and operation of the plants, the focus of the interpretation is on the **local scale**, covering **potential impacts on environment and human health**. The methodology proposed to present a systematic and structured interpretation is derived starting from well-established techniques for impact assessment and management of environmental impacts.*

*Specifically, as far as **potential impacts on the environment** are concerned, the following highlights are reported:*

- *their assessment is based on **impact significance**, an indicator expressing the priority of the impact's associated concern based on a combination of two factors: quantitative relevance with respect to conventional alternative energy supply (i.e.: electricity from grid and thermal energy from natural gas) and sensitivity of the receptor, considered high for natural protected areas, medium for urban areas and low for industrial areas;*

- *under the **most severe scenario** (i.e.: plants in the proximity of natural protected areas) **the majority of the plants is associated with minor or moderate significance of impacts**, implying either negligible effects or indicating the need for monitoring. Limited concerns arise for impacts on ecotoxicity freshwater, followed by acidification and terrestrial eutrophication, in which **a few plants are associated with a level of significance of impacts** suggesting the need to carefully analyze the environmental impacts and implement mitigation measures;*

- *under the **least severe scenario** (i.e.: plants in proximity of industrial areas), **none of the reference plants shows high levels of impacts significance**, indicating that no significant impacts are expected;*

*As far as **potential impacts on human health** are concerned, the following highlights are reported:*

- *their assessment is based on **quantitative relevance** of potential impacts, with reference to conventional alternative energy supply as in the previous case. This approach does not account for the sensitivity of the potential receptor;*

- ***in most plants, the quantitative relevance is low**. **In rare cases** – associated with power production from geothermal fluids rich of non-condensable gases, located in different geographical contexts across Europe – **higher relevance is reached** with respect to non-cancer human toxicity and respiratory inorganics impact categories;*

- ***health effects of hydrogen sulphide emissions**, present in a limited number of cases, are not captured (or properly captured) by current LCIA methods. Even though urgent concerns about the well-known short-term effects of these emissions on human health can be reasonably excluded in the European context, as monitored hydrogen sulphide concentrations in areas of geothermal applications are well below the limits given by the World Health Organisation, a clear understanding of effects of long-term exposure to low concentration of this substance is missing at scientific level.*

*Based on the main outcomes of this study, a set of **recommendations** for the enhancement of the deep geothermal sector in Europe is identified:*

- ***acknowledge the role of geothermal as a renewable energy source to fight climate change and understand the environmental performance variability of the geothermal sector** – according to the results of this study, more than 50% of geothermal installed capacity for power and heat generation presents impacts on global warming potential below 100 gCO_{2e}/kWh. Moreover, for the case of heat production, geothermal energy mostly substitutes fossil fuels (representing 80% of the heat consumption today in Europe).*

However, in order to guarantee a fair development of the sector, inclusive of all the solutions, the diversity and peculiarity of each situation should be taken into account. In this sense, policy making, funding initiatives, financial instruments, technological developments, market maturity and conditions shall be fairly addressed to cover the highlighted variability

- ***improve data availability and data sharing*** *- a harmonisation of available information and a standardisation of data to be collected at international scale should be promoted to facilitate robust scientific outcomes for the environmental assessment of the geothermal sector*

- ***harmonize and promote best practice*** *- it is advisable to collect and harmonize the large amount of scientific knowledge and operational expertise in a reference document, in order to overcome lack of homogeneous information to assess the performance of single geothermal installations*

- ***use complementary assessment methods and tailor LCA methodology for geothermal applications*** *- the complexity of the geothermal sector and its multiple implications on different receptors make of paramount importance the selection of analysis tools that are suitable and effective towards the desired purpose. In addition, in order to ensure consistent and systematic application of the LCA methodology to the geothermal sector, it is recommended that sectoral guidelines with minimum requirements are adopted at European level. This will ensure comparability and consistency across the studies performed*

- ***characterize baseline scenario of existing and future geothermal installations*** *- a crucial aspect to be addressed for future works and further characterisation of effects of energy generation from geothermal resource, is the differentiation between anthropogenically and naturally emitted gases from geothermal systems*

- ***address the development for the most significant life-cycle phases of geothermal energy generation*** *- LCA results show how the largest contribution to the overall environmental impacts of geothermal plants is given, both for power plants and district heating plants, by direct emissions occurring during plant operation (if any), and secondly by the drilling phase. For district heating applications, a relevant share of the impacts is attributed to electricity consumption for fluid pumping, when wells are not self-flowing. To maximize the environmental performance, effort in future development should be prioritized according to these findings*

- ***limit the flow of direct emissions in operation with mitigation measures*** *- direct emissions occurring in some applications during the plants' operation are the most crucial factor for the environmental performance of geothermal applications. Indeed, emissions generated are often of multiple types and associated with a wide range of potential impacts, on health and environment and at local or global scale. Their occurrence shall be avoided or mitigated wherever technologically possible.*

RÉSUMÉ EXÉCUTIF (FRENCH)

La présente étude sur les ***"Émissions des centrales et des applications géothermiques: vue d'ensemble et analyse"*** *est le principal résultat de l'assistance technique demandée par la Commission Européenne pour obtenir une évaluation cohérente, harmonisée et exhaustive sur les éventuelles émissions de gaz à effet de serre et autres polluants atmosphériques émanant du secteur géothermique en Europe. Cette étude porte en particulier sur la géothermie profonde. Elle inclue les applications produisant de l'électricité et/ou de la chaleur, et ne traite pas des systèmes de pompes à chaleur géothermiques peu profonds.* ***La nécessité d'une évaluation claire et complète des émissions des centrales et des applications géothermiques*** *répond au débat croissant dans certaines régions d'Europe sur le sujet. La controverse résulte des positions non harmonisées des différents acteurs concernés, du panorama scientifique fragmenté concernant la représentation de l'état de l'art et de l'absence d'un cadre réglementaire commun au niveau de la politique européenne. Le nombre limité d'études actuellement disponibles ne fournit qu'une analyse partielle des émissions des centrales et des applications géothermiques tout au long de leur cycle de vie.*

L'approche méthodologique *créée spécialement pour répondre à ce besoin se compose des tâches principales suivantes :*

- *définition d'une méthodologie commune pour la collecte de données relatives aux émissions géothermiques, basée sur le regroupement des applications géothermiques en clusters, sur base de paramètres géologiques et technologiques;*
- *collecte de données et définition d'approximations pour calculer les valeurs d'entrée pour un ensemble d'analyses d'Evaluation du Cycle de Vie, effectuées pour une sélection de centrales représentatives définies sur la base des données disponibles, comprenant la fois la production d'électricité et de chaleur;*
- *élaboration d'un ensemble de lignes directrices pour mettre en œuvre les principes de l'Analyse du Cycle de Vie de manière cohérente et transparente pour le secteur de la géothermie profonde;*
- *analyse et interprétation des résultats de l'Analyse du Cycle de Vie, illustrant l'impact des émissions géothermiques provenant de la production d'énergie sur l'environnement et la santé humaine.*

Plusieurs étapes de ***validation*** *ont été incluses au cours des 14 mois de l'étude . Ainsi, un groupe de parties prenantes du secteur de la géothermie profonde a été invité à évaluer et à valider la stratégie proposée et des exploitants d'installations géothermiques ont été consultés notamment lors de la collecte de données.*

En raison du caractère unique de chaque réservoir géothermique et des nombreuses options technologiques pour produire et utiliser l'énergie géothermique, les installations ont été regroupées en groupes sur base de la représentativité géographique et technologique. Le regroupement effectué permet de faciliter la collecte des données et la représentation des résultats. Dans un premier temps, ***la cartographie et la classification des réservoirs*** *à l'échelle européenne est réalisée. L'analyse se base sur l'étude des paramètres considérés comme ayant une forte influence sur les émissions atmosphériques des applications géothermiques. Ces paramètres sont la géologie locale* *(par exemple, contexte volcanique versus sédimentaire), le type de réservoir (par exemple,* réservoirs géothermiques à dominante vapeur versus à dominante liquide *) et les caractéristiques de la ressource géothermique (la composition des fluides, la teneur en gaz et leur composition, la température, la pression). En parallèle,* ***un inventaire des technologies*** *utilisées aux différentes étapes du cycle de vie est réalisé. Il donne un aperçu clair des technologies de pointe utilisées pour l'exploration, la stimulation, les opérations de forage et l'abandon des puits. L'accent particulier a été sur l'analyse des technologies associées à la phase de production, couvrant la production de fluides, la conversion d'énergie, les systèmes de refroidissement, la production de chaleur/froid, les systèmes de contrôle des gaz et la potentielle réinjection. L'inventaire présente également les effets généraux de chaque composant sur les émissions et les possibilités d'amélioration des performances environnementales. En combinant les aspects précédemment introduits,* ***un ensemble de clusters représentatifs*** *des centrales géothermiques en Europe est développé pour les applications produisant de l'électricité (13 clusters) et du chauffage urbain (6 clusters) respectivement. À titre d'indication générale, presque 100 % des centrales géothermiques en Europe sont représentées au sein du clustering, alors que la couverture est d'environ 85 % pour le chauffage urbain.*

Sur la base des conclusions générales de l'inventaire des réservoirs et des technologies, une liste de ***paramètres clés*** *(par exemple : profondeur de forage, teneur en gaz, efficacité du système d'abattement, etc.) est définie, afin d'identifier tous les éléments à collecter pour le calcul d'impact environnemental. Chaque paramètre peut rendre compte de plusieurs émissions. Ces paramètres représentent les données numériques et qualitatives collectées aux fins de l'étude. Ensuite, afin de déterminer les inputs/outputs de matériaux, d'énergie, des émissions spécifiques à chaque système géothermique, un certain nombre de formulations et d'équations mathématiques sont développées. Ces* ***approximations*** *sont basées sur des corrélations statistiques et/ou sur des principes thermodynamiques selon la phase du projet à laquelle sont estimées les émissions. Entre autres, l'estimation des émissions atmosphériques pendant la phase de production inclue la prise en compte des propriétés physiques du fluide géothermique et de la technologie utilisée, impliquant l'application de principes thermodynamiques propres à celle-ci. Les approximations peuvent être spécifiques à un cluster ou s'appliquer à tous les clusters.tous les clusters.*

Les ***"Règles de catégorie de secteurs pour l'analyse du cycle de vie"*** *(RCS) sont rédigées en tant que contribution méthodologique complémentaire à l'étude. L'objectif de ces règles est de proposer un guide méthodologique à suivre lors de la réalisation d'une étude d'Analyse du Cycle de Vie (ACV) appliquée au secteur géothermique. L'existence d'une méthodologie commune pour la définition du cluster et la réalisation de l'évaluation ACV garantit que les résultats de l'étude sont représentatifs des usines/applications appartenant au cluster spécifique. De plus, la méthodologie proposée souligne l'intérêt et le besoin d'introduire des simplifications, des hypothèses et des schémas cohérents pour réaliser des études ACV à l'échelle de clusters, plutôt que des études spécifiques aux centrales et applications. Les lignes directrices abordent également un certain nombre de choix méthodologiques clés : l'exergie est utilisée comme méthode de répartition dans le cas de la production combinée de chaleur et d'électricité, et l'Environmental Footprint 3.0 est choisie comme méthode d'évaluation des incidences. Une référence spécifique est faite au changement climatique, à l'appauvrissement de la couche d'ozone, à la toxicité pour l'homme (cancéreuse et non cancéreuse), aux substances inorganiques respiratoires, à la formation photochimique d'ozone, à l'acidification, à l'eutrophisation (terrestre, d'eau douce, marine) et à l'écotoxicité de l'eau douce.*

Les résultats de l'étude comprennent l'application de la méthodologie développée dans le cadre de la présente étude, ainsi que la dérivation des résultats réels des analyses ACV, complétée d'une interprétation adéquate visant à soutenir le processus de prise de décision.

L'objectif des ACV *est d'évaluer les émissions directes (émissions se produisant sur le site géothermique du fait de la combustion de carburants pendant le forage ou sous forme de rejets pendant les essais et l'exploitation) et indirectes (émissions ne se produisant pas localement, associées à la fabrication de matériaux) associées à la production d'électricité et/ou de chauffage et de refroidissement selon le type de cluster. Pour chaque cluster, l'évaluation est réalisée pour une centrale de référence prédéfinie (i. e. : une centrale théorique représentative de toutes les centrales d'un cluster) et couvre le cycle de vie du début à la fin (c'est-à-dire : exploration ; stimulation ; essais ; forage, tubage et cimentation ; construction des composants de surface ; exploitation ; entretien).*

Les ***Inventaires du Cycle de Vie*** *(ICV) sont réalisés soit en appliquant les approximations élaborées dans le cadre de l'étude et utilisant comme données d'entrée des paramètres clés représentatifs de chaque centrale de référence soit en collectant des données primaires. Il convient de souligner que les principes importants qui sous-tendent la définition des ICV sont la cohérence et l'homogénéité de la collecte et de l'utilisation des données dans tous les clusters, sous réserve de la disponibilité des données. Conformément aux dispositions du SCR, un effort particulier est consacré à l'estimation des émissions directes dans l'atmosphère pendant la phase d'exploitation des centrales en tant qu'application industrielle. De plus, conformément à l'objectif de l'étude et aux caractéristiques particulières du secteur géothermique par rapport aux autres systèmes énergétiques, sont considérées en complément, la caractérisation de la phase de forage, les essais et la stimulation des puits géothermiques. La sélection des émissions atmosphériques à inclure dans les limites de l'étude pour l'industrie est basée sur deux critères principaux, à savoir: les émissions typiquement rencontrées et les émissions plus spécifiques très préoccupantes pour l'environnement et la santé. Ainsi, le dioxyde de carbone, le méthane, le sulfure d'hydrogène, l'azote, l'ammoniac, le mercure, l'arsenic et le dioxyde de soufre sont considérés comme des émissions atmosphériques à inclure dans les ICV.*

Le niveau de qualité *des données collectées atteint est élevé pour certains clusters (les données spécifiques aux centrales sont collectées pour toutes les centrales du cluster) à moyen pour la plupart des autres clusters (les données spécifiques aux centrales sont collectées pour certaines centrales du cluster et des estimations moyennes sont faites pour les autres centrales). Il est cependant essentiel de noter que la collecte des données et le calcul des résultats sont nécessairement affectés par le manque de connaissance de certaines émissions dans certaines zones géographiques (par exemple : émissions naturelles, manque de mesures/données), le choix de l'approche par clusters et les incertitudes intrinsèques à la modélisation des impacts. Tous ces facteurs ont un impact différent sur l'analyse de chaque cluster.*

*Ainsi, l'interprétation des résultats finaux doit tenir compte de l'****incertitude*** *méthodologique et analytique.*

Les résultats de ***l'Analyse d'Impact du Cycle de Vie*** *montrent, en termes généraux, une grande variabilité, soit au sein d'un même cluster, soit en considérant les variations entre tous les clusters. Si la variabilité au sein d'un cluster découle principalement des* *incertitudes intrinsèques inhérentes à la définition des ICV, les différences entre les clusters dépendent principalement de la géologie et des propriétés du fluide géothermique ainsi que des solutions technologiques mises en œuvre pour l'exploiter. Lorsqu'elle se produit, la présence d'émissions atmosphériques directes pendant l'exploitation représente le facteur qui influe le plus sur les performances environnementales des applications géothermiques. Dans ce cas, en fonction de la nature des émissions générées, qui dépend elle-même de la composition du fluide géothermique, des caractéristiques du réservoir et de la technologie utilisée, différentes catégories d'impact sont concernées. À l'inverse, les impacts des centrales sans émissions directes (ou avec émissions négligeables) dans l'atmosphère sont clairement mineurs et limités en quantité. En termes de* ***potentiel de réchauffement climatique****, qui est l'un des résultats les plus solides des analyses et également un indicateur bien reconnu dans l'ACV, les impacts de la production d'électricité géothermique calculés présentent une valeur moyenne - pondérée en fonction de la productivité - de 238 gCO_2e/kWh_e, allant de 5 gCO_2e/kWh_e (aucune émission dans l'air pendant l'exploitation) à 898 gCO_2e/kWh_e (émissions dans l'air pendant l'exploitation) ; 32 % des centrales (correspondant à 45 % de la puissance installée) ont des émissions inférieures à 100 gCO_2e/kWh_e, tandis que 58 % des centrales (correspondant à 48 % de la puissance installée) ont des émissions comprises entre 100 gCO_2e/kWh_e et 500 gCO_2e/kWh_e. La production d'énergie thermique présente une valeur moyenne - pondérée en fonction de la productivité - de 38 gCO_2e/kWh_{th}, allant de 8 gCO_2e/kWh_{th} (aucune émission dans l'air pendant l'exploitation) à 220 gCO_2e/kWh_{th} (émissions dans l'air pendant l'exploitation, production thermique uniquement) ; 60 % des installations analysées (correspondant à 74 % de la capacité thermique installée parmi les installations analysées) ont des émissions inférieures à 100 gCO_2e/kWh_{th}, tandis que 39 % des installations (correspondant à 25 % de la capacité thermique installée) ont des émissions comprises entre 100 gCO_2e/kWh_{th} et 500 gCO_2e/kWh_{th}. Les 1 % restants (correspondant à 1 % de la capacité thermique installée) ont des émissions supérieures à 500 gCO_2e/kWh_{th}*

L'analyse des contributions *se basant sur les résultats de la LCIA souligne que la part de l'impact généré par les émissions atmosphériques dépasse 80 % dans les catégories d'impact touchées. Dans le cas de la production d'électricité sans émissions atmosphériques directes, le forage, qui est la principale activité industrielle du développement du projet, est la phase la plus impactante. Cela est dû principalement à la combustion de diesel pour la production d'électricité destinée à alimenter les moteurs, mais aussi à l'utilisation et à l'élimination des fluides de forage. Dans le cas du chauffage géothermique, la consommation d'électricité du réseau pour assurer un fonctionnement régulier est tout aussi importante. En outre, il apparaît que l'utilisation de produits chimiques pour le traitement des fluides et pour lutter contre l'entartrage et la corrosion peut introduire des impacts non négligeables, en particulier pour la catégorie d'impact "écotoxicité de l'eau douce". Comme dans toutes les activités industrielles, la construction de composants de surface, y compris les impacts liés à la fabrication de matériaux, est importante pour les catégories d'impact concernant la toxicité pour l'homme. Enfin, dans les clusters considérés, l'exploration, la stimulation et les essais entraînent un impact négligeable ou mineur sur l'ensemble du cycle de vie.* ***Une étude de la répartition entre les émissions directes et indirectes*** *est également réalisée, afin de comprendre également l'ampleur des effets locaux, liés aux seules émissions directes. Dans le cas de la production d'électricité, cette part dépend fortement du cluster et de la catégorie d'impact spécifiques. En revanche, dans le cas de la production d'énergie thermique, les émissions indirectes sont généralement prédominantes. En complément, pour comprendre l'influence des hypothèses formulées et afin de fournir des données pour les études futures, une série d'****analyses de sensibilité*** *est incluse. Elle couvre les questions technologiques* *aussi bien que méthodologiques (c'est-à-dire : approvisionnement en électricité pour les opérations de forage, méthode d'allocation, abandon de puits, émissions naturelles, méthode de caractérisation des émissions de sulfure d'hydrogène dans l'air).*

*L'**interprétation** détaillée des résultats quantitatifs finaux permet de tirer des conclusions, de présenter des recommandations et de fournir des informations complètes et compréhensibles aux décideurs politiques. Ces conclusions peuvent donner des indications concernant l'identification des priorités afin d'assurer un développement durable du secteur de la géothermie profonde en Europe. En corrélation également avec les informations disponibles dans les études non ACV (par exemple : épidémiologiques, analyses de dispersion, surveillance de la qualité de l'air, etc.), ces indications fourniront une orientation solide pour l'élaboration des politiques et l'identification des meilleures pratiques.*

***L'étendue et la validité des conclusions** tirées de cette étude sont déterminées par les caractéristiques intrinsèques de l'analyse ACV et de la méthode LCIA choisie, en termes d'applicabilité, de validité et de robustesse, ainsi que par les limites et le niveau de détail fixés dans l'étude elle-même pour respecter le calendrier et l'étendue prévus pour l'activité, par rapport à l'objectif ambitieux de l'étude.*

*Étant donné que les principales préoccupations actuelles concernant l'exploitation de l'énergie géothermique sont liées aux impacts potentiels découlant des émissions directes et de l'exploitation des centrales, l'interprétation est axée sur **l'échelle locale**, couvrant **les impacts potentiels sur l'environnement et la santé humaine**. La méthodologie proposée pour présenter une interprétation systématique et structurée est dérivée de techniques bien établies pour l'évaluation et la gestion des impacts environnementaux.*

*Plus précisément, en ce qui concerne **les impacts potentiels sur l'environnement**, les points suivants sont signalés :*

- *leur évaluation est basée sur **l'importance de l'impact**, un indicateur exprimant la priorité de la préoccupation associée à l'impact en fonction d'une combinaison de deux facteurs : la pertinence quantitative par rapport à l'approvisionnement en énergie alternative conventionnelle (c'est-à-dire : électricité du réseau et énergie thermique du gaz naturel) et la sensibilité du récepteur, considérée comme élevée pour les zones naturelles protégées, moyenne pour les zones urbaines et faible pour les zones industrielles ;*

- *dans **le scénario le plus grave** (c'est-à-dire les centrales à proximité des zones naturelles protégées), **la majorité des centrales sont associées à des impacts d'importance mineure ou modérée**, ce qui implique des effets négligeables ou indique la nécessité d'une surveillance. Des préoccupations limitées apparaissent en ce qui concerne les impacts sur l'écotoxicité de l'eau douce, suivie par l'acidification et l'eutrophisation terrestre, dans lesquelles **quelques centrales sont associées à un niveau d'importance** des impacts suggérant la nécessité d'analyser soigneusement les impacts environnementaux et de mettre en œuvre des mesures d'atténuation ;*

- *dans le scénario le moins grave (c'est-à-dire les centrales situées à proximité de zones industrielles), aucune des centrales de référence ne présente un niveau élevé d'importance des impacts, ce qui indique qu'aucun impact significatif n'est attendu;*

*En ce qui concerne **les impacts potentiels sur la santé humaine**, les points suivants sont signalés :*

- *leur évaluation est basée sur la **pertinence quantitative** des impacts potentiels, en référence à l'approvisionnement en énergie alternative conventionnelle comme dans le cas précédent. Cette approche ne tient pas compte de la sensibilité du récepteur potentiel;*

- ***dans la plupart des centrales, la pertinence quantitative est faible**. Dans de rares cas - associés à la production d'énergie à partir de fluides géothermiques riches en gaz non condensables, situés dans différents contextes géographiques en Europe - **une pertinence plus élevée est atteinte** en ce qui concerne les catégories d'impact de la toxicité humaine non cancéreuse et des substances inorganiques respiratoires;*

- ***les effets sur la santé des émissions de sulfure d'hydrogène**, présents dans un nombre limité de cas, ne sont pas pris en compte (ou de façon incorrecte) par les méthodes actuelles de LCIA. Même si des préoccupations urgentes concernant les effets à court terme bien connus de ces émissions sur la santé humaine peuvent être raisonnablement exclues dans le contexte européen, étant donné que les concentrations de sulfure d'hydrogène surveillées dans les zones d'applications géothermiques sont bien inférieures aux limites données par l'Organisation mondiale de la santé. Une compréhension claire des effets d'une exposition à long terme à de faibles concentrations de cette substance fait défaut au niveau scientifique.*

*Pour finir, les conclusions de l'étude - centrée sur le thème des émissions atmosphériques et dérivée sur base d'analyse du cycle de vie - permettent de définir l'ensemble des **recommandations** suivantes pour une amélioration judicieuse du secteur de la géothermie profonde en Europe :*

- ***reconnaître le rôle de la géothermie en tant que source d'énergie renouvelable pour lutter contre le changement climatique et comprendre la variabilité des performances environnementales du secteur géothermique** - selon les résultats de cette étude, plus de 50 % de la capacité géothermique installée pour la production d'électricité et de chaleur présente des impacts sur le potentiel de réchauffement planétaire inférieurs à 100 gCO_{2e}/kWh. En outre, dans le cas de la production de chaleur, l'énergie géothermique se substitue principalement aux combustibles fossiles (représentant 80 % de la consommation de chaleur en Europe aujourd'hui).*

  Toutefois, afin de garantir un développement équitable du secteur, incluant toutes les solutions, la diversité et la particularité de chaque situation devraient être prises en compte. En ce sens, l'élaboration des politiques, les initiatives de financement, les instruments financiers, les développements technologiques, la maturité et les conditions du marché doivent être traités équitablement pour couvrir la variabilité mise en évidence

- ***améliorer la disponibilité et le partage des données** - il convient de promouvoir une harmonisation des informations disponibles et une normalisation des données à collecter à l'échelle internationale afin de faciliter l'obtention de* *résultats scientifiques solides pour l'évaluation environnementale du secteur géothermique*

- ***harmoniser et promouvoir les meilleures pratiques*** *- il est conseillé de rassembler et d'harmoniser la grande quantité de connaissances scientifiques et d'expertise opérationnelle dans un document de référence, afin de pallier le manque d'informations homogènes pour évaluer les performances des installations géothermiques individuelles*

- ***utiliser des méthodes d'évaluation complémentaires et adapter la méthodologie de l'ACV aux applications géothermiques*** *- la complexité du secteur géothermique et ses multiples implications sur les différents récepteurs rendent primordiale la sélection d'outils d'analyse adaptés et efficaces pour atteindre l'objectif souhaité. En outre, afin d'assurer une application cohérente et systématique de la méthodologie ACV au secteur géothermique, il est recommandé d'adopter des lignes directrices sectorielles avec des exigences minimales au niveau européen. Cela permettra d'assurer la comparabilité et la cohérence des études réalisées*

- ***caractériser le scénario de base des installations géothermiques existantes et futures*** *- un aspect crucial à aborder pour les travaux futurs et la poursuite de la caractérisation des effets de la production d'énergie à partir de la ressource géothermique, est la différenciation entre les gaz d'origine anthropogénique et ceux émis naturellement par les systèmes géothermiques*

- ***aborder le développement pour les phases les plus importantes du cycle de vie de la production d'énergie géothermique*** *- les résultats de l'ACV montrent comment la contribution la plus importante aux impacts environnementaux globaux des centrales géothermiques est donnée, à la fois pour les centrales électriques et les centrales de chauffage urbain, par les émissions directes se produisant pendant l'exploitation de la centrale (le cas échéant), et ensuite par la phase de forage. Pour les applications de chauffage urbain, une part importante des impacts est attribuée à la consommation d'électricité associée au pompage des fluides, lorsque les puits ne sont pas artésiens ou lorsque le pompage est requis (par exemple : pour augmenter la production ou maintenir le fluide sous pression). Afin de maximiser les performances environnementales, les efforts de développement futurs doivent être priorisés sur base de ces observations*

- ***limiter le flux des émissions directes liées à l'exploitation par des mesures de mitigation*** *- les émissions directes associées à certaines applications pendant l'exploitation des centrales apparaissent comme le facteur le plus crucial de la performance environnementale des applications géothermiques. En effet, les émissions générées sont souvent de types multiples et associées à un large éventail d'impacts potentiels, sur la santé et l'environnement et à l'échelle locale ou mondiale. Leur apparition doit être évitée ou atténuée chaque fois que cela est possible sur le plan technologique.*

INTRODUCTION

The European Commission has committed a study on "Geothermal plants' and applications' emissions: overview and analysis" to Ernst & Young, RINA and VITO to provide a consistent, harmonized and exhaustive assessment about the possible release of greenhouse gases and other pollutant emissions in geothermal sector.

The present document represents the main output of the technical assistance, by providing an analysis of the generated emissions flows (through a tailored methodology based on clusters for the creation of dedicated Life Cycle and GHG Inventories) and an evaluation of potential impacts on the environment and human health.

1 BACKGROUND AND CONTEXT

Geothermal energy is derived from the heat generated and stored in the Earth's interior. The geothermal resource is considered as renewable, thanks to the constant heat flow towards the surface and atmosphere from the Earth's interior. Heat is transferred by fluids (water or steam) which act as a natural transfer vector towards the surface. Geothermal fluids are constantly replenished by meteoric and crustal waters which circulate within the crust. Geothermal reservoirs are volumes of naturally fractured rock where fluids are stored and can be extracted by drilling wells and used to produce heat or generate power. Power generation and distribution of heat may be combined in co-generation power plants and cascade utilisation may increase the total efficiency of the energy extraction process. The technology is at different levels of maturity, depending on the specific energy product (electricity or heat) and, in the case of heat, the conversion process, where geothermal energy may be used directly (e.g. district heating) or indirectly (e.g. heat pumps).

At European policy level, a shared regulatory framework that concerns geothermal power plants and their related emissions is not currently addressed. Regulations and requirements vary among the Member States and are to be found in various fields, such as, environmental regulations (air emissions, water emissions, etc.), mining and energy management. Within the process of proposed revision of Renewable Energy Directive (RED), the need of in-depth analysis of all emissions related to geothermal activities was raised by some proposed amendments.

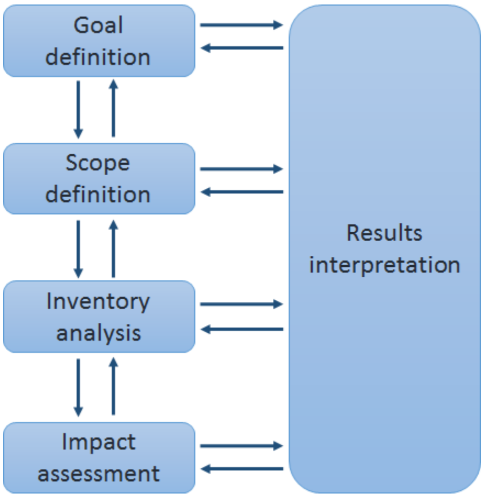
The need for a clear and comprehensive assessment of the emissions from geothermal plants and applications is indeed founded on a growing debate on the topic owing to not-harmonized positions of the various stakeholders involved. The lack of a consistent, harmonized and exhaustive assessment on the basis of the state-of-the-art is retrievable from the scientific panorama.

2 OBJECTIVES AND RATIONALE OF THE STUDY

The present study falls within the outstanding need of a clear and comprehensive assessment of the emissions from geothermal plants and applications, and their potential impacts on environment and human health.

Owing to the uniqueness of each geothermal reservoir and the numerous technological options to produce and utilize geothermal energy, a challenging methodological approach to perform the data collection has been elaborated, through the development of a strategy to cluster the installations by considering geographical and technological representativeness. In order to solve any potential issue of fragmentation of information, uncertainty and doubts about the reliability of data and methods, the process included a validation step by inviting a panel of sectoral stakeholders to evaluate the proposed strategy.

On this basis, the principles of Life Cycle Assessment have been applied in order to tailor a set of common and transparent rules for a sectoral approach.



The **Life Cycle Assessment (LCA)** is a structured, comprehensive and internationally standardised methodology, quantifying the environmental impacts associated to the life cycle of a product, a service or a process, regulated by ISO 14040:2006 and ISO 14044. Within this study, it is used to evaluate the potential environmental impacts associated to the geothermal sector. The LCA methodology consists of four phases (Figure 1):

1. Goal and Scope
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Results interpretation

Figure 1: LCA framework

The developed inventories and the outcoming results of the impact assessment, respectively for power production and heating & cooling applications, are the main outcomes of this study, which can represent valuable input to drive the future developments at research and policy level within the context of renewable energy and decarbonisation targets.

3 VALIDATION OF THE APPROACH AND FINDINGS

Validation of approach and findings constitutes a crucial factor for the robustness of the results of this study. To this purpose, stakeholders' engagement is pursued at different levels, namely:

- synergies with other EU projects and initiatives
    - GEOENVI project: GEOENVI project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 818242.
    - GEOENVI project aims at answering environmental concerns in terms of both impacts and risks, by first setting an adapted methodology for assessing environment impacts to the project developers, and by assessing the environmental impacts and risks of geothermal projects operational or in development in Europe. The project will propose recommendations on harmonised European environmental regulations to the decision-makers and elaborate simplified LCA models to assess environmental impacts of deep geothermal energy production. Continuous communication between the projects is facilitated by the fact that VITO is partner of GEOENVI consortium also, enabling a smooth cooperation of the two research teams. E-mail exchanges

and dedicated teleconferences are ongoing since the first months of activities, for specific presentations, exchange of input and information, data sources, expert's judgement, templates for literature analysis and data collection. Some GEOENVI case studies can be investigated for mutual purpose.

    - GECO is an innovative EU funded research project which aims to provide a clean, safe, and cost-efficient non-carbon and sulfur-emitting geothermal energy across Europe and the World. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 818169.
    - Within the panel of experts participating to the validation workshop of this study, planned at month 5, two representatives of two partners engaged in GECO project were selected (i.e. from Storengy and Magma Energy, controlled by Graziella Green Power), in order to facilitate the possible input from the parallel project, especially as regards possible mitigating pathways. Furthermore, OR – coordinator of GECO project – was contacted and invited to the validation workshop; unfortunately, attendance was not possible owing to some unexpected travel issues, but OR expressed positive commitment in establishing collaborations with our study

- Therefore, OR has been inserted in the list of stakeholders to be contacted for dedicated interviews in case of need for specific insights;
- Under the "Single Market for Green Products Initiative", the European Commission proposed the Product Environmental Footprint (PEF) and Organisation Environmental Footprint (OEF) methods as a common way of measuring environmental performance. The approach was tested between 2013-2018 together with more than 280 volunteering companies and organisations. A new Technical Advisory Board (TAB) is now in place to discuss methodological issues in the context of the Environmental Footprint transition phase. Carlo Strazza, Life Cycle Assessment expert and leader of Task 2 and Task 3 of this study, has been invited to become member of the first Technical Advisory Board (TAB) meeting, that took place on 15 and 16 May 2019 at Centre Albert Borschette (CCAB) in Brussels.
- The TAB is meant to provide advice and expertise to the Commission. The issues to be discussed might include: analysis of the content of newly developed rules, consistency of approaches, technical advice to the Commission in case of issues related to the implementation of existing rules, and new methodological developments seen necessary within the EF context, covering all phases of the process, from the creation of datasets and models up to the review and verification procedures. The TAB meetings will take place at least three times per year. Owing to this direct contact and relation with LCA experts of PEF initiative, additional value for the study can be created for instance for selection of Category Rules, use of dedicated software tools for generation of LCI datasets, and implementation of Life Cycle Impact Assessment methods in line with the recent methodological advancements driven by the European Commission.

- Panel of selected experts

A panel of 10 experts was selected to actively participate to the project, attending the validation workshop and the final workshop, maximising the presence of industry, both from geothermal plants and DHC applications, well covering the different geographical contexts, and including a LCA expert with the assigned role of external LCA reviewer.

The list is reported below (in alphabetical order):

- Fausto Batini (Magma Energy);
- Laurent Escare (Storengy);
- Adele Manzella (CNR-IGG);
- Marco Paci (Enel Green Power);
- Paula Perez-Lopez (Mines Paris Tech);
- Guillaume Ravier (ES Géothermie);
- Dorothee Siefert (ENBW);
- Asgerdur Sigurdardottir (Landsvirkjun);
- Romina Taccone (Enel Green Power);
- Bodo von Duering (CloZEd Loop Energy AG, AATGeothermae d.o.o.).

The experts invited and participating in the workshops were preliminary engaged by sending some background material (i.e.: a working document summarizing the research conducted in the first phases of the project, with preliminary draft of LCA rules definition), in order to optimize the available time during the workshops focusing on finding consensus.

In addition, Luca Guglielmetti joined the team as contributor and reviewer.

- Validation workshop

At month 5 of the project, on April 10th 2019, a methodology validation workshop was held in Brussels, with the main objective to fine-tune the methodology proposed by the Consortium and to ensure the support of the sectorial players for the investigation and the analysis to be conducted.

The findings of the study were presented by Carlo Strazza and Nicolò Olivieri (RINA), Ben Laenen (VITO), Anna Karamigkou (EY). From EC side, Matthijs Soede (DG RTD), Eva Hoos (DG ENER), and Susanna Galloni (INEA) have participated to the event.

After presentation of the study and objectives of the workshop, accompanied by single introductions of the participants, an interactive discussion was held, aimed to investigate any technical issues to refine and validate the methodology proposed for the study.

In particular, a selection of highlights was pointed out on the proposed approach by the panel of 10 selected experts, to be considered for the future developments of the study.

- Final workshop

At month 14 of the project, on February 4th 2020, a final workshop was held in Brussels with the aim of presenting the results of the study to interested experts and stakeholders and discuss technical issues and to collect suggestion for improvement.

The final workshop was organized to be part of a wider initiative called “Two days Geothermal Brussels events” (Brussels, 4th and 5th February 2020), promoted by EGEC.

The findings of the study were presented by Lorenzo Facco, Alessandro Venturin, Giorgio Urbano, Silvia Vela (RINA) and by Ben Laenen and Virginie Harcouet-Menou (VITO). From EC side, Matthijs Soede (DG RTD) attended the event.

During the event, also members from the GEOENVI project presented the status of work and intermediate findings of the GEOENVI project.

In order to guarantee the participants the possibility of contribute to the validation phase, after the workshop, they were sent the support slides and they were asked to provide feedback in written form. In parallel, also comments on the draft report from the panel of experts, GEOENVI and EGEC organisation were collected.

All the relevant comments received have been integrated for the drafting of the final version.

METHODOLOGY

This chapter introduces the full methodological framework developed for the purpose of this study, including the clusterisation of geothermal installations by geological and by technological features, the presentation of the key parameters used for data collection and calculation as well as the methodological guidelines to perform an LCA-based study addressing the impacts of the geothermal sector.

4 MAPPING AND CLASSIFICATION OF RESERVOIRS

4.1 Methodological Approach

Gas emissions of geothermal applications display a large variability. Emissions of the geothermal installations depend both on geological and technological factors.

The direct emissions are strongly related to the local geology (e.g.: volcanic setting vs. sedimentary basin), the type of geothermal play (i.e.: volcanic vs. hydrothermal) and the characteristics of the geothermal resource (e.g.: fluid composition, gas, content and composition, temperature, pressure). They also strongly depend on the type of production technology and operation plants parameters (e.g.: reinjection, presence or not of abatement systems).

On the other hand, indirect emissions associated with materials manufacturing and energy production are also influenced by the type of production technology (e.g.: construction materials for heat exchangers, turbine), operational plant parameters (auxiliary power consumption) and by geothermal resource characteristics (e.g.: depth, composition of the brine).

Consequently, the assessment of the impact of direct and indirect gas emissions of the geothermal sector in Europe must take the variability of these parameters into account.

4.2 Main Geothermal Areas of Europe

In the study, the range of geological conditions encountered in Europe is covered by mapping the characteristics geological and reservoir conditions in the main geothermal areas of Europe: i.e. the Pannonian Basin (covering Hungary, Serbia, Croatia, Slovakia, Romania, Austria), the Molasse basin (Germany, …), the South Permian Basin (covering United Kingdom, The Netherlands, Denmark, Germany, Poland and Lithuania), the Paris and Aquitaine basins (France, Luxemburg), the Upper Rhine graben (France, Germany), the Iberian Peninsula (Spain, Portugal), the Italian peninsula (Tuscany, Campania Emilia-Romagna, Sicily & Sardinia) and Iceland, the southern Balkan region (Albania, Bosnia Bosnia-Herzegovina, Bulgaria, Greece) and the Greek Islands (Greece).

For each area, information on the type of resource, type of host rock, depth range, temperature range, gas content, fluid and gas composition and presence of hydrocarbons has been mapped. All information has been stored in a relational database for easy access and further data analyses.

4.3 Classification of the Geothermal Resources

The geothermal resources can be classified based on different criteria, that can impact direct and/or indirect gas emissions from geothermal applications.

The main criteria that can be used when classifying the resources are the following:

- temperature of the system;
- depth of the system;
- dominant phase (liquid, vapor or gas);
- type of host rock (igneous, carbonates,sandstones, ...);
- reservoir type (matrix, void, fracture, ...);
- stimulation requirements (hydrothermal or EGS).

4.3.1 Temperature

Geothermal systems are commonly classified based on the formation temperature into:

- low (<100°C);
- intermediate (between 100°C and 250°C);
- high temperature (>250°C) geothermal systems.

This classification reflects the different uses of geothermal depending on the resource temperature (Fridriksson et al., 2016). Low temperature systems are generally suitable for direct applications. In Europe they are widely used for district heating, industrial drying, greenhouses and spa applications, etc. Additionally, intermediate and high temperature systems are suitable for industrial heat processes, combined heat and power production and for purely power production, using different energy conversion technologies. In Europe, power production from high temperature systems (>250°C), is most commonly achieved using direct (dry steam) or flash steam turbine technology. The high temperature systems are restricted to Iceland and Italy. Furthermore, power from intermediate temperature geothermal systems is achieved by using binary technology in France, Belgium, Austria, Germany, Portugal and Romania.

4.3.2 Dominant Phase

Geothermal systems can also be classified based on the dominant state of the fluid in the reservoir. Whereas low and intermediate systems are always single phase liquid, high temperature systems can be either liquid or vapor dominated. Liquid-dominated geothermal systems are the most common type in Europe whereas vapor-dominated (dry steam) systems are only present in Tuscany (Italy) and Iceland. Additionally, steam dominated zones or “steam caps” within liquid-dominated reservoirs in production are also exploited for power production in Iceland and Italy.

The type of dominant phase of the system has implications on the presence of geothermal gases as they partition preferentially into the vapor phase (Fridriksson et al., 2016). Hence, geothermal power plants producing from vapor-dominated systems or steam zones as opposed to fully liquid-dominated reservoirs tend to have higher gas emissions.

4.3.3 Depth of the Reservoir

Geothermal systems can also be classified based on the depth of the reservoir. Shallow geothermal covers systems that can be used to extract and store heat for heating and cooling by means of groundsource heat pumps. For this study, the focus is on geothermal systems where the heat is directly used for either electricity production of for heating and/or cooling. Generally speaking, it concerns systems that target geothermal fluids at a depth greater than 1,000 meters, because from that depth the heat can usually be used directly for space heating. The term ultra-deep geothermal systems is also used to discrimate systems with depth greater than 4,000 m.

The depth of the reservoir will influence its pressure and temperature, which can impact the gas partition in the geothermal fluid. Moreover, the depth will influence the indirect emissions of a geothermal project, since deeper wells require higher amount of materials. Indeed, the deeper the reservoir the deeper the wells to be drilled and the more material needs to be used for the casing and cement. Additionally, permeability usually decreases with depth and some stimulation is likely to be required in deep and ultra-deep projects.

4.3.4 Host Rock

Geothermal systems can also be classified based on the reservoir host rock. In Europe, geothermal reservoirs are hosted by several types of rocks, including, igneous rocks, sandstones, carbonates and metamorphic rocks.

Igneous rocks are the host of most high temperature geothermal systems (for example in Iceland), however they can also occur in carbonates or metamorphic rocks. In Tuscany the main part of production is from metamorphic rocks including phyllites, gneiss and micaschist and, locally, granite. In Europe, carbonates also constitute the host rocks of low and medium temperature geothermal systems in France (Aquitaine Basin, Paris basin), Gemany (Molasse basin), Hungary (Pannonian Basin), Austria (Molasse basin and Pannonian Basin), Belgium (Paris-Hamsphire basin and West Yorkshire-Netherlands Basin), Croatia (Pannonian Basin) and Italy (Po Valley Foredeep, Tuscany) Poland (Carpathian Foredeep), and Romania (Pannonian Basin).

The nature of the host rock and the burial history of the basin have some implications on the fraction of the CO_2 in geothermal fluids. Indeed, a large fraction of CO_2 is derived from chemical interactions between the geothermal fluid and the host rock. CO_2 concentrations in the fluid depends on equilibrium between carbonate minerals (mainly calcite) in the rock and the fluid (e.g.: Arnorsson, 1986 and Giggenbach, 1980). Hence, carbonate rocks are prone to release larger amount of CO_2 than igneous rocks. The same holds true for carbonate-dominated metamorphic rocks such as marbles, dolomitic marbles and calc-schists dominate reservoir rocks where the calcite content of the host rock provides a large potential source of CO_2 when it equilibrates with the fluid.

Note that additionally to the nature of the host rock, Ármannsson (2016) states that the origin of CO_2 in fluids from Icelandic high-temperature geothermal systems is predominantly magmatic. In Krafla, CO_2 can enter the geothermal system from below in pulses following magmatic intrusions. There, gas concentrations in steam were relatively high during the late seventies and eighties due to magmatic gas.

4.3.5 Types of Geothermal Systems: Hydrothermal Versus EGS

Finally, geothermal systems are often divided into two main types, hydrothermal systems and Enhanced Geothermal Systems (EGSs).

Naturally occurring geothermal system are known as hydrothermal systems and are defined by three key elements: heat, fluid, and permeability at depth. The technology associated with hydrothermal power and heat production may be considered as mature.

Additionally, Enhanced Geothermal Systems cover projects for which the productivity/injectivity of one or several wells is not high enough even after post drilling acidification (common practice) and for which additional stimulation is required. Note that hydrothermal plants also perform stimulation sometimes using small amounts of acids to clean the near wellbore region. In EGS projects, the stimulation can be chemical, thermal or hydraulic.

EGS is not yet considered as a fully mature technology. It has been proven in small scale projects since 2007 but is still in development. In Europe, several projects can be qualified as EGS projects, among others, Soultz-sous-Forêt, Rittershoffen, Le Mayet (France), Falkenberg, Horstberg, Landau, lnsheim, Bad Urach (Germany), Basel, St. Gallen (Switzerland), Fjallbacka (Sweden), Rosemanowes (UK), and Otaniemi (Finland). Except for Soultz-sous-Forets, Rittershoffen, Insheim and Landau, the listed projects were research / demonstration projects that were not taken into production.

To date, the large majority of geothermal energy extraction is done from hydrothermal resources and few small EGS in operation exist (JRC report, 2014).

Treyer et al (2015) underline that the number and depth of wells and the lifetime achieved by the wells have a higher influence on environmental impacts than the differences between petrothermal and hydrothermal per se.

4.4 Inventory of the Operational Geothermal Plants within the EU

Besides the classification of the geothermal resources, to tackle the link between the type of resource, their geographical location and the type of applications, an inventory of the geothermal plants that are in operation within the EU has been made. A desk-based review of the publicly available data and literature, complemented by data collected from plant operators was performed.

4.5 Definition of Resource Categories

The inventory has been used to define a number of resource categories that are representative for the geological conditions encountered in geothermal reservoir within Europe. There are presented in Table 1. First, the resources have been classified based on the geological play, the dominant phase, the temperature, the type of host rock lithology. Additionally, to show the differences in geothermal applications, each category is linked to a given use. The geographical coverage of the categories is also specified.

Table 1: Resource categories

Geological play	Dominant phase	Temperature	Host rock/Lithology	Use	NCGs	Country	Geological setting
Volcanic	Vapor	150-250	Basalt	Electricity and co-generation	CO_2, H_2S, CH_4, H_2, N_2, Hg, As, NH_3	Iceland	Iceland Mid Oceanic Ridge (IS)
	Liquid+Vapor	130-300°C	Volcanics	Electricity	CO_2, H_2S, CH_4, N_2, NH_3	Portugal (Acores)	Azores Triple Junction (PT)
	Liquid	75°C	Basalt	DH	N_2, Ar	Iceland	Iceland Mid Oceanic Ridge (IS)
Magmatic intrusive	Vapor	>200°C	Carbonates, metamorphic	Electricity, co-generation	CO_2, CH_4, H_2S, Hg, As, NH_3	Italy (Tuscany)	Back-arc basin (IT)
	Liquid+Vapor	>150°C	Carbonates, metamorphic	Electricity, co-generation	CO_2, CH_4, H_2S, Hg, As, NH_3	Italy	Back-arc basin (IT)
	Liquid	140<T<220°C	Carbonates, metamorphic	Electricity, co-generation	CO_2, CH_4, H_2S, Hg, As, NH_3	Italy	Back-arc basin (IT)

Geological play	Dominant phase	Temperature	Host rock / Lithology	Use	NCGs	Country	Geological setting
Basement	Liquid	<100°C	Granite	DH, Agriculture		Czech Republic, (Finland)	Bohemian Massif (CR, D, PL, A), Rhodope Massif (BU, GR), Bosnian-Serbian-Macedonian Massif (MK), Fennoscandian shield (FIN)
Extensional, fault-controlled	Liquid	>110°C	Sandstones, Granite	Electricity, co-generation, heat production for industrial use	CO_2, CH_4, N_2	France, Germany	Rhine Rift (D, FR)
	Liquid	<100°C	Limestone	DH		Switzerland	Rhine Rift (CH)
	Liquid	<100°C	Carbonates, dolomites, limestones, Sandstones	DH	CH_4, CO_2, H_2S	Hungary, Austria, Croatia, Romania, Serbia, Slovakia, Slovenia	Pannonian Basin (HU, SL, PL, AU,RO, SR)
	Liquid	>150°C	Carbonates	Electricity	CO_2, H_2S	Croatia	Pannonian Basin (HU, SL, PL, AU,RO, SR)

Geological play	Dominant phase	Temperature	Host rock / Lithology	Use	NCGs	Country	Geological setting
Intracratonic	Liquid	>100°C	Carbonates, dolomites, limestones	Co-generation	CO_2, CH_4, N_2	Belgium	West Yorkshire-Netherlands Basin (GB, NL, BE)
	Liquid	<100°C	Sandstones, limestone, dolomite, carbonates	DH, Agriculture	CO_2, CH_4, H_2S, N_2	France, Germany, Belgium, Netherlands, Poland, UK, Spain, Sweden, Denmark, Lithuania	Aquitaine Basin (FR), Paris-Hampshire Basin (FR, GB, BE), North German Basin (D, NL), Warsaw Basin (PL), West Yorkshire-Netherlands Basin (GB, NL, BE), Castilian Basin (ES), Danish-Norwegian Basin (DK), Baltic basin (LT,LV,EE)
Orogenic	Liquid	100-150°C	Carbonates, limestone	Co-generation	CO_2, CH_4, N_2	Germany, Austria	Molasse basin (A, D, CH)
	Liquid	<100°C	Limestone, sandstone, dolomites, carbonates	DH, Agriculture	$C0_2$, CH_4, N_2	Austria, Germany, Italy, Poland, Romania	Molasse basin (A, D, CH), Po Valley Foredeep (IT), Carpathian Foredeep (PL, UA)

5 INVENTORY OF TECHNOLOGIES

5.1 Methodological Approach

Besides the characteristics of the geothermal resource, direct and indirect emissions depend on the design of the well field and the surface installations and the way they are installed. This section depicts the inventory of technologies used for geothermal reservoir exploration, development, engineering, production and abandonment.

Emissions can occur at the different stages of a geothermal project, from exploration to closure. Several emissions influencing technology or design related factors can be identified at each stage. It is worth noting that the representation of the different phases as a purely linear process (such as in Figure 1) is not correct. There are usually several iterations of the different stages. For example, the drilling of a first well can be followed by a phase of testing then by a stimulation step and back to the drilling of a second well that can itself be followed by testing. Additionally, wells can be abandoned during the operational phase of a plant and new wells may be drilled to replace the abandoned ones.

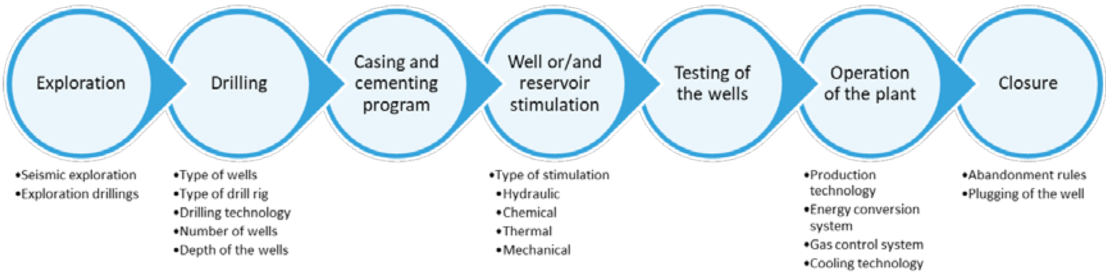


Figure 2: Phases of a typical geothermal project

5.1.1 Exploration Phase

Before the actual development of a geothermal well field, an exploration phase takes place. The only exploration activity that can impact the emissions and whose emissions can be quantified is the seismic exploration. It is the most common exploration technique for low to medium temperature geothermal resources in Europe. The key parameter in terms of emissions is the fuel consumption rate of the trucks and other vehicles that are used during the seismic campaign and the duration of the campaign.

Additionally, exploration wells can be used in the exploration phase. These exploratory wells are used to identify and evaluate geothermal prospects, some of them being used afterwards as production or injection wells and some abandoned and plugged after the exploration phase. There are several options for exploration wells, either exploratory drilling or slim holes or large diameter casings for production wells can be drilled. If the exploration is successful and the exploration wells cannot be used as actual operational wells, additional wells are drilled. Emissions related to exploration wells are related to energy consumption generated by the drilling of the wells.

5.1.2 Geothermal Well Fields

Once the presence of the geothermal resource has been proven, geothermal fluids are extracted through wells drilled into the geothermal reservoir that are ultimatly connected to a power/heating facility. To prevent depletion of the resource as well as to mitigate possible environmental impacts from the discharge of waste fluids or pressure issues in the reservoirs, cooled geothermal fluids are usually re-injected into the reservoir through injection wells. Depending on the application that is targeted (heat and/or power) and on the local geological conditions, the depth of the wells can extend to several kilometers. So-called production and injection wells are used during the actual operation phase of geothermal plants.

Globally, there are more wells being drilled during the lifetime of a project than the actual number of wells currently active. Indeed, many well workovers are executed each year in active geothermal fields to remedy the consequences of the corrosive and solids-laden brines produced to the surface (Richter et al., 2017).

Emissions related with the development, maintenance and abandonment of the well field depend chiefly on the way the wells are drilled, tested, stimulated and abandoned.

The drilling program specifies the type of rig to be used (diesel or electric power rig), the mud program, the casing and cementing program, as well as the well / reservoir stimulation program. It has been reported that the main energy consumers during the drilling phase are the top rig drive, the mud pumps, the draw works and the casing process (Bello and Teodoriu, 2012; Chemwotei, 2010; Legarth and Saadat, 2005).

In this section we present an inventory of drilling technologies, well completion schemes, well/reservoir stimulation techniques and well abandonment that are commonly used in geothermal energy development and production in Europe.

Inventory of Drilling Technologies

The drilling technologies include all the equipment used for drilling geothermal wells that impact direct (diesel burned to supply the engines) and indirect emissions (amount of materials used).

Drilling Methods

Drilling technology plays a key role in the exploration as well as in the production phases of geothermal reservoir development. In terms of financial impact, drilling represents 30 % to 50 % of the cost of a hydrothermal geothermal electricity project and reaches more than 50% of the total cost of EGS. The drilling can also have significant impact on the emissions of geothermal plants.

Several parameters related to the resource characteristics influence the type of drilling technique to be used, among others the:

- temperature of the geothermal fluid;
- type of host rock (sedimentary, hard rocks, …);

- presence and nature of fluid and gases;
- depth of the reservoir and diameter of the holes.

In Europe, the established rotary drilling methods have been largely applied in the development of geothermal wells, especially when drilling into hydrothermal liquid-water and vapor-dominated geothermal reservoirs. When using the classical mechanical drilling the rocks are crushed or scratched by means of a rotating drilling bit. Roller cone bits and drag bits are the two main possible designs. The roller cone bits are preferably used in hard rock formations where they are used to crush the rocks. The drag bits, on the other hand, scratch and shear the formation (Teodoriu & Cheuff, 2011). Combination of the two methods is also possible.

Promising innovative drilling technologies and additional information about drilling are presented in ANNEX I.

Drill Rig

Diverse LCA studies showed that diesel consumption of the drilling rig has one of the biggest impacts on the environment (Frick et al., 2010; Gerber and Marechal, 2012; Lacirignola and Blanc, 2013). It is as such a key factor to consider when addressing emissions from geothermal plants.

Geothermal drilling rigs are mainly manufactured by oil and gas drilling rig manufacturers. There are three different types of rigs on the market today: mechanical, electric and fully hydraulically operated rigs. The amount of fuel or energy consumption depends on the site-specific machine capacity.

Rotary drilling, which is the most common drilling practice, can be applied by diesel-electric rigs to create boreholes.

Diesel rigs imply the use of diesel fuel as a mean of generating the required power for the equipment in the rig. Diesel is used by generators to produce the required electric power for both the DC and AC equipment on the rig. Diesel is also used by the air compressor machines used during aerated mud drilling process. The average diesel consumption of the drilling rig (liters of fuel per day of operation) will directly impact the emissions from the drilling phase. The highest CO_2 emissions from geothermal power plants are often indirect emissions resulting from drilling with diesel powered rigs. Any reduction in the drilling time will as such reduce the fuel consumption and hence indirect emissions.

One alternative to diesel rigs is the use of electric rigs. A quantitative comparison of physical size and economics shows that rigs powered by the electrical grid can emit fewer emissions and have a smaller surface footprint than conventional diesel-powered drilling, (Verma, 2009). Treyer et al. (2015) mention that in Switzerland, the energy source for the drill rig was electricity from the grid. Diesel is only used as a stand-by and for activities on or related to the drill site. Electricity from the grid was also used in several projects in the Netherlands and while drilling the geothermal wells of the Balmatt plant in Belgium.

Another possibility, in multi-production well geothermal developments, is to use the power generated by modular small power plants run on steam from previous wells. By doing so, the total CO_2 emissions are considerably reduced. This setup however requires some adjustment to the existing drill rigs. Kigen (2016) mentioned such a setting, where part of the electrical power from wellhead units can be used at the rigs to substitute electrical power from the generators. The author mentioned that by doing this they could achieve savings of up to 70% of the total fuel consumed by the rigs. This is possible when drilling on the same pad as the wellhead units or when the rig is drilling on a pad near a wellhead generator. The remaining 30% of the fuel will continue to be used by the rig aerated system since the equipment are engine driven. Alternatively, the rig can also take power from the utility grid. Verma (2019) concluded that electricity as an alternate energy source with peak shaving technology can be used to power the rig.

5.1.3 Well Completion Schemes

Although fiber glass casing can be a solution to reduce carbon footprint and increase the lifetime of the wells (no corrosion), such a casing can currently only be applied in low temperature reservoir (<100°C). As a result, most of the geothermal boreholes are protected by steel casings. And for each geothermal well that is drilled a well's casing programme is prepared in compliance with the practice codes for deep geothermal wells. The casing program is designed uniquely as each well will have a specific diameter and depth depending on the local geological conditions. Casing is required for several reasons such as to prevent the hole from collapsing, to support drilling and permanent wellheads. Casing is also necessary to prevent contamination of subsurface aquifers from well fluids and from mixing different aquifer waters as well as to counter circulation losses during drilling, and to protect the integrity of the well against corrosion, erosion or fracturing. The casings are arranged one inside another until the target depth is reached. The final diameter is only a small fraction of the initial diameter on the surface.

Dumas et al. (2013) stress that the large flow rates required in geothermal applications necessitate large diameter production casings and liners. Typical standard diameter wells utilise a standard API 9 5/8" casing as production casing and either 7" or 7 5/8" diameter slotted liner in an 8 ½" diameter open hole. Typical large diameter wells utilise a standard API 13 3/8" casing as production casing and either 9 5/8" or 10 ¾" diameter slotted liner in a 12 ¼" diameter open hole. In general, the diameters and depths for casings depend on geological and thermal conditions.

In parallel to the casing program, a cementing program is prepared for each well. Geothermal cements aim at tying well casing to the rock formation. They hydraulically isolate the well from geological strata other than those related to production and injection and must resist attack by substances present in geothermal reservoirs.

Steel and cement use are a function of well depth and diameter as well as the design of the casing (length of the different sections).

Casing and cementing do not generate direct emissions, however, the type of cement and type of material used for the casing will impact the indirect emissions. Additionally, the technique to be used for the casing and cementing may impact the duration of the drilling operation. Technologies such as casing while drilling or expandable casing that are being developed tend to reduce the energy consumption and drilling time.

5.1.4 Summary - Drilling Impact on Emissions

Pratiwi et al (2018) mentioned that the fuel consumption of the drilling range between 3.9 GJ and 7.4 GJ per meter of well drilled for the wells of Soultz-sous-forêts and Rittershoffen and other literature studies reported values between 2.1 GJ/m and 9 GJ/m. All studies assumed diesel for energy use, except for the study in Switzerland where electricity is used. Treyer et al. (2015) mention that the values for diesel are valid for the input of diesel, whereas the electricity stands for the actual energy used. Treyer et al. (2015) assume that the variability may result from the difference in rock type, the technology and equipment and the actual progress of the drilling process.

In general, drilling energy consumption tend to increase exponentially as a function of the well depth, the well diameter, the drilling mud used and the capacity of the drilling rig (Bello and Teodoriu, 2012; Legarth and Saadat, 2005).

Table 2: Energy consumption for drilling according to various studies - Modified from Treyer et al. (2015)

Energy consumption for drilling of geothermal wells	GJ/m		Diameter [cm]	Depth [m]
	Diesel input	*Electricity use*		
Rogge (2004); EGS	5		n.s.	>3,000
Kayser (1999); EGS	2.1		n.s.	1,300-2,500
Treyer and Bauer (2012); EGS	7		20-40	5,500
Frick *et al.* (2010); Léda Gerber and Maréchal (2012); EGS	7.5		n.s.	n.s.
Lacirignola and Blanc (2013); EGS	4.0		n.s.	n.s.
Treyer et al. (2015)		8.5/11.3/14.1	25.4 (smallest diameter)	3,000/4,000/5,000
Pratiwi et al. (2018) GRT-1/GRT-2/assumption taken for Illkirch	4.21/7.08/5.8			2,580/3,192/3,192
Pratiwi et al. (2018) SsF GPK-3/SsF GPK-4	3.9/7.4			5,100/5,200

In addition, while drilling a geothermal well, emissions of natural gas from the ground are avoided as much as possible but remain possible. Such gas emissions depend on the site's geological characteristics. Gas emissions include gas escaping from the mud during regular circulation as well as (unforeseen) gas kick when entering a gas pockets or gas-containing reservoirs. In the latter type of gas emissions can be expected, it is regulare practice to install equipment to handle any gas break-out, e.g., a blow-out preventor, gas gathering system, flare.

5.1.5 Inventory of Well / Reservoir Stimulation Techniques

Geothermal reservoirs presenting low permeability can be stimulated to improve the connectivity of the boreholes with the reservoir. Two main types of stimulation are used: hydraulic stimulation and chemical stimulation. Additionally, in hot temperature reservoirs, thermal stimulation can be applied to the system to increase the permeability. Finally, radial jetting which is a technique that has been used extensively in the oil and gas sector is being developed for the geothermal sector. These four techniques and their impact on emissions are detailed in the following sections.

Hydraulic Stimulation

Hydraulic stimulation is achieved by injecting a large quantity of fluid into the subsurface under carefully controlled conditions, which cause pre-existing fractures to re-open, or new fractures to open creating permeability. Hydraulic, often augmented by chemical stimulation, is the most common stimulation technique used in EGS systems.

Hydraulic stimulation requires diesel power (Sullivan et al. 2014). Therefore, the emissions from the construction of EGS plants are higher than those for HT plants. Josifovic et al. (2016) state that studies have shown that over 90% of the emissions of CO_2 and other pollutants that occur during a hydraulic fracturing operation are associated with the pumps required to provide the high pressure and flow.

Treyer et al. (2015) made a first estimate of energy and water use for the hydraulic stimulation based on data on Basel published by Ladner and Häring (2009), which results in an electricity use of approximately 11 kWh per m^3 of water used.

IEAGHG (2013) indicates a minimum, mean and maximum diesel consumption of 3.6, 7.2 and 10.8 liters per m^3 of fracking fluid used. Sullivan et al. (2010) give a value of 118.5 m^3 fuel used per stimulation. Treyer et al. (2015) together with another report by the same authors on water consumption (Clark et al., 2011), estimated that the electricity use amounts to 102–133 kWh/m^3. In contrast, calculations from Frick et al. (2010) showed again a quite low energy use of only 14 kWh/m^3.

The amount of water used depends on the geological conditions and as such will be somehow site specific.

Direct greenhouse gases emissions due to flaring of natural gas from the subsurface layers during the stimulation are possible but as during the drilling phase they are sent to a flare stack and for the most part burned with CO_2 as a product.

Table 3: Water and energy use for hydraulic stimulation of EGS systems - Modified from Treyer et al. (2015)

References	Water use	Energy use	Energy use / water use
	m^3/stimulation	*kWh/stimulation or*	*kWh/m^3 or*
		MJ/stimulation	*MJ/m^3*
		l diesel/stimulation	*l diesel/m^3*
Ladner and Häring (2009) * energy use from Treyer et al. 2015	12,000	118,799*	11*
IEAGHG (2013)/ shale gas; * energy use in kWh from Treyer et al. 2015	20,000		171-513
		5,803,200	145-435
		144,000	3.6-10.8
Sullivan *et al.* (2010) + clark et al. (2012); * energy use from Treyer et al. 2015	26,939		102-133
		4,775,550	177.27
		118,500	4.40
Frick *et al.* (2010); * energy use from Treyer et al. 2015	260,000	3,564,000	14.00
		3,000,000	11.54
		74,442	0.29
Treyer et al. (2015)	40,000	4,000,000	100.00
Clark et al. presentation	22,390	1,326,541	59.25
		4,775,550	213.29
		118,500	5.29
Lacignorela & Blanc (2013)	20,000		
		1,400,000	70.00
		34,739	1.74

Chemical Stimulation

Chemical stimulation of geothermal wells is a common practice in hydrothermal systems and EGS. Acidisation is one of the oldest stimulation technologies in the oil and gas industry. This low-cost stimulation treatment is also the most common soft stimulation technique in geothermal well operations in carbonate reservoirs. Several studies have shown the utility of chemical stimulation in geothermal wells (Straw 1980; Epperson 1983; Bareli et al., 1985; Barrios et al., 2002; Serpen and Türeyen 2000; Nitters et al., 2000).

It aims at improving well productivity/injectivity by enhancing rock permeability without damaging the host rock.

Acidizing is accomplished by injecting a low pH fluid to dissolve and/or disperse materials that impair well production with application pressure less than the fracturing gradient. The choice of acid depends on the underground reservoir characteristic and the specific intention of the treatment, for example near wellbore damage removal, dissolution of scale in fractures. The design of the acid treatment must account for the type of rock, number and thickness of the permeable zones, extent of skin damage and level of steam fraction (Akin, et al., 2015). Matrix acidizing typically uses HCl in carbonates with acid concentration of ~15% HCl to dissolve blocking minerals. Additives to the acid mixtures include corrosion inhibitors and intensifiers to reduce the corrosion rate of the casing and equipment, using pre-flush and post-flush to reduce the formation of insoluble precipitates.

Thermal Fracturing

Thermal fracturing is a stimulation phenomenon that occurs when a fluid (e.g.: produced water, seawater, aquifer water or surface water) is injected into a considerably colder host formation (Flores et al., 2005). Injection of the cooler water leads to thermal contraction of the reservoir rock in the region near the injection well, reducing the stresses and hence leads to consequent expansion of fractures. In that sense, thermal stimulation is distinct from hydraulic stimulation as it does not rely on the raise of fluid pressure to create or expand fractures.

In the field, in injection wells it has often been observed that injectivity increases with injection time, and with the temperature contrast between reservoir and injection temperature (Lim et al., 2011, Grant 2012). The occurrence of thermal fracturing during cold-water injection into porous and permeable classic formations is well documented. The technique is better suited for high temperature wells. Indeed, thermal fracturing will not always be a technically suitable solution – for example, if large enough thermal gradient cannot be reached or if it is required to dissolve material that is blocking the flow.

When thermal fracturing is technically feasible there are several advantages compared to other stimulation techniques to generate a near wellbore fracture network that will reconnect to a main reservoir flow system. Besides being a low-cost technique, the fluid that is used is much less aggressive than usual acids presenting minimal health, safety & environmental issues and is easy-to-prepare because of its simple chemistry. In addition, thermal fracturing requires mobilisation of a minimum of equipment and high pump pressures are normally not required.

Radial Jetting

Radial jetting relies on the creation of a large number of small canals (laterals) to generate better connection between the wellbore and the geothermal reservoir.

Radial jetting is frequently used in the oil and gas industry. In recent years, the application of the radial water jet drilling (RJD) technology has been considered and investigated to perforate and stimulate low performing wells (e.g. Buset et al., 2001; Bruni et al., 2007; Cirigliano and Talavera Blacutt, 2007; Seywald and Marschall, 2009; Abdel-Ghany et al., 2011; Elliott, 2011; Cinelli and Kamel, 2013). Reinsch et al. (2017) describe in detail the RJD technology. First a bottom hole assembly (‘deflector shoe’) connected to a tubing is lowered to the target depth, where the laterals must be jetted. For cased hole intervals, first a hole must be milled into the casing. For open hole completion, this step is not necessary. Subsequently, a jetting assembly which consists of a self-propelled jetting nozzle attached to a flexible hose is lowered in the well. This technique can jet up to 100 m into the formation.

If the technique proves to be applicable successfully in deep geothermal wells it will most probably be used extensively in context of deep and ultradeep geothermal developments in Europe. However, this will imply both, many laterals and high acid concentration at high temperatures due to low jetting pressure (due to severe pressure loss over 5000 meters 5/8“ coil tubing).

With regards to emissions, the use of materials depend mostly on the lifetime of the coil tubing and the technique requires the use of pumping power for the jetting operation. The composition of the chemicals to be used in combination with high temperature reduces the lifetime of the coil tubing sometimes to less than 10 jobs. Additionally, the replacement of a coil will impact the direct emissions as increase the jetting time with 10 to 50%.

Radial jetting is not considered as a mature technology in the geothermal sector.

5.1.6 Well Testing

During the well testing phase direct emissions of GHG can happen while geothermal fluid is being discharged at the surface to the basin. The quantity of CO_2 and other gases released depends on the chemical composition of the geothermal fluid and on the solubility of the gasses.

5.1.7 Well Abandonment

At the end of their lifetime or of the lifetime of the geothermal plant, the wells will be abandoned. This phase is particularly important because of aging, the well can suffer from corrosion and might allow communication between different aquifer layers. Consequently, to avoid contamination of ground water in the aquifers cross cut by the wells after their closure, critical sections of the wells must be plugged by cement. The proper plugging of the wells is also important to prevent blowouts which typically occur due to the failure of some well component or well-casing corrosion.

The plugging of the wells is also important to prevent any gas emissions from the abandoned wells.

5.2 Inventory of Technologies Related with the Production of Geothermal Energy

In the following section, an inventory of technologies used to produce the energy is presented. It includes geothermal fluid production technologies, power and heat/cooling generation technologies, cooling technologies, and gas control technologies.

The inventory is used to define a number of representative geothermal plant typologies in Europe.

5.2.1 Geothermal Fluids Production Technology

To use geothermal energy, it is necessary to get geothermal fluids and steam to the surface.

In steam geothermal systems (back pressure, condensing, two-phase binary), the driving force for the flow of the geothermal fluid from the subsurface to the plant is the pressure difference between the geothermal resource and inlet at the power plant. Therefore, no pumping is needed.

However, geothermal processes using a liquid (single-phase or pumped binary) usually require the use of pumps to lift the geothermal fluid from the subsurface to the plant. Although, sometimes fluids may also flow naturally to the surface (self-flowing).

Additionally, downhole pumps can be installed not only to lift the geothermal fluid to the surface, but also to prevent the release of non-condensable gases. When the geothermal fluid presents a high carbon dioxide content the fluid must be maintained under pressure to reduce corrosion and scaling. Even in self-flowing reservoirs, pumps may be installed to increase the flow rate or to keep the geothermal fluid under pressure to avoid boiling and release of gas, compatibly with the temperature status of the fluid. Geothermal fluids production technologies are detailed in ANNEX.

The main impacts on direct and indirect emissions, related to the different production technologies of geothermal fluids, are summarized in Table 4.

Table 4: Geothermal fluids production technology impact on emissions

Production Technology	Impact on Direct emissions	Impact on Indirect Emissions
Self-flowing	✓ In high temperature settings if the temperature is above the boiling point or if there is a high gas concentration degassing can happen leading to direct emissions of geothermal gas.	
Downhole pumps	✓ NCG can be separated from the geothermal stream and can be treated or rejected; ✓ possibility to prevent degassing by maintaining a sufficiently high pressure.	✓ Additional power consumption; ✓ material use for the pump manufacturing; ✓ replacement of the pump. Typical operational life 4-7 years (ES Geothermie, pers. Com.).

5.2.2 Energy Conversion Technologies

Power

Four basic types of energy conversion technologies are used for geothermal power production. They include condensing plants, two-phase (flashing) binary plants, and single-phase (pumped) binary plants. Power plants where two or more power cycles are combined are referred to combined cycle power plants.

All these technologies, except for the single-phase binary plants with full-reinjection, emit effectively CO_2 and eventually other non-condensible gasses to the atmosphere. Note that the feasibility of total reinjection depends on the gas content in the original geothermal fluid. Today, there is no full-reinjection and zero emission plant worldwide (also based on binary technology), fed with a geothermal fluid characterized by a gas content higher than 1% wt. (Manzella et al. 2017). When combining the technologies, such as in flashing binary plants, the brine can be reinjected as well as the CO_2 in the liquid brine, leading to partial reinjection of the CO_2. However this not a commercial and fully developed technology.

The selection of energy conversion process for a geothermal project depends on several parameters, such as resource temperature, pressure, flow rate, and chemical content.

In geothermal power plants geothermal fluids drives a turbine that generates electricity. The heat is transformed into mechanical energy and then into electricity. Different technologies exist to generate the energy. The fluid sent to the turbine can be the geothermal fluid extracted from the ground (direct or flash steam systems) or a secondary fluid heated by the geothermal fluid through a heat exchanger (binary systems).

The three major conventional geothermal technologies utilized to provide power include:

- dry steam systems;
- flash systems;
- binary systems, based on the Kalina or the Organic Rankine cycle.

Nowadays, both dry steam and flash systems operate with a condensing turbine combined with cooling system (consisting of condenser and cooling tower).

Power conversion technologies are detailed in ANNEX I.

Today, Europe has 117 geothermal power plants in operation, 56 of which in the EU (EGEC Geothermal Market report 2017). The following Figure summarizes the different technologies and the number of plants of each technology as well as their detailed locations.

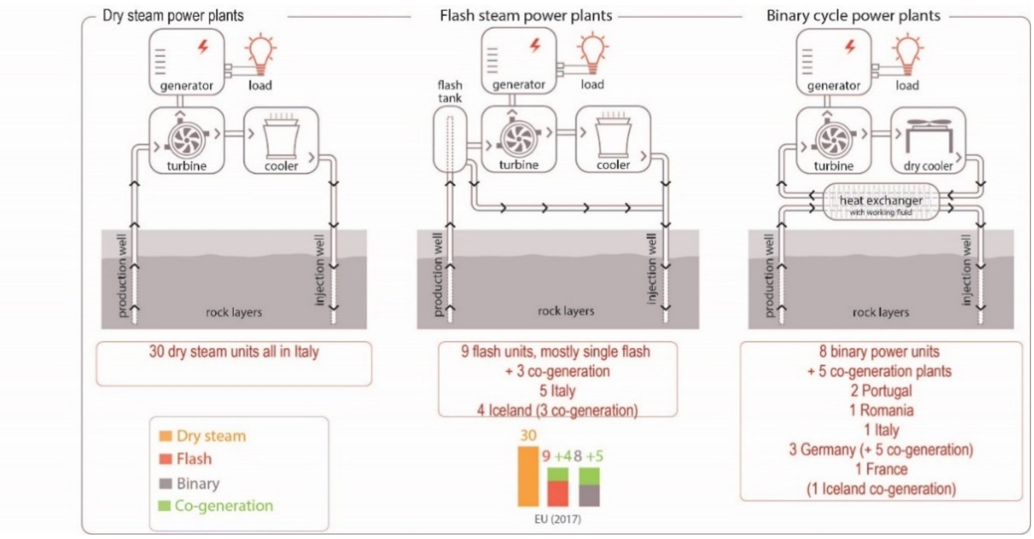


Figure 3: Technologies and comparison of number of units in operation – Modified from ETIP Vision 2018 (EGEC Geothermal Market Report, 2016).

Combined Heat and Power Plant

To increase the efficiency of the power plants, several technologies and type of plants can be combined. For example, combined-cycle flash steam plants use the heat from the separated geothermal brine in binary plants to produce additional power before re-injection.

One of the possible uses of geothermal energy is to provide both electricity and heat to residential, commercial, industrial, or institutional users. Such systems are possible for EGS and hydrothermal systems.

Furthermore, the thermal energy of the brine may also be extracted via heat exchangers prior to re-injection. The overall efficiency of flash plants can be increased by adding heat exchangers and producing hot water since the conversion factor in a heat exchanger is far greater than converting heat to electricity.

In case of geothermal CHP plants, the back-pressure exhaust steam from the main turbine can be used for heating and cooling applications where steam is essential.

Heating and Cooling Applications

In addition to power and CHP plants, in 2017 Europe counted 288 plants for Geothermal District Heating (Geo DH), 198 of which in the EU (EGEC Geothermal Market report 2017). Due to economic and environmental reasons, geothermal plant design includes district heating supply in most of the cases. The use of the heat is particularly likely in areas where a deep geothermal power plant is constructed near an existing district heating network.

In most GeoDH, deep Geothermal installations consist of the extraction of fluids from the underground and their reinjection after use, in a typical doublet or triplet system. Depending on the temperature of the geothermal fluid, the heat from the fluids can be used directly, or enhanced by ground source heat pump (GSHP) technologies. Heat pumps can be used to adjust the temperature of geothermal fluids to the (higher) level needed, for example, in a residential building, or to adjust the temperature of heat coming from cooling the building to the (lower) level required to inject it into the ground.

Direct use is mostly used with temperatures below 150 °C. Direct use covers applications with the direct thermal extraction for heating and cooling without heat pumps. Note that in general, the geothermal fluid is not suitable for direct use due to fluid chemistry [Karlsson & Ragnarsson 1995] and as a consequence, heat exchangers connecting to a secondary water circuit are used in most cases. In many European countries, the cooled water is re-injected. In Iceland, Lund 1998 reported that the cooled geothermal fluid is often disposed of at the surface.

The main components of a direct use system are:

- the downhole and circulation pumps;
- pipelines, and heat exchangers.

The material used for piping for transmission and distribution is usually carbon steel, especially when temperatures above 100°C are involved. However, in low temperature district heating networks, fibre-reinforced plastic (FRP) and polyvinyl chloride can also be used.

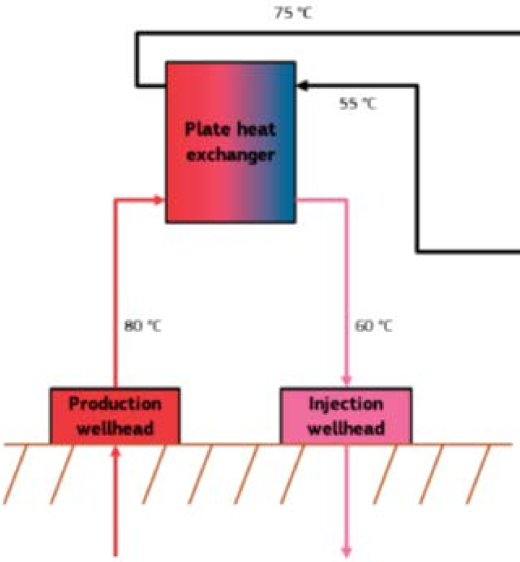


Figure 4: Schematic process flow diagram for direct use system with heat exchanger - Adapted from (Lund, 1998)

Different types of heat exchangers are suitable for direct use of geothermal energy, the most common are plate, shell-and-tube, and downhole heat exchangers (Lund 1998). In the present study the different technologies are not detailed as their impact on emissions is assumed to be negligible.

In the JRC report from 2014 it is mentioned that geofluids from direct-use plants may contain elevated concentrations of toxic elements, but direct CO_2 emissions are typically negligible.

Summary - Technology for Energy Conversion Impact on Emissions

The main impacts on direct and indirect emissions, related to the different production technologies of geothermal fluids, are summarized in the following table.

Table 5: Energy conversion technology impact on emissions

Type of generation unit	Impact on direct emissions	Impact on indirect emissions
Dry steam plants	Gas emissions from cooling tower after NCG treatment	Turbine, collection pipelines
Flash steam plants	Gas emissions from cooling tower (in some case after NCG treatment)	Turbine, collection pipelines
Binary plants	Theoretically no direct operational emissions	ORC Auxiliary power for the pumps
Heating	Theoretically no direct emissions	

Type of generation unit	Impact on direct emissions	Impact on indirect emissions
Combined heat and power	Depends on mainly on the power power technology	

5.3 *Cooling System*

The cooling system is another key parameter for geothermal plants, it directly influences the conversion efficiency.

The cooling step aims to condense the vapor after it leaves the turbine to maximize the temperature drop between the incoming and outgoing vapor and increase the pressure drop over the turbine, hence increasing the efficiency of the operation. The condensate can be used for re-injection and/or as feed water for the cooling tower.

The present technology for cooling the power plant condensers may use either or both water or air and includes (Mendrinos et al.):

- direct contact condensers;
- cooling with water evaporation in air draft by wet type cooling towers;
- cooling with air by dry coolers.

Condensers can be divided into two categories: 1) those in which the coolant and condensing vapor are brought into direct contact (Direct Contact Condensers) and 2) those in which the coolant and condensate stream are separated by a solid surface (Surface Condensers). Najafabadi (2015) provides a detailed description of the main subdivisions of condensers. Additionally, different types of condensers exist as mentioned by Bertani (2017), water-cooled or air-cooled (ACC) condensers. Following this second proposed division, the water-cooled condensers need a closed loop of cooling water, itself cooled by another flow (ambient air or water evaporation in ambient air) or an open water loop with fresh water continuously provided by local water resources (river or sea). The detailed description of the three cooling systems is given in ANNEX I.

The main impacts on direct and indirect emissions, related to the different cooling systems, are summarized in Table 6.

Table 6: Cooling systems impact on emissions

Cooling Systems	Impact on Direct Emissions	Impact on Indirect Emissions
Direct contact condensers	A small fraction of the NCG stays in the condensate and cannot be treated by primary abatement systems, it is either evaporated through the cooling tower, reinjected with the condensate or treated by secondary abatement systems.	Electricity consumption for transporting water (pipes, pumps etc.) may not be at all negligible
Wet cooling towers	Secondary emissions from the cooling tower due to evaporation of condensate.	Auxiliary power consumption
Dry coolers	Evaporation of condensate water is avoided, no direct emissions of NCGs. Secondary emissions from cooling tower are eliminated.	Auxiliary power consumption, (twice as much electricity than wet cooling towers).

5.4 Heat / Cold Generation

The two main technologies to generate heat and cold from geothermal resource are adsorption and absorption heat pumps/chillers. They are thermally driven (here by geothermal heat). In an absorption heat pump compressing is done by a combination of an absorber, pump, heat exchanger, generator, rectifier and expansion valve. An adsorption heat pump/chiller is based on the same principle as the absorption heat pump/chiller, however a solid is used instead of a liquid as sorption medium. The two systems are detailed in ANNEX I.

The main impacts on direct and indirect emissions, related to the different cooling systems, are summarized in Table 7.

Table 7: Heat/Cold generation systems impact on emissions

Cooling Systems	Impact on Direct Emissions	Impact on Indirect Emissions
Absorption chillers/heat pumps	No direct emissions	Leakages of refrigerant or absorbent
Adsorption chillers/heat pumps	No direct emissions	Leakage of refrigerant

5.5 Gas Control Systems

In most geothermal power plants, the NCG is vented to the atmosphere, though some abatements steps are often taken. Indeed, removing the NCG stream from the condenser is an intrinsic part of the power generation process. Solutions are being tested to compressthe NCGs and to reinject them fully or partially together with the brine into the geothermal aquifer (for example, at the Balmatt plant in Belgium). This technique is not yet a commercial solution. Additionally, it is common practice to remove H_2S from the NCG before venting to the atmosphere.

In open systems (dry and flash steam plants), non-condensable gases are carried in the geofluid in dissolved form. NCG are sometimes removed upstream of the turbine (partially or completely, by means of wellhead separators and flashers), or they are separated from the steam turbine exhaust in the plant condenser. However, the accumulation of NCG in the condenser will cause a significant reduction in turbine power output due to an increase of backpressure on the turbine. Hence, they need to be removed from the condenser and can handled by gas control systems.

In liquid dominated systems (including binary plants and heating applications) high dissolved gas content may also require the utilisation of some kind of degassing technology, e.g. for the protection of the surface equipment, or for the prevention of pump cavitation. In any case, a detailed gas analysis of the geothermal fluid is necessary to determine the technologies to be used to perform the degassing. Additionally, instead of simple degassing (venting of the gas) some degassing technologies include facilities that make use of the released gases. For example, carbon dioxide can be used in horticultures, whereas methane can be collected, cleaned and burned in simple gas boilers (increasing the temperature of the extracted thermal water).

In Europe, depending on the characteristics of the resource and the type of plants, different gas control systems are/can be implemented in the geothermal plants. They include:

- NCG removal systems;
- Flaring of combustible gases;
- Valorisation of combustible gases;
- NCG abatement systems;
- NCG reinjection.

All these systems are detailed in ANNEX II. The main impacts on direct and indirect emissions, related to the different gas control systems, are summarized in Table 8.

Table 8: Gas control systems impact on emissions

Gas control systems	Impact on Direct Emissions	Impact on Indirect Emissions
Wellhead separators and flashers	NCG are separated from the geothermal stream and can be treated or rejected.	
Gas separators downstream of the turbine	NCG are separated from the geothermal stream and can be treated or rejected.	
Flaring of combustible gasses	✓ Emissions of CH_4 are avoided. ✓ CO_2 is emitted	

Gas control systems	Impact on Direct Emissions	Impact on Indirect Emissions
Gas turbine to valorize combustible gasses	✓ Prevent emissions of combustible gasses. ✓ CO_2 is emitted	Additional power production-less power consumption
NCGs abatement systems	✓ In general, abatement systems reduce by 90% to 99.9 % of the emissions of H_2S; ✓ AMIS tested efficiency of 95 % Hg removal. Overall H_2S abatement efficiency ~90%; ✓ NH_3 abatement systems efficiency of 75% minimum.	Auxiliary power consumption
NCGs reinjection	Emissions to the atmosphere (CO_2, H_2S and Hg) are completely avoided.	Auxiliary power consumption

5.6 *Matrix of Technologies*

A matrix of technologies used in geothermal power generation and geothermal heating is presented in the following Tables. Each column of the table summarizes the common technologies used at the different stages.

Table 9: Matrix of technologies used in geothermal power generation

Production Technology	Power generation unit	Cooling system	Gas control system
Self-flowing	Dry steam	Direct-contact condenser	Wellhead separators and flashers
Downhole pumps	single flash	Wet cooling tower	Gas separation tank
	Double flash	Air-cooling tower	Flaring of combustible gasses
	Binary	Hybrid (AC-DC) cooling	Gas turbine to valorize combustible gasses
	Hybrid (Flash/binary)		NCGs abatement systems
			NCG injection

Table 10: Matrix of technologies used in geothermal heating / cooling generation

Production Technology	Heat generation unit	Cooling system	Gas control system
Self-flowing	Heat exchanger	Ad/absorption chillers	Gas separation tank
Downhole pumps			Flaring of combustible gasses
			Gas boiler to valorise combustible gasses
			NCG injection

6 DEFINITION OF GEOTHERMAL ENERGY CLUSTERS

6.1 Methodological Approach

Typical clusters of technologies for geothermal plants in Europe have been defined. First, 'plant typologies' for power and heating plants have been defined based on the inventory previously introduced and combined with the elements of Table 9 for power and Table 10 for DHC, respectively. For this exercise only the most relevant technological clusters typical for Europe have been selected.

Table 11: Geothermal power production typologies

	Geothermal power production typologies
a	Self-flowing dry steam power/CHP plant with wet cooling system and NGC treatment and condensate reinjection
b	Self-flowing flash power plant with wet cooling system and NGC treatment and condensate reinjection
c	Self-flowing flash power plant with wet cooling system and no NGC treatment and condensate reinjection
d	Self-flowing hybrid/CHP flash/binary plant with wet cooling system and NGC treatment and condensate (partial) reinjection
e	Self-flowing binary power plant with air cooling system with NCG separation and valorisation and reinjection of geothermal fluid
f	Self-flowing binary power plant with wet/dry cooling with NCG separation and reinjection of geothermal fluid only
g	Pumped binary power plant with wet/dry cooling, Pressure higher than gas break out with full reinjection

	Geothermal power production typologies
h	Pumped binary CHP plant with wet/dry cooling, with NGC separation and reinjection of the geothermal fluid
i	Pumped binary CHP plant with wet/dry cooling, Pressure higher than gas break out with full reinjection
j	Pumped binary CHP plant with air cooling system, with NGC separation and re-injection of the geothermal fluid and NGCs
k	Self-flowing CHP flash plant with wet-cooled condenser, no NGC treatment and condensate reinjection
l	Self-flowing CHP flash plant with wet-cooled condenser, NGC treatment and condensate reinjection + NCGs reinjection

Table 12: Geothermal heat production typologies

	Geothermal Heating Typologies
a	Self-flowing/pumped heating plant with reinjection of the geothermal fluid
b	Self-flowing heating plant without reinjection of the geothermal fluid
c	Pumped heating plant Pressure higher than gas break out with full reinjection
d	Self flowing (pumped) heating plant with NGC partial separation and with reinjection of the geothermal fluid
e	Pumped heating plant with NGC separation, with reinjection of the geothermal fluid and NGCs

The following step consisted in correlating the results of the definition of representative geological clusters of the geothermal regions in Europe (based on geothermal resources mapping) - with the technology typologies to define typical plant typologies for power and heat plants for the different areas of Europe. The exercise has been performed for power and heat plants. The results of the clustering exercise are presented in Table 13 and Table 14. For each of the cluster defined, a real case study is identified to validate the results. At this stage the case studies have been selected based on the case studies proposed for the GEOENVI H2020 project and on the literature review.

Table 13: Typical clusters for power & CHP plants in Europe

Power cluster	Geological play	Dominant phase	Temperature	Host rock/Lithology	Typical plant typology	Country	Geological setting
1P, 1P CHPa, 1P CHPb	Volcanic	Vapor	150-250	Basalt	c/k/l	Iceland	Iceland Mid Oceanic Ridge (IS)
2P	Volcanic	Liquid+Vapor	130-300°C	Volcanics	f	Portugal (Acores)	Azores Triple Junction (PT)
3P CHP	Magmatic intrusive	Vapor	>200°C	Carbonates, metamorphic	a	Italy (Tuscany)	Back-arc basin (IT)
4P, 4P CHP	Magmatic intrusive	Liquid+Vapor	>150°C	Carbonates, metamorphic	b/d	Italy	Back-arc basin (IT)
5P, 5P CHP	Extensional, fault-controlled	Liquid	>110°C	Sandstones, Granite	g	France, Germany	Rhine Rift (D, FR)
6P	Extensional, fault-controlled	Liquid	>150°C	Carbonates	e	Croatia	Pannonian Basin (HU, SL, PL, AU,RO, SR)
7P CHP	Intracratonic	Liquid	>100°C	Carbonates, dolomites, limestones	i/(j)	Belgium	West Yorkshire-Netherlands Basin (GB, NL, BE)
8P, 8P CHP	Orogenic	Liquid	100-150°C	Carbonates, limestone	g/i	Germany, Austria	Molasse basin (A, D, CH)
udP	Magmatic intrusive	Liquid	140<T<220°C	Carbonates, metamorphic	g	Italy	Back-arc basin (IT)

Table 14: Typical clusters for heat plants. Note that dominant phase is liquid in case of purely heat plants

Heat cluster	Geological play	Temperature	Host rock/Lithology	Typical plant typology	Country	Geological setting
1DHC	Volcanic	75°C	Basalt	a/b	Iceland	Iceland Mid Oceanic Ridge (IS)
2DHC	Extensional, fault-controlled	>110°C	Sandstones, Granite	c	France, Germany	Rhine Rift (D, FR)
3DHC	Extensional, fault-controlled	<100°C	Carbonates, dolomites, limestones, Sandstones	d	Hungary, Austria, Croatia, Romania, Serbia, Slovakia, Slovenia	Pannonian Basin (HU, SL, PL, AU,RO, SR)
4DHCa, 4DHCb	Intracratonic	<100°C	Sandstones, limestone, dolomite, carbonates	c/e	France, Germany, Belgium, Netherlands, Poland, UK, Spain, Sweden, Denmark, Lithuania	Aquitaine Basin (FR), Paris- Hampshire Basin (FR, GB, BE), North German Basin (D, NL), Warsaw Basin (PL), West Yorkshire-Netherlands Basin (GB, NL, BE), Castilian Basin (ES), Danish-Norwegian Basin (DK), Baltic basin (LT,LV,EE)
5DHC	Orogenic	<100°C	Limestone, sandstone, dolomites, carbonates	c	Austria, Germany, Italy, Poland , Romania	Molasse basin (A, D, CH), Po Valley Foredeep (IT), Carpathian Foredeep (PL, UA)
udDHC	Basement	<100°C	Granite	c/d	Czech Republic, Macedonia, (Finland)	Bohemian Massif (CR, D, PL, A), Rhodope Massif (BU, GR), Bosnian-Serbian-Macedonian Massif (MK), Fennoscandian Shield (FIN)

In Table 15, the main geological and technological parameters describing respectively P clusters and DHC clusters are summarized, to provide an overview of their main characteristics.

Table 15: Main parameters describing P clusters

Parameters			1P	1P CHPa	1P CHPb	2P	3P CHP	4P	4P CHP	5P	5P CHP	6P	7P CHP	8P	8P CHP
Geological	**NCG composition**	CO_2	x	x	x	x	x	x	x	x	x	x	x	x	x
		CH_4	x	x	x	x	x	x	x	x	x	x	x	x	x
		H_2S	x	x	x	x	x	x	x					x	x
		H_2	x	x	x	x	x	x	x						
		N_2				x	x	x	x	x	x		x	x	x
		Hg	x	(x)	x	(x)	x	x	x						
		Ar					x	x	x	x	x				
		NH_3	x	(x)	x	x	x	x	x						
		Rn					x	x	x	(x)	(x)		(x)		
		As	x	(x)	x		x	x	x						
	Host rock	Volcanics	x	x	x	x									
		Carbonates					x	x	x			x	x	x	x
		Sandstones								x	x				
		Metamorphic					x	x	x						
		Granite								x	x				

Parameters			1P	1P CHPa	1P CHPb	2P	3P CHP	4P	4P CHP	5P	5P CHP	6P	7P CHP	8P	8P CHP
	Geological setting	Volcanic	x	x	x	x									
		Magmatic intrusive					x	x	x						
		Extensional, fault controlled								x	x	x			
		Intracratonic											x		
		Orogenic												x	X
	Reservoir depth	<1000 m					x								
		1000-4000m	x	x	x	x	x	x	x	x	x		x	x	x
		>4000m					x	x	x	x	x		x	(x)	(x)
	Reservoir temperature	< 100° C													
		100-150° C											x	x	x
		150-250° C	X	x	x	x	x			x	x	x			
		250-350° C	x	x	x		x	x	x						
Technological	**Stimulation**	Chemical					x	x	x	x	x		x		
		Hydraulic								x	x				
		Thermal													
	Production technology	Self-flowing	x	x	x	x	x	x	x			x			
		Pumped								x	x		x	x	X

Parameters		1P	1P CHPa	1P CHPb	2P	3P CHP	4P	4P CHP	5P	5P CHP	6P	7P CHP	8P	8P CHP
Conversion technology	Dry steam					x								
	Flash steam	x	x	x			x							
	Binary				x				x	x	x	x	x	x
	CHP		x	x				x		x		x		x
	Hybrid (Flash/binary)							x						
Cooling technology	Air coolers				x				x	x	x	x	x	x
	Wet cooling tower	x	x	x	x	x	x	x	(x)	(x)			x	x
	Direct water cooling													
NCG treatment	Combustion/valorisation										x			
	Abatment system H2S		x			x	x	x						
	Abatament system Hg					x	x	x						
	Abatment system As					x	x	x						
	Abatment system NH3							x						
	Abatement system CO2		x											
	Keep P>Pbubble point								x	x		x	x	x
	NCG partial reinjection													
	Degassing to the atmosphere	x	x	x	x	x	x	x			x			

Parameters			1P	1P CHPa	1P CHPb	2P	3P CHP	4P	4P CHP	5P	5P CHP	6P	7P CHP	8P	8P CHP
	Re-injection	Total (brine +condensate)								x	x		x	x	x
		Not in place													
		Partial	x	x	x	x	x	x	x			x			
	Surface network	Steam network	x	x	x		x	x	x						
		No steam network				x				x	x	x	x	x	x

Table 16: Main parameters describing DHC clusters

Parameters			1DHC	2DHC	3DHC	4DHCa	4DHCb	5DHC
Geological	**NCG composition**	CO_2	(x)	x	x	x	x	x
		CH_4		x	x	x	x	x
		H_2S	(x)			x		
		H_2						
		N_2	x	x	x	x	x	x
		Hg						
		Ar	x					
		NH_3						
		Rn		(x)				
		As				x		
		C1-C5				x		
	Host rock	Volcanics	x					
		Carbonates			x	x		x
		Sandstones		x	x	x	x	x
		Metamorphic						
		Granite		x				

Parameters			1DHC	2DHC	3DHC	4DHCa	4DHCb	5DHC
	Geological setting	Volcanic	x					
		Magmatic intrusive						
		Extensional, fault controlled		x	x			
		Intracratonic				x	x	
		Orogenic						x
	Reservoir depth	<1000 m	x					
		1000-4000m		x	x	x	x	x
	Reservoir temperature	< 100° C	x		x	x	x	x
		100-150° C						x
		>150° C		x				
Technological	**Stimulation**	Chemical		x		(x)		(x)
		Hydraulic		x				
		Thermal		x				
	Production Technology	Self-flowing						
		Pumped	x	x	x	x	x	x

Parameters			1DHC	2DHC	3DHC	4DHCa	4DHCb	5DHC
	Conversion technology	Absorption heat pump					x	
		Heat exchanger	x	x	x	x	x	x
		Direct use	x	x				x
	Gas treatment	Flaring	x		x			
		CHP			(x)			
		Scrubbing						
		Keep P>Pbubble point		x		x	x	x
		NCG partial reinjection						
		Partial degassing to the atmosphere			x			
	Re-injection	Total		x		x	x	x
		Not in place						
		Partial	x		x		x	
	Side products (re-use of CO_2)	no reuse		x			x	x
		reuse	(x)					

6.2 Clusters Features

In this section, the main features of the clusters, directly feeding the modelling of LCA inventories, are summarized.

Specifically, the number of plants belonging to each cluster, the total electrical and/or thermal installed capacity and respective annual energy production in typical operating conditions are reported in Table 17 and Table 18 for P-clusters and DHC-clusters, respectively.

The set of plants covered within the P-clusters is a highly representative an inclusive share of power applications within the geographic boundaries of the study, covering almost 100% of the capacity according to data available in EGEC market report (2018), with referece to the Countries covered in this study.

For the case of DHC clusters, and taking into account the thermal energy derived through combined heat and power configurations, the coverage is in the order of 85% the overall capacity for DHC applications within the geographic boundaries of the study, according to the same reference as above.

With this respect, it is highlighted that Turkey, characterized by an extensive engagement of geothermal resource for power and district heating applications, and also notably associated with air emissions during the operation phase, are not covered by this study.

Table 17: European coverage of P clusters

	1P	1P CHPa	1P CHPb	2P	3P CHP	4P	4P CHP	5P	5P CHP	6P	7P CHP	8P	8P CHP
Number of plants	4	1	1	3	30	3	3	3	1	1	1	2	5
Electrical installed capacity [MW_e]	253	303	120	35	792	60	61	68	3	10	0.2	12	20.
Thermal installed capacity [MW_{th}]	0	138	133	0	117	0	21	0	3	0	8	0	103
Annual net electricity production [GWh/y]	1,998	3,331	2	204	4,993	530	530	37	22	25	2	60	102
Annual thermal production [GWh/y]	0	1,833	0.6	0	172	0	32	0	9	0	29	0	222

Table 18: European coverage of DHC clusters

	1DHC	2DHC	3DHC	4DHCa	4DHCb	5DHC
Number of plants	37	1	71	87	3	55
Installed capacity [MWh_{th}]	1,063	25	473	797	33	544
Annual thermal production [MWh/y]	3,930	175	1,144	2,550	62	1,492

For each cluster, a representative plant has been defined, with its main characteristic, in order to be able to quantify proxies describing the main input and output flows associated.

The representative plant is intended as a theoretical plant, modelled through proxies, which is itself a proxy of the real plants belonging to the clusters. It is also highlighted that also in those cases where the cluster is composed by one plant only, the reference plant does not necessarily and entirely correspons to the specific real plant, but it is a scientific-based model.

From case to case, the plant can be representative of the clusters with different levels of accuracy, depending on the number of plants within the cluster, the types of plants within the cluster, the size of plants within the cluster. The more homogeneous the real plants are within a cluster, the more the representativeness of the plant increases.

Table 19: Main characteristics of the representative plant of P clusters

	1P	1P CHPa	1P CHPb	2P	3P CHP	4P	4P CHP	5P	5P CHP	6P	7P CHP	8P	8P CHP
Electrical installed capacity [MW_e]	86	303	120	14	20	60	60	3	3	10	1	6	5
Thermal installed capacity [MW_{th}]	0	133	300	0	3	0	21	0	3	0	12	0	23
Annual electricity production [GWh/y]	682	2	1	85	126	523	530	22	22	25	5	30	25
Annual thermal production [GWh/y]	0	1	1	0	4	0	32	0	9	0	43	0	45
Number of wells	31	85	44	6	5	16	14	2	2	4	2	2	2
Average drilled depth of wells [m]	2,010	1,190	1,960	1,46 0	3,500	780 - 3,400	780 - 3,400	3,500	3,500	2,350	4,000	4,450	4,450
Emissions reduction systems		CO_2, H_2S			Hg, H_2S	Hg, H_2S	Hg, H_2S, NH_3						
Lifetime [years]	30	30	30	30	30	30	30	30	30	30	30	30	30
Representativeness	High	High	High	Medi um	High	High	High	High	High	High	High	High	High

Table 20: Main characteristics of the representative plant of DHC clusters

	1DHC	2DHC	3DHC	4DHCa	4DHCb	5DHC
Thermal installed capacity [MW_{th}]	n.a.	25	6	10	11	14
Annual thermal production [MWh/y]	n.a.	180	16	38	29	49
Number of wells	n.a.	2	3	2	2	2
Average drilled depth the wells [m]	n.a.	2,900	1,800	2,000	2,235	3,200
Emissions reduction systems			In some cases, use of separated gas (methane) in auxiliary equipment (Opera, 2016)[1]			
Lifetime [years]	30	30	30	30	30	30
Representativeness	n.a.	High	Medium	Medium (at cluster level), high (for Paris Basin)	High	Medium/High

[1] This beneficial effect is not accounted in this study

7 DEFINITION OF KEY PARAMETERS

7.1 Methodological Approach

The inventories developed for mapping the geothermal resource and for the existing technologies, as well as published LCA for geothermal plants and gas emission data have been used to define a set of key parameters that can be used to estimate direct and indirect emissions. Ideally, the identified key parameters should to be easy to collect from factsheets, overviews and publications regarding the use of geothermal energy in Europe. In practice due the large variability of accessibility to information it proved to be a real challenge for some clusters to get the key parameters data.

7.2 Identified Key Parameters based on Geological and Technological Inventories

A list of key parameters identified based on the resource mapping and technology inventories is given in Table 21. A single parameter may account for several emissions during different stage of geothermal projects. For instance, reservoir depth can be used as a the main parameter to estimate inventory data related with drilling and completion of wells, as well as to estimate reservoir temperature, pressure and dissolved gas concentrations and may correlate with well productivity in a specific type of reservoir.

Table 21: List of identified influencing parameters and impact on emissions

Parameter	Category	Impact on
Geological		
Background emissions	✓ No natural NCGs emissions; ✓ existing natural emissions.	✓ Actual impact of geothermal applications on emissions.
Gas content	✓ NCG content.	✓ NCG treatment technology; ✓ production technology; ✓ cooling technology; ✓ reinjection.
Gas composition	✓ NCGs type; • CO_2, • CH_4, • H_2S, • H_2; • N_2, • Hg, • Ar, • NH_3, • Rd, • As.	✓ Type of NCG treatment; ✓ solubility of minerals and on dissolved gasses.
Host rock	✓ Volcanics (low carbonate content); ✓ Carbonates (including metamorphic basement); ✓ Sandstones.	✓ Composition of the geothermal fluid (dissolved solids and gasses).

Parameter	Category	Impact on
Reservoir depth	✓ Shallow (< 1,000 m); ✓ Deep; ✓ Ultradeep (> 4,000 m).	✓ Drilling activities, well maintenance, well abandonment and associated emission; ✓ reservoir pressure and temperature; ✓ stimulation technology.
Reservoir Temperature	✓ < 100° C; ✓ 100-150; ✓ 150-250; ✓ 250-350.	✓ Well completion and production technology ✓ solubility of minerals and on dissolved gasses ✓ scaling and corrosion.
Reservoir Pressure	✓ Hydrostatic; ✓ over-pressured.	✓ Well completion and production technology; ✓ solubility of minerals and on dissolved gasses; ✓ scaling and corrosion.
Technological parameters		
Drill Rig	✓ Diesel; ✓ electrical.	✓ Indirect emissions (fuel consumption); ✓ Energy consumption of the plant if electricity from the plant is used; ✓ Energy consumption from the grid.
Production technology	✓ Pumped; ✓ self-flowing.	✓ Energy consumption of heating (and cooling) plants; ✓ Net electricity supply of geothermal power plants; ✓ Indirect emissions (e.g., materials used and maintenance/replacement).
Power conversion technology	✓ Dry steam; ✓ Flash steam; ✓ Binary; ✓ CHP; ✓ Hybrid (Flash/binary).	✓ Emissions of non-condensable gases (NCGs); ✓ Net energy output of the geothermal plant; ✓ Indirect emissions (e.g., materials used and maintenance/replacement, construction related emissions).
Heating conversion technology	✓ Absorption heat pumps; ✓ Heat exchanger; ✓ Direct use.	✓ Net energy output of the geothermal plant; ✓ Indirect emissions (e.g., materials used and maintenance/replacement, construction related emissions).

Parameter	Category	Impact on
Cooling technology	✓ Air cooling; ✓ Wet cooling tower; ✓ Direct water cooling; ✓ Hybrid cooling.	Only for power generation: ✓ Net energy output of the geothermal plant; ✓ Amount of NCGs that can be treated versus rejected through cooling towers; ✓ Indirect emissions (e.g., materials used and maintenance/replacement, construction related emissions).
Gas treatment	✓ None; ✓ Combustion; ✓ Valorizatoin ✓ Scrubbing; ✓ AMIS; ✓ NCG re-injection; ✓ keep P>Pbubble point CO2; ✓ Degassing to the atmosphere.	✓ Extent and type of direct emissions; ✓ Energy consumption of the plant; ✓ Possible direct emissions in case of degassing; ✓ Indirect emissions (e.g., materials used and maintenance/replacement, construction related emissions).
Re-injection	✓ In place; ✓ Not in place; ✓ Partial.	✓ Extent and type of direct emissions; ✓ Energy consumption of the plant; ✓ Drilling activities, well maintenance, well abandonment and associated emissions.
Stimulation	✓ Chemical; ✓ Hydraulic; ✓ Thermal.	✓ Energy consumption for the stimulation.
Flow rate	✓ Pumped flow rate; ✓ Artesian flow.	✓ Energy consumption of the plant; ✓ Net energy output.
Utilisation		
Commodity	✓ Power; ✓ Heat & Power; ✓ Heat; ✓ Heat & Cold.	✓ Used to calculate the functional unit (kWh of the supplied commodity; in case of combined heat & power, the emissions will be assigned to either commodity based on the amount of geothermal energy supplied corresponding conversion technology).

7.2.1 Literature Review

In addition to the inventories for reservoirs and technologies, a literature review has been performed to identify and test the usability of the key parameters used in previous studies for the assessment of the emissions from geothermal plants.

This review included:

- LCAs of geothermal projects available in the scientific literature;
- other general studies on air emissions and externalities of geothermal energy, such as the analysis recently published by the Geothermal Energy Association;
- study on Greenhouse Gases from Geothermal Power Production published by the World Bank.

The popularity of using Life Cycle Assessment (LCA) as a tool to evaluate the environmental impacts of geothermal plants throughout their entire life cycle is steadily increasing. In this context, methodologies and tools have been proposed to assess the emissions of geothermal applications from the development phase until the abandonment phase. While some of the published studies are generic (for example emissions from geothermal power sector see Fridriksson et al. (2016), ENREL report, 2018), some studies are more site, technology or/and region specific. For example, Frick et al. (2010) focuses on theoretical case studies of CHP binary power plants from low-temperature enhanced geothermal systems (EGS). Karlsdóttir et al. (2015), on the other hand, looked at specific technological/regional cluster considering geothermal flash CHP plant in Iceland while Pratiwi et al., (2018) recently proposed a tool to determine CO_2 emissions from existing and future geothermal plants (ORC, Heat and CHP) in the Upper Rhine Valley.

Moreover, since conducting a detailed LCA exercise is time consuming and the quality and the degree of accuracy of the input data is sometimes questionable as well as their influence on the resulting GHG emissions estimate, several studies investigated the main influencing parameters on the emissions from geothermal plants. In particular, Lacirignola et al. (2014; 2016) investigated the most critical parameters responsible for most of the variability on GHG emissions. Lacirignola et al. (2016) developed a simplified model enabling a rapid and simple estimate of GHG emissions from EGs plants in Europe using only five key parameters (installed power capacity, drilling depth, number of wells, flow rate and lifetime of the system).

Pratiwi et al. (2018) also looked at simplified modeling tool to assess GHG emissions. They developed two sets of models, one basic model for which only a few basic easily available parameters are required and an advanced model that requires more knowledge of the plant parameters (usually only in the possession of the plant owners or operators).

As a result of the review, Table 22 gives an overview of which key parameters can be used to derive information about emissions from geothermal applications and provides some illustrative example of emissions values encountered, especially expressed as global warming potential which is the most used indicator for this type of studies.

It is highlighted that these values have not been used for the calculation of the impacts in this study, but should be intended as a reference.

Table 22: Parameters used to estimate CO_2 emissions of geothermal applications

Source	Key parameters	Assumptions	Applicability
Lacirignola et al (2016)	✓ P_{ORC}; ✓ Depth of well; ✓ Number of well; ✓ Flow rate; ✓ Lifetime of the system.		✓ EGS power plants in Europe.
Frick et al. (2010)	✓ Change of reservoir temperature Conversion efficiency; ✓ Flow rate.		✓ Theoretical case studies of binary cycle power plants with co-generation of electricity and heat from low-temperature enhanced geothermal systems (EGS).
World Bank study (2016)	✓ Host rock (volcanics verus carbonates); ✓ Conversion technology; ✓ Average GHG concentration in steam or total fluid; ✓ Well productivity; ✓ Steam or fluid consumption factor.	✓ Global average CO_2 emission factor 128 gCO_2e/kWh (if gas composition unknown); ✓ High emission factor in carbonate reservoirs 790 gCO_2e/kWh; ✓ Pumped binary, assume emission factor=0; ✓ As a conservative approach, assume that all NCGs entering the power plant are discharged to the atmosphere via the cooling tower; ✓ Fugitive CO_2 and CH_4 emissions due to well testing and well bleeding are considered negligible; ✓ If plant cycle emissions (upstream and downstream emissions) are to be included in GHG accounting for a given geothermal power project, a value of 10 g/kWh should be used for a project lifetime of 30 years.	✓ GHG emissions from geothermal power projects; ✓ Estimation of emission factors for geothermal power projects at different stages of development.

Pratiwi et al. (2018)	✓ In basic mode: • Depth, • Production temperature, • Flow rate, • ORC efficiency, • Ambient temperature, • Capacity factor, • Lifetime. ✓ Advanced mode. Well parameters: ✓ Total number of wells; ✓ Number of production wells; ✓ Total well length; ✓ Drilling machine; ✓ Total flow rate required; ✓ Productivity index; ✓ Production temperature; ✓ Ambiant temperature; ✓ Well-head-Pressure; ✓ Degassing pressure; ✓ Column pressure drop; ✓ Artesian static level; ✓ Casing density; ✓ Reinjection; ✓ Electricity mix. Equipment parameters: ✓ ORC efficiency; ✓ ORC lifetime; ✓ Working fluid; ✓ PumpElectric Motot efficiency;	✓ In basic mode: • Brine properties, • Productivity index, • Well configuration, • Average distance to suppliers, • Electricity mix, • Cooling system, • Well-headpressure, • Frication pressure drop, • Artesian static level, • % pump electric efficiency, • Equipment lifetime, • ORC liquid, • % leakage, • Drilling machine, • Full brine reinjection.	✓ Geothermal plant (ORC plant, heat plant, co-generation plant) in the Upper Rhine Valley.

Source	Key parameters	Assumptions	Applicability
	✓ LSP pump lifetime; ✓ Overall project lifetime; ✓ Capacity factor; ✓ Days of restart; ✓ Average transport distance. Coefficients: ✓ Brine Cp; ✓ Brine density; ✓ Gas to Liquid ratio; ✓ Ambiant brine CO_2 content.		

7.3 The Use of Proxies to define Direct and Indirect Emissions

The methodology proposed in the current study rely on the use of proxies to calculate input data for the assessment of direct and indirect emissions from geothermal applications. In turn, input data for proxies are represented by key parameters characterizing each cluster, as introduced in general terms in section 7.2.

Following the general analysis performed in previous paragraphs, Table 23 below illustrates – by phase - the quantities estimated for the purpose of this study, feeding the LCA methodology, and the key parameters on which they depend on based on the assumptions developed. The equation or model allowing the calculation of each quantity from the relevant key parameters is referred to as proxy.

Whenever possible, the usability of the parameters has been validated through applications in a number of case studies that are representative for the main plant typologies and geological/reservoir conditions.

Table 23: List of key parameters to be collected to apply the proxies defined to characterize emissions of geothermal plants

Phase of the geothermal project	Estimated quantity	Key parameters
Exploration	✓ Fuel consumption	✓ Duration of exploration campaign.
Drilling	✓ Energy used	✓ Well depth; ✓ Well design.
	✓ Fuel consumption	✓ Well depth; ✓ Well design.
	✓ Materials consumption	✓ Well depth; ✓ Well design.
Testing	✓ Direct emissions	✓ Flow rate ✓ Volume produced during testing ✓ Gas content and composition
	✓ Energy used	✓ Flow rate ✓ Productivity of the well ✓ Volume
Stimulation	✓ Energy used	✓ Type of stimulation ✓ Volume injected ✓ Pressure.
Operation	✓ Direct emissions	✓ Energy produced per year ✓ Production technology (steam, binary or heating/colling) ✓ Mean flow rate; ✓ Inlet and outlet enthalpies; ✓ Inlet and outlet pressures ✓ Gas content and composition; ✓ Efficiency of Abatement system ✓ Capacity of the plant;
	✓ Eused	✓ Productivity/injectivity; ✓ Flow rate;
	✓ Auxiliary operations	✓ Production technology (steam, binary or heating/colling) ✓ Capacity of the plant;
Construction	✓ Materials consumption	✓ Installed capacity of the plant; ✓ Number of wells;
Replacement	✓ Materials consumption	✓ Replacement rate

The key parameters for each representative plant considered in this study are presented in ANNEX III, together with life cycle inventories.

The first step to define reliable proxies was to collect and process as much data as possible from the ongoing geothermal operations in Europe. In a second step, a statistical analysis on the collected data has been conducted to define the proxies for the estimation of inventory data to be used in the implementation of the LCA models.

The proxies used within this study are described in detail in the definition of Life Cycle Inventories.

8 SECTOR CATEGORY RULES FOR LCA

The aim of the ”Sector Category Rules for LCA” is to draft a methodological guidance to be followed when performing a LCA study related to the geothermal sector.

Within this study, a first elaboration of a set of guidelines to implement the principles of Life Cycle Assessment coherently and transparently to the case of the deep geothermal sector is thus performed and reported. Further work is to be continued within GEOENVI project (Blanc et al., 2020)..

Similar to the Product Category Rules (PCR) defined within ISO 14025 for developing EPDs for a specific product category, the objective is to provide rules, requirements, and guidelines for performing a LCA study.

First, the “Product group classification: UN CPC 171 AND 173 - Electricity, steam and hot/cold water generation and distribution” (Version 3.0, 2007:08) document from the EPD International® programme has been taken as a reference: all the rules (goal and scope, functional unit, system boundaries, etc.) defined in the generic PCR were customized in order to be adapted to LCA studies about a specific geothermal plant/application.

As a second instance, the above-mentioned specific rules were adapted in order to obtain a simplified methodology to evaluate the environmental impacts of clusters. Clusters are defined (in our specific case) as group of geothermal plants having common characteristics in terms of geological and technological parameters.

Representative clusters were defined along with their specific characteristics in terms of parameters and data to be collected, considering that for each cluster, average data (proxies) can used to finalize and complete the life cycle inventory. The existence of a shared methodology in defining the cluster and in performing the LCA assessment ensure that the results of the study is representative of plants/applications of the single cluster.

This is why the present guideline is called Sector Category Rules (SCR): the guidelines provided allows to perform LCA which a wider scope, i.e. not only related to a specific plant/application but referred to an entire cluster of the geothermal sector.

Of course, studies related to specific plant/application are able to provide more solid results: in that case, all the life cycle phases can be evaluated and specific data collected. The studies referred to a whole cluster need to introduce some simplifications, to omit some phases and to use proxies. However, due to the high variability of existing geological sources and technologies to foster them, differences among clusters can be significant, and even a result for the whole cluster can provide some insights, useful to evaluate the impact of a certain cluster. These insights could be the starting point to further assess the impacts of that cluster, focusing on a specific plant/application (case study).

When performing an LCA related to a cluster, some general rules have been identified:

- the major efforts should be made in collecting data related to geothermal fluid composition, as well as gas content and composition and consequently direct emissions. The relevance of the direct emissions is such as to justify a huge effort for data collection; for each cluster, information should be collected for different case studies, to ensure that the reported information is representative of the cluster;

- proxies can be used to model the cluster. Some processes can be parametrized. For example, the drilling processes and the construction and installation of the sub-surface components, are strongly dependent on the depth of the well and on the geological characteristics of the reservoir, and a good parametrisation of these processes can provide solid proxies to be applied to different clusters.

When performing a simplified life cycle assessment related to the geothermal sector, with reference to a cluster of the sector itself, different aspects should be considered; this SCR is intended to be a guideline to define the following items, detailed in the following chapters:

- Goal: to define unambiguously what the intended application is, the motivations that lead to the study and the type of public to which it is intended, that is, to which people the results of the study will be communicated to;

- Scope: to define the boundaries of the system, functional unit and data quality:

  - the system boundaries define the width of the considered system, in terms of:

    - physical,
    - geographical,
    - temporal borders

  - the functional unit represents the reference system, related to its specific service, to which all the physical flows recorded in the inventory and all the inputs and outputs of energy and materials are referred. The choice of the functional unit in the LCA is made according to the objective to be achieved,
  - cut-off rules clarify and describe the rules for omitting inventory data that are not relevant in the study,
  - allocation rules define how the environmental impacts should be divided over the different outputs of the analyzed system e.g. heat and electricity,

- data quality: to define the degree and criteria of data collection and the authoritativeness and reliability of the sources, according to geographical, technological and temporal relevance;

- impact categories and impact assessment methodology.

8.1 Definition of the product group

The product group in the scope of this SCR includes electricity and thermal energy produced with any geothermal plant/application. Indeed, in the geothermal sector, two main applications can be distinguished:

- Power production,

- District Heating & Cooling applications (DHC).

Providing different function, respectively:

- Electrical energy production;

- Heat production[2].

In some cases, a power plant can provide two functions:

- Combined Heat and Power production (CHP).

For each plant, different life cycle stages can be identified, as depicted below.

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[2] geothermal district cooling is actually poorly developed in Europe thus there is a lack of availability of useful data and, as a consequence, it is not included in this document.

Figure 5: Life cycle stages

According to the specific plant considered, they can be further specified as follows.

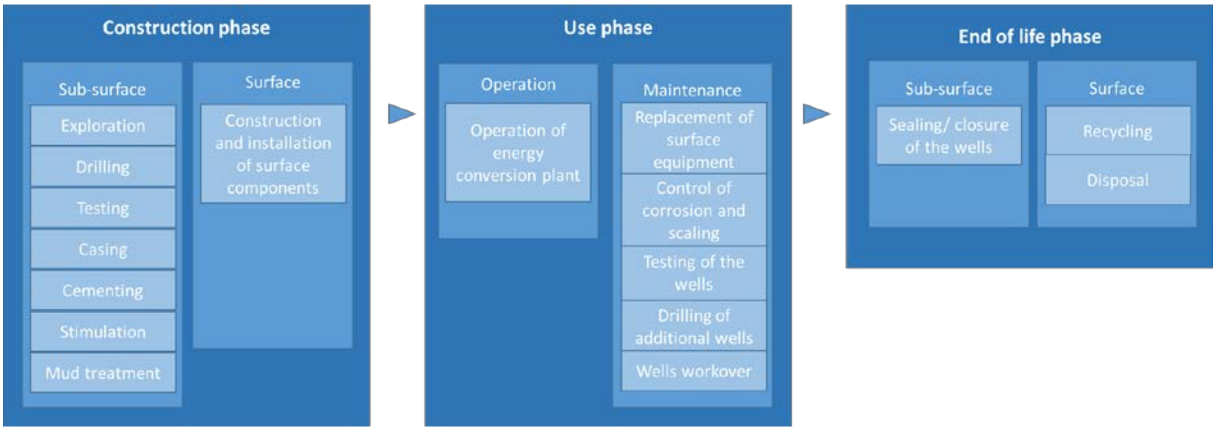

Figure 6: Life cycle stages and main processes

For each process, material and energy flows should be considered, with particular attention to direct emissions.

The variety of geothermal plants/applications is high, but the different plant typologies can be clusterized by considering their geographical and technological representativeness. Indeed, by mapping and classifying the reservoirs and listing an inventory of technologies, it is possible to define a list of different clusters that are representative of the whole geothermal sector.

For each cluster, both geographical and technological characteristics are accounted for. These differences are highlighted in Chapter 2.3.

8.2 Sector LCA – Cluster application

The following chapters report, in form of guidance synthetized in the blue boxes, the general sectoral rules for the geothermal sector in terms of Goal and Scope, evaluated considering the different clusters in order to provide an overview of the environmental impact of the geothermal sector.

As said, if the intention is to evaluate the impacts for a cluster, rather than for a specific plant/application, some simplifications can be introduced. They should be in line with the objective of the study.

8.2.1 Goal

This SCR is applicable for studies aimed at assessing the emissions from geothermal plants and applications – in particular, the aim of this document is to provide instruments to **evaluate the direct and indirect emissions associated with the production of electricity, steam, hot water through any technology exploiting geothermal energy**.

The study must specify and refer to a specific cluster.

LCA practitioners should clearly define the goal and the intended application of their study as well as explain the motivations that lead to the study and the type of public to which it is intended.

In the geothermal sector, different functions can be distinguished:

- Power production;
- Heating & cooling applications;
- Combined Heat and Power production.

LCA practitioners should include a clear definition of the product system under study: they should include a description of the technology used and of the characteristics of the geothermal resource. As a consequence, they should make reference to a specific cluster. Then they should clearly define the provided function: electricity, heat or both. For the cluster delivering heat, it is necessary to specify the feed and return temperature.

In addition, they should indicate at least one case study (e.g.: a specific plant within the cluster) to be used as reference to collect specific data, where needed.

For the technology used, it should at least be specified:

- Plant size (MW);
- Operation of the plant (h/y);
- Operating life (y);
- Number of wells (production and reinjection);
- Well depth;
- Production technology;
- Conversion technology (if applicable);
- Cooling system (if applicable);
- Gas treatment system (if applicable);
- Reinjection system (if applicable);
- Well stimulation (if applicable).

For the geothermal resource, it should be at least specified:

- Reservoir type;
- Geothermal Fluid Composition and Gas Content;
- Gas content;
- Temperature.

The goal definition above explained implies specific **limitations of the usability of the study results** due to the applied methodology. These limitations shall be clearly identified and later be prominently reported.

In the specific case of the present study, the **limitations** are due to the fact that the analysis will cover a whole sector, divided by clusters. Thus the assessment of specific plants will be complemented by proxies and the average will be taken as representative to the cluster they belong. In order to do so, some simplifications of the methodology will be made.

Impact coverage related limitations must be fully addressed and justified.

The study “Geothermal plants' and applications' emissions: overview and analysis” covers only the **indicators** that are related to **emissions**, due to the original goal and scope of the European Commission requests. The study includes both direct (deriving directly from the e.g. ground due to drilling phase operations or the emissions to atmosphere during operation phase) and indirect emissions (e.g.: linked to the extraction of materials constituting the equipment of the plant).

The impacts will be expressed through a series of indicators. The indicators are extracted from the version 3.0 of the Product Environmental Footprint – chosen as impact assessment method (see section 8.3.4). Among the whole list, only the ones more relevant for the evaluation of emissions will be taken into account (e.g.: climate change) as reported within sub-chapter 8.3.4 below. On the contrary the indicators not connected to emissions assessment (e.g.: land use or resources depletion) will not be included.

The target audience must be specified, i.e. to whom the results are intended to be communicated.

The **target audience** of the study “Geothermal plants' and applications' emissions: overview and analysis” is composed by the European Commission, the workshop experts and as final instance the wider public interested in knowing the impact of such energy production technology. The same methodology can be applied to similar studies but in different contexts.

The European Commission has committed this study on “Geothermal plants' and applications' emissions: overview and analysis” to provide a consistent, harmonized and exhaustive assessment about the possible release of greenhouse gases and other pollutant emissions in geothermal sector. The study focuses on electricity production and heating & cooling applications.

Thus, European Commission is considered as first recipient of the study. However, the same information can be considered useful also to other stakeholders.

8.2.2 Scope

System boundaries

To define the system boundaries for the SCR, the Life cycle phases of energy systems reported within the PCR UN CPC 171 and 173 Electricity, steam and hot/cold water generation and distribution, 2007:08, Version 3.0, developed within the International EPD programme, have been taken as reference (dashed lines represent optional phases):

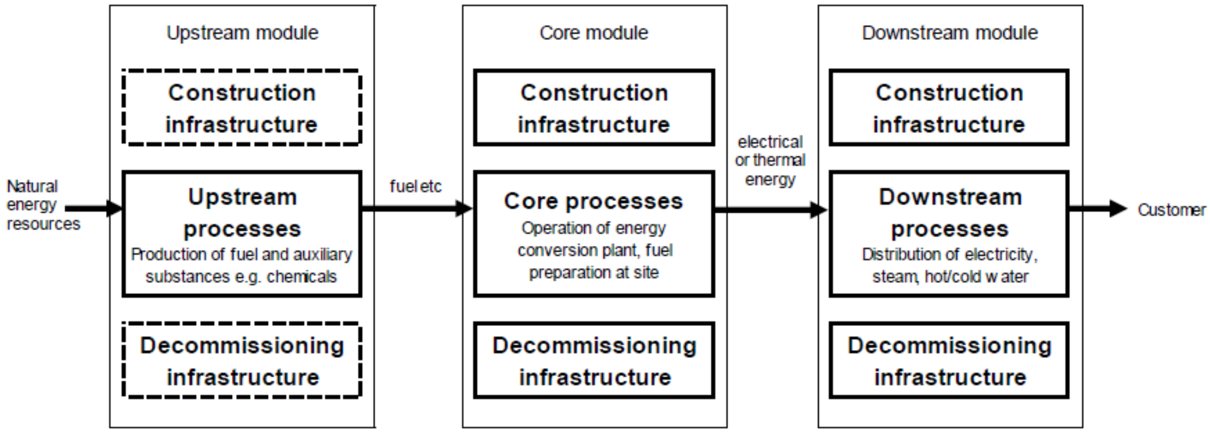

Figure 7: Illustration of the life cycle structure and rough system boundaries

The **system boundaries** define what to include or not in the assessment.

For this kind of assessment, referring to this division and using the same jargon, the system boundaries for geothermal energy sector can be represented as follows, considering the life cycle stages presented above (dashed lines represent optional phases, usually not included).

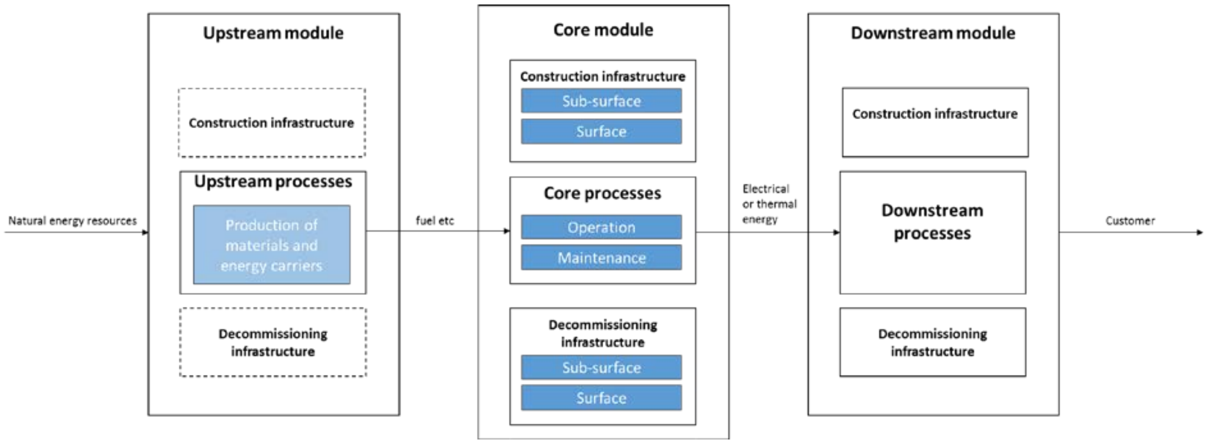

Figure 8: Illustration of the life cycle structure and rough system boundaries for the geothermal sector

Within the modules and the phases within, for each cluster, it is necessary to **define and describe** the process and materials and energy flows involved.

The upstream processes of the upstream module are represented by the production and transportation of materials and energy carriers that are used in the subsequent core module. Examples are the production of steel used to build the plant equipment, chemicals that can be used for the chemical stimulation of the well or the corrosion inhibitors, as well as the diesel that is used for the drilling operations. Secondary data can be used to model these processes.

For each plant/application the core module is represented by the operation stage of the energy conversion plant (system) until the delivery point to the distribution system and by the related core processes (operation and maintenance). The core processes shall be included in the assessment, since they represent the core of the system: they include the operation of energy conversion plant with all the associated input and output flows, in terms of materials, energy and emissions and the maintenance processes. The main outcome of the core module is the electrical or thermal energy, according to the specific plant/application. In addition, the operation stage can be responsible of direct emissions or leakages. The energy consumption associated to the cooling system or the gas treatment system should be accounted for[3], as well as water and other material flows used during the plant operation phase, such as chemicals for the control of corrosion and scaling or for the control of the geothermal fluid characteristics. The maintenance processes include the replacement of the surface equipment, when necessary.

The core construction infrastructure includes both the sub-surface and surface contributions. Both Surface components and Sub-surface activities and materials will be considered since they gain a relevant role especially for what the amount of steel and cement concerned, in particular for infrastructures and wells. For the core construction infrastructure, since the amount of material is mainly dependent respectively on the dimensions of the infrastructures and equipment and on the depth of the well, a parametric input and a common proxy can be used.

The decommissioning infrastructure includes the dismantling of both surface and subsurface components. Currently, there are no or very few useful data available on the end of life of geothermal plants due to the fact that only few plants reached their end of life. As a consequence, this phase should be modeled based on assumptions and hypothesis that could not give considerable added value to the assessment of emissions.

Furthermore, according to the NREL study "Systematic Review of Life Cycle Greenhouse Gas Emissions from Geothermal Electricity" (Eberle et al., 2017), it is demonstrated, analyzing 29 LCA studies on geothermal energy, that the contribution during the lifetime of a geothermal plants or well, of the decommissioning phase impact of GHG emissions is negligible, independently from the type of plant analyzed.

Finally, as best practice, at the end of wells lifetime or of the lifetime of the geothermal plant, to avoid contamination of ground water in the aquifers cross cut by the wells after their closure, to prevent blowouts and to prevent any gas emissions from the abandoned wells, critical sections of the wells are plugged by cement.

For these reasons, it has been decided to exclude the decommissioning phase from system boundaries and to consider it as optional. It means that it must be included only if robust data are made available to the analyst.

The downstream module, which consists of the distribution of the electrical or thermal energy produced, from the plant/application to the customer, is as well omitted from the analysis. This simplification is made because the main focus of the study is to consider the emissions derived from the electrical and thermal energy production from geothermal sources. The focus of the assessment will be on the core module and, since the geothermal downstream section presents analogies with other downstream modules of other energies sources, it is not particularly distinctive for the geothermal energy sector.

For the present study, a **cradle to gate approach** is considered.

The omitted phases are the decommissioning phase within the core module, the whole downstream module (energy distribution).

Figure below reports the effective boundaries as per the requests of the study.

[3] The self-consumption should be subtracted from the total production, in order to consider only the net production

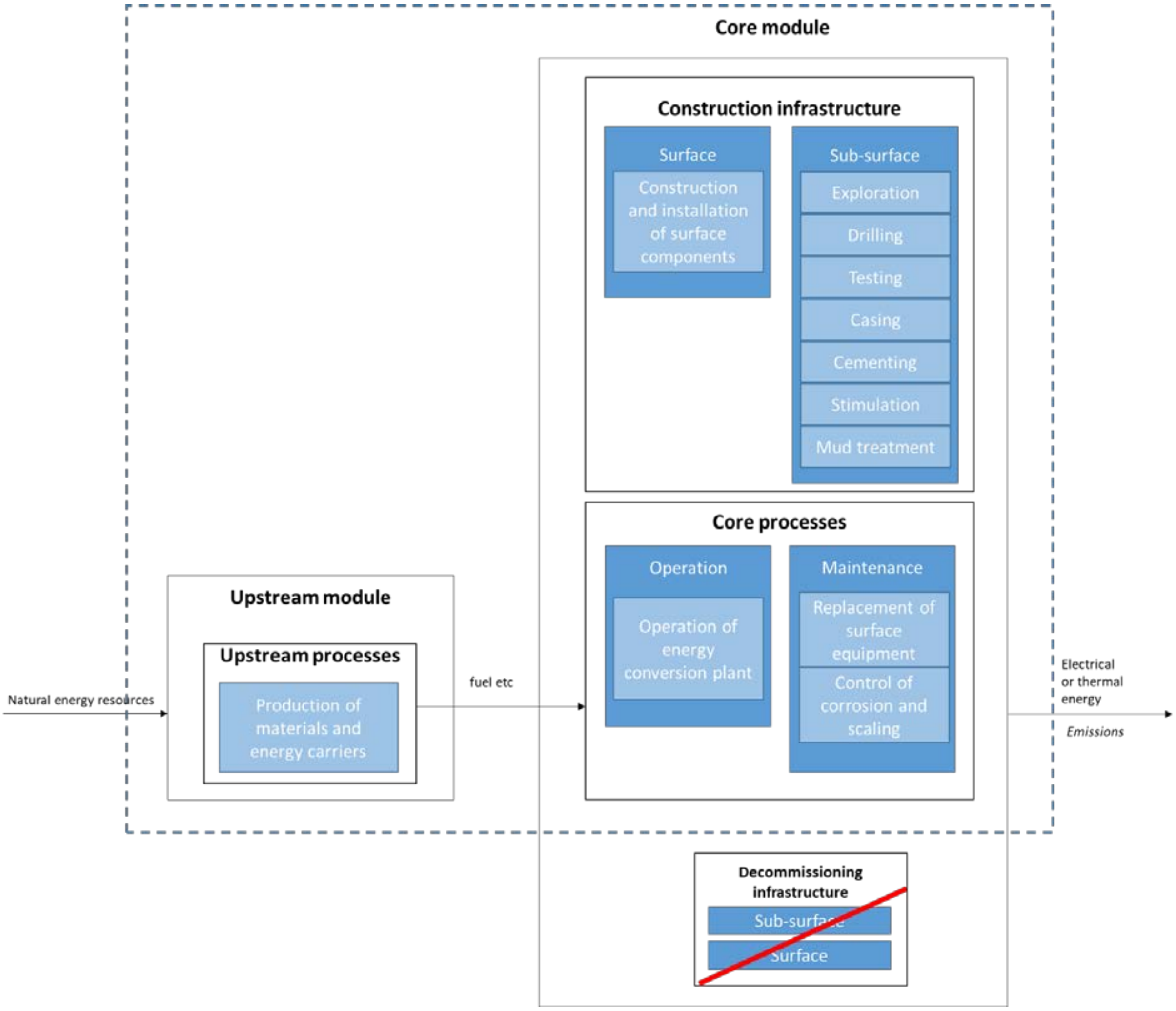

Figure 9: System boundaries for geothermal cluster LCA, following the study requests

According to the different plant/application/cluster, these processes and the related input/output flows can present some differences.

Core processes

The main core processes are represented by:

- the operation of energy conversion plant:
  - the main output of this process is represented by the electrical or thermal energy produced, that should be quantified,
  - eventual emissions, release of non-condensable gases or leakage during operation should be accounted for,
  - the energy consumed during the operation phase should be quantified (e.g. the energy consumption associated to the cooling system or the gas treatment system) and if it is from self-consumption, subtracted from the gross production,
  - the material flows entering the plant operation phase should be included (e.g.: inhibitors);
- eventual stimulation for reservoir enhancement; stimulation can be:
  - hydraulic,
  - chemical,

- thermal;

- maintenance process:
  - replacement of the surface equipment,
  - control of corrosion and scaling ,
  - testing of the wells.

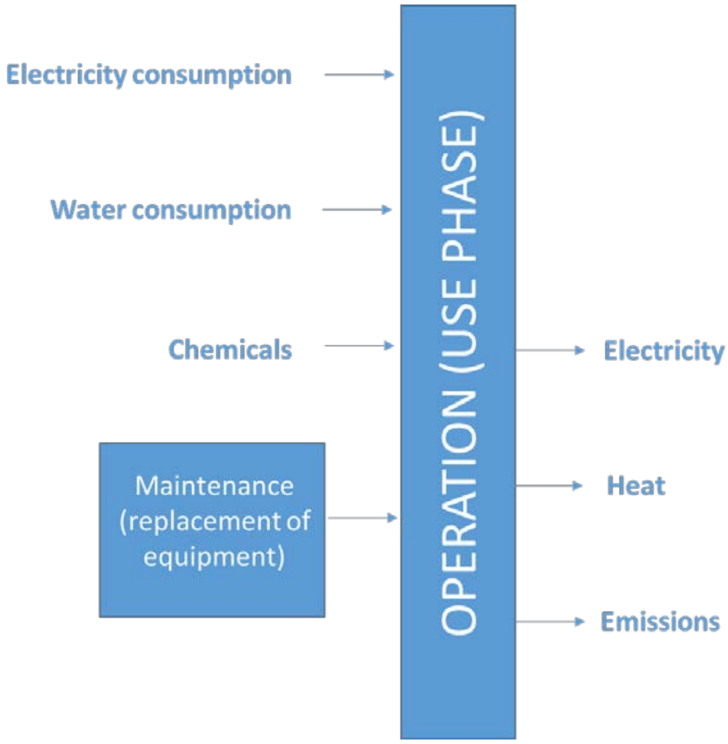

Figure 10: Core processes

<u>Core Construction infrastructure</u>

The core construction infrastructure includes both sub-surface and surface contributions; the sub-surface contributions include:

- Production well;
- Reinjection well.

The main processes associated to their construction are:

- exploration;
- drilling;
- testing;
- casing;
- cementing;
- (eventual stimulation for reservoir enhancement);
- mud treatment.

For each process, materials and energy flows, as well as emissions should be considered.

The surface contributions are represented by the construction and the installation of the surface equipment:

- Production Technology;
- Conversion technology;
- Cooling technology;
- Gas treatment.

Also transport pipes (collection pipeline) should be included among surface components.

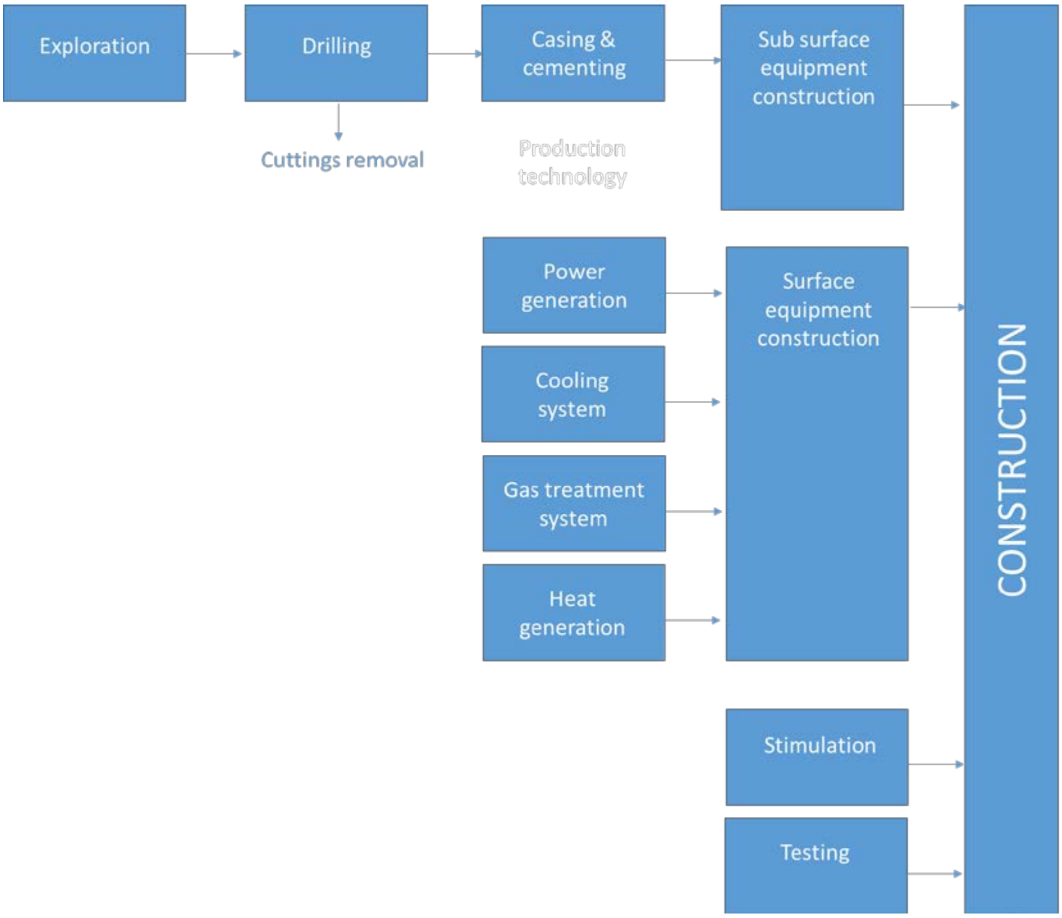

Figure 11: Core construction infrastructure

Physical Boundaries

In the LCA study, it is necessary to define how the plant is operating: data for the core processes shall be specific for the geological and technological characteristics of the plant.

The technology used for **energy conversion** (which represent the core of the system) shall be described and characterized.

Installation year shall be reported as well as a technical specification including, installed capacity, annual generation during defined reference period, conversion efficiency, full load hours (capacity factor or other information so that full load hours can be calculated), and technical service life. The basis for the estimation of the technical service life shall be given.

Geographical Boundaries

In the LCA study it is necessary to define where the plant is operating: data for the core processes shall be site-specific.

This means that the data related to the operation of the energy conversion plant (e.g.: emissions, leakages, energy production) should be referred to the site and to the geological conditions. **A cluster can be representative of more countries, having the same characteristics**. This should be clearly stated, and the analogies among the plants in the different countries underlined.

Temporal Boundaries

In the LCA study it is necessary to define when and how long the plant is operating: data for the core processes shall be time-specific.

As **time boundaries**, input and output data of the core module shall reflect one reference year or an annual average of a defined reference.

8.2.3 Declared Unit

The declared unit is the flow (or flows in case of multifunctional processes) to which all other input and output flows quantitatively relate. It is realizing the functional unit: the declared unit can be expressed in direct relation to the functional unit.

The **declared unit** is defined as 1 kWh net of electricity generated and/or 1 kWh of steam or hot water generated.

The environmental impact shall be given per declared unit during the technical service life of the energy conversion plant based on the status of the plant in the defined reference period.

During the first phase of the study, a thorough literature analysis has been performed, in order to understand in other similar or LCA studies which were the choices made in terms of methodology to be applied during the environmental assessment. The other possible options of declared unit, found in literature, are the MJ delivered or “the production of 400 liters of HW (equal to the needs of a 6 people family house)” (Chiavetta et al., 2011).

The declared unit of 1 kWh net of energy (electrical and/or thermal) has resulted largely the most used by the other studies’ practitioners. For the present study, in order to be aligned with the rest of the studies, the choice falls in the same direction.

8.2.4 Cut-Off Rules

"Cut-off" refers to the omission of not relevant life cycle stages, activity types, specific processes and products and elementary flows from the system model.

Certain flows can be omitted is their contribution is considered negligible or not affecting the results. Inflows not included in the LCA should be documented in the LCA.

8.2.5 Allocation Rules

Some geothermal plants are multifunctional system, since they produce both electricity and thermal energy (CHP). When dealing with multifunctional system, specific allocation procedures are needed.

Exergy methodology is recommended when dealing with CHP plants within geothermal sector.

The electricity and heat allocation factors αE and αQ are defined as[4]:

$$\alpha_E = 1 - \alpha_Q$$

$$\alpha_Q = \frac{Q \cdot \tau}{E + Q \cdot \tau}$$

Allocation criteria are to be identified for those cases where allocation is required to be applied to solve multi-functionality of not further sub-dividable unit processes. A criterion determining the underlying relationships between the system different products or functions should be defined.

In the case of CHP Plants, different methodologies for allocation factors exist, as reported in the paper "Allocation factors in Combined Heat and Power systems – Comparison of different methods in real application". Among them:

- Energy methodology;
- Exergy methodology;
- Power bonus (or heat bonus);
- Alternative generation;
- Price.

In the following table, the different methods are summarized, together with their strong and weak points, in order to provide a complete overview of all the possible alternative that have been considered to deal with allocation in CHP systems. For each method, the electricity and heat allocation factors αE and αQ are described.

[4] Details for the calculation of the allocation factors are provided within the following table

Methodology	Description	Allocation factors	Strong point(s)	Weak point(s)	Information needed
Energy methodology	The energy methodology relies on the share of energy produced for each type, i.e. heat and power	$\alpha_E = E/(E+Q)$ $\alpha_Q = Q/(E+Q)$ with E and Q being the amount of electricity and heat produced by the CHP system in a given time frame.	*Very simple method, dependent only on power-to-heat ratio *Independent from external parameters *Not dependent on the nation	*Do not consider the quality of energy (i.e. the exergy content) *It underestimates the share of the emissions allocated to electricity production (this method allocates lower impact to electricity than to the other methods)	*E: electricity produced by the CHP system *Q: heat produced by the CHP system

Methodology	Description	Allocation factors	Strong point(s)	Weak point(s)	Information needed
Exergy methodology	The exergy methodology takes into account the energy quality, i.e. the exergy contained into the energy outputs of the system[5]	$\alpha_E = 1 - \alpha_Q$ $\alpha_Q = \frac{Q \cdot \tau}{E + Q \cdot \tau}$ Where τ is the exergetic temperature factor, which can be expressed as: $\tau = \left(1 - {T_{ref}}/{T_Q}\right)$ Where T_{ref} is the reference temperature[6] and T_Q is the mean logarithmic temperature of the heat produced by the CHP unit, calculated as: $T_Q = \frac{T_S - T_R}{\ln({T_S}/{T_R})}$ where T_S and T_R are the supply and return temperatures (in Kelvin units). T_Q can also represents the temperature at which heat Q crosses the system boundary[7]	*Reflect the difference in terms of energy quality among the two functions provided by the system *Not dependent on the nation *It is largely used in LCA studies related to the geothermal sector *It is judged as the fairest method, from a thermodynamic point of view, for dividing the benefits of the CHP production between electricity and heat (Tereshchenko et Nord, 2015)	*Dependent on external parameters (e.g. the reference temperature) *For exergy analysis, the characteristics of the reference environment must be specified completely: the results of the exergy analyses, consequently, are relative to the specified reference environment	*E: electricity produced by the CHP system *Q: heat produced by the CHP system *T_S: supply temperature *T_R return temperature

Methodology	Description	Allocation factors	Strong point(s)	Weak point(s)	Information needed
Power bonus **(a similar approach is applicable for the heat bonus)**	This method considers heat as main product, while all power is considered as a bonus. The primary energy is allocated to the electricity produced in the CHP plant.	$\alpha_E = 1 - \alpha_Q$ $\alpha_Q = \frac{f_{P,dh} \cdot Q_{del}}{Q_{del} + E_{del}}$ Where $f_{P,dh}$ is the primary energy factor of the DH system and Q_{del} is the delivered heat at the border of the supplied building	*It takes into account the total primary energy used by the CHP plant (i.e. all energy used in the production of heat and electricity): this includes the primary energy related to fuel handling and combustion as well as primary energy needed for the production of additives, handling of ashes, construction, and dismantling of the CHP plant, etc. *Some primary energy factors are provided as examples in the Annex B of EN 15316-4-5:2017	*Dependent on primary energy factors which can vary according to National conditions and policies *If the energy efficiency of the CHP units is higher than the one associated to the reference primary energy factor, the allocation factor for heat may become negative (in this case the heat allocation factor is set to zero, but the results are distorted)	*E: electricity produced by the CHP system *Q: heat produced by the CHP system *$f_{P,dh}$: primary energy factor

5 In the case of electricity, the energy and the exergy content coincide, but for heat the exergy content is dependent on the temperature at which it is produced

6 The reference temperature can be fixed by specific reference conditions (e.g. usually 15°C, 25°C or 0°C) or calculated as the average outdoor temperature during the analysis time frame

7 https://pubs.acs.org/doi/pdf/10.1021/ef800841w?rand=3ch4pojc

Methodology	Description	Allocation factors	Strong point(s)	Weak point(s)	Information needed
Alternative generation or PES (Primary Energy Saving)	The alternative generation method considers the primary energy that would have been consumed if heat and electricity have been produced in separate plants. The relationship of distribution is expressed as percentage of the fuel needed for each alternative proves with respect to the total quantity needed. NB: The alternative plants use the same fuel as the CHP plant: in geothermal application, the “fuel” is represented by the geothermal fluid.	$\alpha_E = \frac{E/\eta_{E,ref}}{E/\eta_{E,ref} + Q/\eta_{Q,ref}}$ $\alpha_E = \frac{Q/\eta_{Q,ref}}{E/\eta_{E,ref} + Q/\eta_{Q,ref}}$ where $E/\eta_{E,ref}$ and $Q/\eta_{Q,ref}$ are the reference electricity and heat efficiency for separate production respectively[8]	*It is selected as allocation method within the PCR UN CPC 171 and 173, Electricity, steam and hot/cold water generation and distribution, Version 3 of the International EPD® System *Within Annex B of EN 15316-4-5:2017, a template to specify the reference efficiency is provided. In addition, informative default values of efficiency of external reference systems are provided (for all type of fuel, $\eta_{E,ref}$ =0,4 and $\eta_{Q,ref}$=0.9). The same values are reported in the PCR.	*Additional input data about two external reference systems shall be defined *At the present there is no uniform standard for the selection of plant parameters *If average electricity efficiency is considered, it can vary according to the considered nation	*E: electricity produced by the CHP system *Q: heat produced by the CHP system *$\eta_{E,ref}$: reference electricity efficiency for separate production *$\eta_{Q,ref}$: reference heat efficiency for separate production

[8] The electricity efficiency is usually the average of the National power plants, while the heat efficiency is set to a conventional natural gas boiler (but also a heat pump could be considered).

Methodology	Description	Allocation factors	Strong point(s)	Weak point(s)	Information needed
Price	The price method allocates the impacts according to the different economic value of the functions delivered (i.e. electricity and heat)	$\alpha_E = \frac{E \cdot P_E}{(E \cdot P_E + Q \cdot P_Q)}$ $\alpha_Q = \frac{Q \cdot P_Q}{(E \cdot P_E + Q \cdot P_Q)}$ Where P_E and P_Q the specific prices for electricity and heat	*Simple to apply	*Dependent on the definition of price, which can include: the price paid to the final users, the revenues obtained by selling heat and power, or the avoided cost of the separate production of heat and power, etc. *The prices can vary in the considered time frame *The prices can vary in the different nations considered time frame *The economic-based allocations are easily influenced by decision and policy makers	*E: electricity produced by the CHP system *Q: heat produced by the CHP system *P_E: specific price for electricity *P_Q: specific price for heat

There is no unique solution to solve the allocation problem; this is why different methodologies have been developed and are currently used. However, it has been chosen in this specific framework to rely on the exergy methodology for different reasons: the first one is that this method valorizes the quality of the thermal energy produced, taking into account the supply (and return) temperature. Indeed, from the literature review performed, it has been noticed that the majority of geothermal studies dealing with allocation has chosen the exergy one. Another important aspect is that this method allows to define the allocation factors based on parameters related to the specific plant[9] (or in this case, specific cluster) without considering external parameters, which should be subjected to assumptions and hypothesis: the alternative energy methodology, for example, even if is recommended within the PCR UN CPC 171 and 173, Electricity, steam and hot/cold water generation and distribution, Version 3 of the International EPD® System, is depended on the efficiency of external reference systems (i.e.: the plants producing electricity and heat separately) and for this reason has been excluded. It has also decided to avoid any method dependent on the nation (e.g.: price allocation), since a cluster could be representative of different nations.

8.3 Data Quality

Data quality is composed of accuracy (i.e.: representativeness and methodological appropriateness and consistency), precision/uncertainty and completeness of the inventory.

As a general rule, since each cluster could consist of different plants, **the more information is collected for the different plants, the more solid data could be derived (as weighted average of the collected information).** For upstream processes, generic data can be used. More efforts are required to model the core processes, for which primary data are necessary.

Selected generic and other generic data can be used for the upstream processes, since they represent processes supporting the system function (i.e.: materials extraction and transformation) and for which the level for initiatives is more limited.

Data fulfilling the requirements selected generic data of processes performed in Europe may be found in the following databases:

[9] Except for the choice of the reference temperature

Steel	World steel Association
Primary copper Copper products	ICA (International Copper Association) European Copper Institut (Deutsches Kupferinstitut – Life Cycle Center)
Electricity	Ecoinvent Data for different power technologies combined with IEA (International Energy Agency) statistics on electricity generation mixes for nations, regions etc.
Fuels	Ecoinvent
Aluminium	EAA (European Aluminium Association)
Plastics	PE Plastics Europe
Chemicals	PE Plastics Europe, ecoinvent
Electronic components	EIME (Environmental Information and Management Explorer) EcoBilan
Transports	NTM or regional alternatives2
Waste management	Ecoinvent
Other construction material	Ecoinvent The ILCD database

In general, generic data (e.g.: derived from the Gabi PE International or the Ecoinvent v3.5 databases) can be used for the inventory of the background system. The dataset should be selected based on their representativeness in terms of geographical coverage, time period and technological coverage.

If available data sources do not supply the necessary data or if data fulfilling the quality requirements mentioned above, other generic data may be used and documented. As a minimum requirement those other generic datasets should comprise meta information and should have undergone external review. The environmental impact of the processes where the other generic data are used must not exceed 10% of the overall environmental impact from the product system.

In any case, selected generic and other generic data used should not be older than 10 years.

8.3.1 Specific Data

Specific data should be used to represent the core module, in terms of technological and geological representativeness.

The specific data can directly feed the LCA model (e.g.: measured emissions) or could be used to calculate proxies (e.g.: emissions of the plant, based on the geothermal fluid composition, pressure, temperature, solubility, etc).

A list of data than should be collected for each cluster (and for as many plants as possible) is reported below:

- geothermal fluid composition;
- geothermal fluid pressure;
- geothermal fluid temperature;
- geothermal fluid solubility;
- plant size (MW);
- operation of the plant (h/y);
- direct emissions (if available);
- electricity, water and chemical consumption.

Also data used to model the construction infrastructure should be plant-specific. The information required are:

- number of wells;
- well depth (m);
- materials for construction.

8.3.2 Generic Data

Generic data can be used to model the background processes as well as to model processes that are similar for all the cluster.

In order to get a better picture of the full variability, a statistical analysis on the available data has been conducted to define proxies for the main direct and indirect emissions based on correlations of (sets of) key parameters with emissions data for similar plants. Some of the proxies can be used to model background process, while other need to be refined with specific data (defined in the previous chapter). For the construction infrastructure module, for example, some generic can be defined for all the cluster (e.g.: diesel consumption of steel usage for meter of well) and then specific data (e.g.: number of wells and well depth) should be used to customize the proxy for a specific plant.

The **usability of the proxies** shall be tested and validated through applications in a number of case studies that are representative for the main plant typologies and geological/reservoir conditions.

Proxies are described in details in Chapter 3, together with the results generated by their application.

8.3.3 Inventory and Calculation Rules

Core Module

Data regarding the core process, i.e. the operation of the energy conversion plant or system of energy conversion plants, can be gathered from reports to authorities and from the environmental management system or other similar documents as well as from expert estimates (e.g.: on processes that will be performed in the future such as dismantling or reinvestment rates).

The reference flow shall be an annual average of generated kWh for one year or a period of years.

Core Infrastructure

Regarding the core infrastructure, the material composition can be gathered e.g. from the documentation from the construction process, such as plans, invoices, project reports, environmental impact assessments, etc. Proxies can be used.

The reference flow for infrastructure shall be an annual average of produced kWh multiplied by the expected technical service life of the system, i.e. the expected lifetime production of the system.

8.3.4 Impact Categories and Impact Assessement

The **Impact Categories and Impact Assessement** method shall be declared within the study.

Different Impact Categories and Impact Assessement methods can be used. In the context of "Geothermal plants' and applications' emissions: overview and analysis" study, it has been decided to use the most updated impact assessment method released in the Reference Package (Environmental Footprint - EF 3.0)[10].

The use of this methodology for impact assessment is justified considering the it results from the European Commission's effort in the development of a harmonized methodology for impact assessment. In addition, update reference material and guidelins (Fazio et al., 2018; Sala et al. 2019; Saouter et al. 2018) are easily accessible and clearly presented, providing the LCA practitioner a solid set of guidelines for the correct implementation of the analysis.

It is highlighted that despite within the EF3.0 framework, significative efforts have been made in developing new characterisation factors for freshwater ecotoxicity, human cancer and non-cancer impact categories, one of the possible limitations of the study is that some emissions are still not well characterized. The characterisation factors could be further improved to better characterize certain emissions and this could lead to slightly different results.

The LCA results shall be reported separately for the following life cycle stages:

[10] https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

- Upstream Module;
- Core Processes;
- Core Infrastructure Construction.

The **direct emissions** measured during the operational phase or during other phases (if available) shall be reported separately.

8.3.5 Potential Environmental Impacts

The potential environmental impact per declared unit shall be reported in the LCA, divided into phases. The reference for the choice of the environmental impact categories is recent report from the JRC on the Environmental Footprint methodology (Fazio et al., 2018), which has been established at the European level within the framework of the "Single market for green products" communication, which provides a selection of recommended indicators for organisations aiming to communicate the life cycle environmental performances of their products. Within this report, a summary of recommended methods is reported, including indicator, units and method package, as reported below.

Recommendation at midpoint				
Impact category	**Indicator**	**Unit**	**Recommended default LCIA method**	**Source of CFs**
Climate change[3]	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq	Baseline model of 100 years of the IPCC (based on IPCC 2013)	EF 3.0[4]
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11eq	Steady-state ODPs as in (WMO 1999)	EF 3.0
Human toxicity, cancer effects[*3]	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox 2.1. model (Rosenbaum et al, 2008)	EF 3.0
Human toxicity, non- cancer effects[*3]	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox 2.1. model (Rosenbaum et al, 2008)	EF 3.0
Particulate matter/Respiratory inorganics	Human health effects associated with exposure to $PM_{2.5}$	Disease incidences[5]	PM method recommended by UNEP (UNEP 2016)	EF 3.0
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235}	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	EF 3.0
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe 2008	EF 3.0
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EF 3.0
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	EF 3.0
Eutrophication, aquatic freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EF 3.0
Eutrophication, aquatic marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	EF 3.0
Ecotoxicity freshwater[*3]	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe	USEtox 2.1. (Rosenbaum et al, 2008)	EF 3.0
Land use	Soil quality index[6] (Biotic production, Erosion resistance, Mechanical filtration	Dimensionless, aggregated index of: kg biotic production/ (m^2*a)[7] kg soil/ (m^2*a)	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	EF 3.0

Recommendation at midpoint				
Impact category	**Indicator**	**Unit**	**Recommended default LCIA method**	**Source of CFs**
	and Groundwater replenishment	m^3 water/ (m^2*a) m^3 g.water/ (m2*a)		
Water use	User deprivation potential (deprivation-weighted water consumption)	kg world eq. deprived	Available WAter REmaining (AWARE) in UNEP, 2016	EF 3.0
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML Guinée et al. (2002) and van Oers et al. (2002).	EF 3.0
Resource use, energy carriers	Abiotic resource depletion – fossil fuels (ADP-fossil)[8]	MJ	CML Guinée et al. (2002) and van Oers et al. (2002)	EF 3.0

* excluding long-term emissions (occurring beyond 100 years).

The EPD PCR "Product group classification: UN CPC 171 AND 173 - Electricity, steam and hot/cold water generation and distribution" (Version 3.0, 2007:08) from the EPD International® reports the following as main environmental impact categories:

- Emission of greenhouse gases (expressed as the sum of global warming potential, GWP, 100 years), in carbon dioxide (CO_2) equivalents. Emission of biogenic CO_2 shall be included in GWP but reported separately;

- Emission of acidifying gases (expressed as the sum of acidification potential, AP) in sulphur dioxide (SO_2) equivalents;

- Emissions of gases that contribute to the creation of ground level ozone (expressed as the sum of ozone creating potential, POCP), in C_2H_4 (ethylene) equivalents;

- Emission of substances to water contributing to oxygen depletion (expressed as the sum of eutrophication potential, EP), in phosphate (PO_4^{3-}) equivalents.

And, the following as other environmental indicators:

- LCI emission data supporting the environmental impact categories (main contributions);

- LCI emissions of radioactive isotopes in kBq, at a minimum C-14, Rn-222 and Kr-85,

- LCI emissions of particle matter (PM) preferably in separate categories of particle size (at a minimum a qualitative description of particle size);

- LCI emissions of toxic substances;

- LCI emissions of oil to water and ground.

Among the indicators reported above, only the ones **more relevant for the evaluation of emissions** are considered, while the indicators not connected to air emissions assessment are not included, in line with the scope of the study.

Making a confrontation among the two lists and considering that the PEF from JRC has the most updated unit of measure and method associated to the impact categories and indicators, the following impact categories have been selected, to be calculated in accordance with the PEF indications:

- Climate change;
- Ozone depletion;
- Human toxicity, cancer effects;
- Human toxicity, non-cancer effects;
- Particulate matters/respiratory inorganics;
- Photochemical ozone formation;
- Acidification;
- Eutrophication, terrestrial;
- Eutrophication, aquatic freshwater;
- Eutrophication, aquatic marine;
- Ecotoxicity, freshwater.

RESULTS

This chapter presents the results of the application of the methodological framework described in the previous chapters. From this perspective, it encompasses the presentation of life cycle inventories and of proxies used to calculate the inventories, and, as a result of the LCA analyses, it presents the greenhouses gases emissions inventories and the life cycle impact analysis. Finally, a quali-quantitative analysis is implemented for the interpretation of the results and the impacts at local scale.

9 SETTING THE LIFE CYCLE ASSESSMENTS

The analysis and overview of emissions from geothermal plants and applications is performed through the realisation of multiple LCA analyses.

In detail, a life cycle assessment is implemented for each clusters' representative plant, introduced in previous Table 19 for power clusters and in Table 20 for district heating and cooling clusters. Thus, a total of analyses is run, taking into account that due to data unavailability the analysis for cluster 1DHC cannot be performed within this study.

The analyses are developed in accordance to the Sectoral Category Rules presented in section 8, thus:

- the target audience for the set of LCAs is composed by the European Commission, the workshop experts and as final instance the wider public interested in knowing the impact of such energy production technology;
- the goal of each LCA is to evaluate the direct and indirect emissions associated to the production of electricity, steam, hot water through the exploitation of geothermal energy through the technology associated to each reference plant;
- each LCA covers life cycle phases of geothermal energy exploitation from cradle-to-gate, with specific reference to: exploration, stimulation, testing, drilling casing and cementing, operation and maintenance;
- the functional unit is defined as 1 kWh_e of net electricity generated for the case of power plants and as 1 kWh_{th} of steam or hot water generated for district heating plants;
- the characterisation method used in EF3.0, updated to the latest version at time of the study;
- the implemented allocation method in case of multiple outputs systems (i.e.: CHP plants) is the exergy method, as foreeen by the sector category rules. Th e method require as input the electrical and thermal production as well as the supply and return temperature for thermal energy delivered. In those cases where primary data are not available, default temperatures of 100°C and 50°C are assumed, based on the typical performances of thermal plants in Europe (Rutz et al. 2019; Gadd and Werner, 2014;Basciotti et al. 2011). To this purpose, it is highlighted that the temperatures play only a marginal role in the calculation of the allocation factors,

which are strongly dominated by the ratio between electrical and thermal production.

The software used is GaBi ts©, developed by Thinkstep AG/Sphera, with related professional database (8.7, service pack 39) and including EcoInvent 3.5 database.

10 LIFE CYCLE INVENTORIES

This section includes the definition of Life Cycle Inventories (LCIs) that identify and quantify the input flows and output flows of a system, within the boundaries considered. They are the direct results of data collection phase and proxies definition and they feed the models to calculate LCA emissions and consequently estimate impacts.

It is highlighted that the identified key parameters are determined specifically for each cluster and are used to calculate the inventory data, through the proxies defined. Thus, inventories are constituted by calculated data, featuring the respective cluster, and in general not by plant-specific data available.

LCIs are defined and presented by phase and by representative plant of the cluster, with the purpose of highlighting the large variability of flows and of quantities throughout the entire geothermal sector.

Proxies and related uncertainties are synthetically described in the sections below, while more extended details are provided in ANNEX III.

10.1 Surface Construction

10.1.1 Construction and Installation of Surface Components

This sub-phase includes materials used for construction of surface components, including power and heat equipment, collection pipeline (whenever applicable) and plant structure.

Proxies for construction of equipment for energy production are proposed separately based on the type of plant, i.e.: single flash, double flash, binary and heat supply.

They are derived using a model based on data reported by Sullivan et al. (2010). The overall usage of metals is also further specified based on figure reported for single and double flash plants reported by Karlsdóttir et al. (2015) and Pratiwi et al. (2018) for heating plants. For binary plants, the figures reported by Frick et al. (2010) and data about two binary plants supplied by machine manufacturers were used.

Material flows applicable to all the technologies are steel, stainless steel, aluminum, copper, mineral wool, plastic.

These materials are used for the manufacturing of the main machinery used in the plants. It includes the manufacturing of turbines, compressors, heat exchangers, collection pipelines, air coolers, generator and transformers. The presence of a given component depends on the type of plants. For example heating plants will have neither turbines nor transformer or generator.

In addition, for the case of single and double flash plants, titanium and transformer oil are included (Karlsdóttir et al., 2015), and for the case of binary plants also the presence of organic chemicals circulating in the ORC (based on pers. information provided by manufacturers).

The materials used for the plant's building are also calculated. In detail, proxies for steel and concrete defined as polynomial function of the capacity are used. They are based on Sullivan et al., (2010).

In detail, aluminum is primarily dedicated to wall and roof cladding, copper is needed for electrical wires and plastic is dedicated to piping works for the systems.Additional proxies for construction of the plant's building which are linearly proportional to the capacity of the plants plastic are based on data published by Karlsdóttir et al., (2015) and cover stainless steel, aluminum, copper, mineral wool and plastics.In detail, aluminum is primarily dedicated to wall and roof cladding, copper is needed for electrical wires and plastic is dedicated to piping works for the systems.Additional proxies for construction of the plant's building which are linearly proportional to the capacity of the plants plastic are based on data published by Karlsdóttir et al., (2015) and cover stainless steel, aluminum, copper, mineral wool and plastics.In detail, aluminum is primarily dedicated to wall and roof cladding, copper is needed for electrical wires and plastic is dedicated to piping works for the systems.Additional proxies for construction of the plant's building which are linearly proportional to the capacity of the plants plastic are based on data published by Karlsdóttir et al., (2015) and cover stainless steel, aluminum, copper, mineral wool and plastics.In detail, aluminum is primarily dedicated to wall and roof cladding, copper is needed for electrical wires and plastic is dedicated to piping works for the systems.

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Finally, the estimation of the amount of steel, aluminum, mineral wool and concrete for collection pipelines is estimated following a two-step approach, based on the estimation of the pipeline length as a function of the capacity of the plant – derived from primary data - and on the estimation of materials amount for unit length. (Karlsdóttir et al., 2015).

Finally, fuels for installation operations and transportation of materials to site are excluded from the boundaries.

Overall, the uncertainty range of construction materials depends on the specific material flow, ranging from approximately 10% (especially for metals) to 50%.

Full inventories and references for construction of surface component are reported by cluster in ANNEX III.

10.2 Sub-surface Construction

10.2.1 Exploration

This sub-phase includes exploration activities carried out before the beginning of construction works to characterize soil properties. The length and type of exploration campaign vary from cluster to cluster. The inventory covers only diesel consumption used for electricity generation onsite, assuming that connection to grid is not available.

According to primary data collected, diesel consumption for one-day seismic campaign is 2,000 l/day (+/-500 l/day).

For some clusters, namely 1P, 1P CHPa and 1P CHPb data about exploration activities were not available and, for the purpose of the study, they have been considered as no exploration activities were perfomed. Nevertheless, it is likely that for high temperature fields as in this case, magnetotelluric methods are used. Such methods have not been modelled within this study. In addition, also for clusters 4DHCa and 4DHCb data could not be retrived reliably.

The neglection of this contribution may lead to an underestimation of impacts, however, it is still consistent with the suggested approach which is primarily focused on the collection of data for direct emissions during production.

Full inventories and references for exploration phase are reported by cluster in ANNEX III.

10.2.2 Drilling, Casing, Cementing and Mud Treatment

This sub-phase includes on-site activities for wells construction. Such activities include:

- Drilling: the drilling operation consists in the perforation of the ground to obtain boreholes of suitable sizes for subsequent wells construction. Drilling equipment requires a certain energy supply, which depends on the specific machineries used, on the ground properties and on the depth of the wells.

  The energy consumption for drilling is estimated by the following proxy:

  $$log(E)=0.000319\times d+2.04$$

  with d the total depth (m) and E the consumption in MWh.

  In case of electricity demand, supply can be provided either through diesel generation or grid connection; in these inventories, it is assumed that electricity is produced by diesel generators with a conversion efficiency of 40%.

  The energy consumption for other site activities during wells construction is calculated based on drilling times reported for geothermal wells Europe.

  In addition, in order to guarantee proper penetration of the drill and stability of the borehole, drilling fluids are injected during the process. The composition of such fluids is site specific, depending on the ground properties and their total volume depends on the volume of the size of the borehole and the physical and chemical properties of the formation. In general terms, drilling muds contain chemicals and constituents to control such factors as density and viscosity and to reduce fluid loss to the formation. Based on a cost model for geothermal wells developed by VITO, drilling fluids amount is estimated as 0.157 m^3/m, with a reliability of the assumption of 15%. The composition of the fluid (w/w), based on generic data, is: 65% water, 4% bentonite, 30% barite and 1% inorganic chemicals.

- Casing and cementing: once the hole is drilled, is it is reinforced through proper steel casing and cement jets. The following proxies are used to estimate the amount of cement (not including cellar and construction of drilling floor) and steel required:

  $$log(cement)= 1.23\times log(d)-2.15$$

  $$log(steel)= 1.22\times log(d)-1.78$$

with d the total depth of the well, cement the amount of cement used in m^3 and steel the amount of steel used in tons.

It is here assumed that cement is constituted by 70% of Portland type cement and 30% of sand as inert, while water used for mixing is neglected.

- Mud treatment: along the processes described, muds composed by residuals of drilling fluids and cuttings from the ground are generated and need to be disposed through suitable treatments. The volume of cuttings is calculated from the well design of selected geothermal wells covering the ranges in depth and final hole diameter encountered in geothermal wells drilled in Europe. The correlation with total drilled length is:

  $$cuttings = 0.0948 \times d^{1.046}$$

  with d the total depth of the well, and cuttings the volume of cuttings generated in m^3.

Full inventories and references for drilling, casing, cementing and mud treatment phase are reported by cluster in ANNEX III.

10.2.3 Testing

Testing activities are associated to a certain energy demand, associated with pumping the geothermal fluid when it is not self-flowing and are responsible of releases of gasses embedded in the geothermal fluid.

The flowing equation is used as a proxy for energy demand calculation:

$$E = (\Delta P \times V)/(3.6 \times 10^4 \times n_p)$$

with E the energy consumption in MWh, ΔP the pressure difference delivered by the pump in bar, V the pumped volume in m^3 and np the efficiency of the pump. The defulat value for the pump efficiency is set to 65 %. For those cases where primary data are not available or not applicable, it is assumed as default testing phase has been not considered in the inventory.

Direct gas emissions during testing are based on the concentration of specific gasses in the geothermal fluid and the solubility of the gasses in the fluid.

$$G = \max\lfloor 0,\ m_g + s_0 - s_i,\ m_g + s_0 - s_a \rfloor \times V$$

with G the mass of gas released during testing in kg, V the volume of fluid produced during testing in m^3, mg the measured gas content of the geothermal fluid in kg/m^3, s_0 the solubility of the gas in the geothermal fluid under measurement conditions in kg/m^3, s_i the solubility of the gas the geothermal fluid under wellhead conditions and s_a the solubility of the gas the geothermal fluid under atmospheric conditions in kg/m^3.

Unless information about the analytical method is available s_0 is set at 0 kg/m^3. The solubility of CO_2 in the geothermal fluid is calculated using the model published by Duan and Sun (2006). For CH_4, the model published by Bebout and Bachman (1981) is used, for H_2S the model published by Suleimenov and Krupp (1994). For other gasses, full degassing is assumed.

It is highlighted that for clusters 1P, 1P CHPa, 1PCHPb, 2P and 6P data about testing phase could not be retrieved and it is thus assumed that all the flows of the inventory are zero. The neglection of this contribution may lead to an underestimation of impacts, however, it is still consistent with the suggested approach which is primarly focused on the collection of data for direct emissions during production.

As a general indication for further studies, it can be expected that the types of non condensable gases released during testing phase represent a minimum fraction of the gases emitted during the plant's operation.

Full inventories and references for testing phase are reported by cluster in ANNEX III.

10.2.4 Stimulation

Stimulation treatments consists in the injection of fluids into a reservoir to increase permeablity and/or connectivity; they can be of different types, namely: acid, thermal, hydraulic for hydrothermal reservoirs or for EGS.

Such treatments require a certain amount of fluid, to be injected, and energy inputs for pumping the fluid into the stimulated volume. The amount and type of fluids used for the inventories are gathered from secondary data, retrieved from literature studies, while the energy consumption for pumping is calculated by the flowing equation presented in ANNEX II.

Table 24 summarizes the parameters assumed for stimulations treatments, including default values to apply the flowing equation when more significant information is not available.

Table 24: Parameters for stimulation treatment

Flow	Acid	Thermal	Hydraulic hydrothermal	Hydraulic EGS
Energy consumption	ΔP *[bar]*= 0.030 x d	ΔP *[bar]*= 0.015 x d	ΔP *[bar]*= 0.062 x d	ΔP *[bar]*= 0.125 x d
Injected fluid	*V*= 250 m^3 of HCl	*V*= 10,000 m^3 of water	*V*= 15,000 m^3 of water	*V*= 27,000 m^3 of water

Only stimulation treatments performed during construction phase are included in the inventories, whereas any treatment that may be performed to enhance the performance of the plant during its operative lifetime is not accounted, due to the high specificity and low availability of data for the process.

The uncertainty attribute to the stimulation phase is not associated with the number of treatments accounted, but with the flows reported in previous table.

Full inventories and references for stimulation phase are reported by cluster in ANNEX III.

10.3 Core Processes – Operation

Before the actual development of inventories for operation cases, considering the importance of such flows within the inventory, a specific focus is developed with the aim of discussing which specific air emissions flows should be included within the inventory.

10.3.1 Analysis of Flows to be Included in the Inventory

Depending on the specific technology installed and on the geothermal fluid characteristics, energy generation is associated with different types and amounts of air emissions.

Several are the direct emissions that are associated with geothermal plants. They are strongly related to the local geology and the type of geothermal play, as well as to the characteristics of the geothermal resource (e.g.: fluid composition, temperature, pressure). CO_2 is the most widely emitted gas, typically constituting more than 95 percent of the total NCG content (Bonafin et al., 2019), but geothermal fluids can, depending on the site, contain a variety of other minor gases, such as hydrogen sulphide (H_2S), hydrogen (H_2), methane (CH_4), ammonia (NH_3) and nitrogen (N2). Mercury, arsenic, radon and boron may be present (Schütz et al., 2013).

The technical report of ESMAP, “Greenhouses gases from geothermal power production” (ESMAP, 2016), illustrates the typical composition of geothermal gas (weight % dry gas), as are reported in Table 25 below.

Table 25: Typical composition of geothermal gas (weight % dry gas) – ESAMP report

Value	CO_2	H_2S	H_2	CH_4	NH_3	N_2	Ar	Hg, B, Rn
Median	95,4	3.0	0.012	0.15	0.29	0.84	0.02	Trace
Maximum	99.8	21.2	2.2	1.7	1.8	3.0	0.04	
Minimum	75.7	0.1	0.001	0.0045	0.005	0.17	0.004	

ESMAP provided also indications related to the potential impacts of the different contaminants (Fridriksson, 2016), summarized in Table 26 below.

Table 26: Potential impacts related to geothermal gas

	CO_2	H_2S	H_2	CH_4	NH_3	N_2	Ar	Hg, B, Rn
GHG	X			X				
Toxic		X			X			X
Odor		X			X			
Corrosive		X						
Flammable		X	X	X				

To provide a first overview of the emissions that are likely to be found in the different cluster, the NCG compositions for the different clusters are reported in Table 27 and Table 28 below (values in brackets indicate the likely presence of the element in gas composition, retrieved on geological basis, but no data refereed to geothermal plants could be encountered).

Table 27: NCG composition in the different P clusters

Clusters	NCG composition									
	CO_2	CH_4	H_2S	H_2	N_2	Hg	Ar	NH_3	Rn	As
1P	x	x	x	x	x	x		x		x
1Pa	x	x	x	x	x	(x)				(x)
1Pb	x	x	x	x	x	x				x
2P	x	x	x		x	(x)		x		
3P	x	x	x			x	x	x		x
4P	x	x	x			x	x	x		x
5P	x	x			x				(x)	
6P	x	x								
7P	x	x			x				(x)	
8P	x	x			x					
udP	x		x			x				

Table 28: NCG composition in the different DHC clusters

Clusters	NCG composition										
	CO_2	CH_4	H_2S	H_2	N_2	Hg	Ar	NH_3	Rn	As	C1-C5
1DHC	x		X								
2DHC	x	x			x		(X)		(x)		
3DHC	x	x			x						
4DHCa	x	x			x		(x)				x
4DHCb	x	x			x						
5DHC	x	x			x						
udDHC	x		X								

As specified above, carbon dioxide (CO_2) is the predominant emission, and is retrievable in almost all clusters.

Methane (CH_4) is the primary organic gas emitted by geothermal plants, followed by ethane and propane. The US Environmental Protection Agency's inventory of methane emission from electric plants does not list geothermal, confirming that methane emissions from geothermal are generally insignificant, however, due to its relatively strong global warming potential (estimated to be more than 36 times higher than CO_2), CH_4 may have a significant contribution to the overall GHG emissions from geothermal power plants.

Methane emission estimates are uncertain, however, because they are usually accidental or incidental to biological processes, and they are not always present in geothermal systems. Other Reactive Organic Gases (ROGs), such as benzene, a known carcinogen, are generally not of concern to the geothermal community, as they are injected back into the system (Kagel et al., 2005). Generally the only hydrocarbon emission registered is methane.

Among the emissions, hydrogen sulphide (H_2S) remains the pollutant of greatest concern for geothermal energy production, since it is a noxious gas that is acutely toxic at high concentrations (Goff et al., 2004). Specific abetment system are installed on the geothermal plants to reduce its emission to the atmosphere. H_2S forms a secondary particulate, and it can be washed by rain or it can be oxidized to SO_2 (while geothermal plants do not emit sulfur dioxide directly) (Matek, 2013).

Arsenic (As), even if can be found in very low concentration in geothermal fluid, in monitored since it is an extremely toxic and carcinogenic substance. In general, small and very variable amounts may be emitted by the drift in cooling towers, since arsenic remains in the aqueous phase and can be easily reinjected (Manzella et al., 2018).

In some clusters presenting mercury and hydrogen sulphide amissions, due to the restrictions especially imposed by the Italian regulation, the AMIS process is applied: AMIS is a primary emissions abatement method that aims at the abatement of not only H_2S emissions but also Hg emissions.

Mercury (Hg), where present, is emitted both in NCG and, as salt, it is dissolved in the drift. Since it is volatile, mercury vapour can be transported into the atmosphere and transformed into the very toxic methylmercury in animal organisms, also reaching the human food chain.

In addition, in some cases, for clusters characterized also by ammonia (NH_3) emissions, abatement systems have been developed. For example, as it appears from the report "Monitoraggio delle aree geothermiche toscane, Controllo alle emissioni delle centrali geotermiche, Anno 2017", prepared by ARPAT, in the region of Mount Amiata, the geothermal resource is characterized by a high concentration of ammonia (compared to other geothermal areas). To mitigate this emissive impact of ammonia (NH_3), the Tuscany Region had prescribed the installation of a system of abatement for ammonia for a selection of power plants. The minimum abatement efficiency requirement is 75% (with respect to the ammonia entering the plant). The principal treatment is based on the acidification, with sulfuric acid, of the circulating condensates thus obtaining the salification of ammonia to ammonium sulphate, with the consequent unavailability of the same to be stripped by the aeriform emitted by the evaporative tower. This acidification of the condensates also favours the distribution of H2S towards the gaseous phase compared to the liquid phase, thus increasing the amount sent to the AMIS treatment. In Italy, for H_2S, the abatement requirement is more than 90% (with respect to the pollutant entering the plant).

In France, radon may be present, although no abatement systems are required[11].

The study "Environmental monitoring of geothermal power plants in operation" (Haraldsson, 2011) reports a list of potential environmental concerns in the operation of geothermal power plants, together with an explanation about the necessity of monitoring. This information is summarized below in Table 29.

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[11] Study on 'Geothermal Plants' and Applications' Emissions: Overview and Analysis' - Interim report - July 2019

Table 29: Potential environmental concerns in the operation of geothermal power plants

What to monitor	Why to monitor
H_2S	• Toxicity (high concentration) • Odour nuisance (low concentration) • Cause of corrosion of various metals and alloys, such as aluminium, copper, steel and silver
CO_2	• Greenhouse gas
CH_4	• Greenhouse gas
H_2 N_2 O_2 Ar	• For information about fluid composition and reservoir geochemistry
B	• Boron compounds can result in respiratory irritation • Has not been found in dangerous concentrations in geothermal gas, but need to be watched
Hg	• Mercury vapour can cause effects in the central and peripheral nervous systems, lungs, kidneys, skins and eyes. It is mutagenic and affects the immune systems • Mercury can accumulate in sediments and organism • Has not been found in dangerous concentrations in geothermal gas, but need to be watched
Rn	• For information about geothermal reservoirs • Carcinogen: can cause lung cancer if inhaled in high enough concentration due to ionizing radiation • Has not been found in dangerous concentrations in geothermal gas, but need to be watched
NH_3	• Corrosive to the eyes, skin and lugs • Flammable over a concentration range • Has not been found in dangerous concentrations in geothermal gas, but need to be watched

Considering what previously stated about the type and properties of emissions associated to geothermal plants, various national and local environmental standards and regulations exist.

At European policy level, a shared regulatory framework that concerns geothermal power plants and their related emissions is not currently addressed. Regulations and requirements vary among the Member States and are to be found in various fields, such as, environmental regulations (air emissions, water emissions, etc.), mining and energy management. Within the process of proposed revision of Renewable Energy Directive (RED), the need of in-depth analysis of all emissions related to geothermal activities was raised by some proposed amendments[11].

Regarding the substances emitted by geothermal plants, Italian regulations establish air quality standards only for hydrogen sulphide, mercury and arsenic, and define Emission Limit Values as mass flow or as a combination of mass flow and concentration.

According to the Dlgs-152/2006 - Parte V - allegato 1 - parte IV - sezione 2 - punto 3, geothermal fluids must be dispersed by means of cooling towers and chimneys of suitable characteristics and specific Emission Limit Values for plants that use geothermal fluids must be respected, as reported in Table 30 below.

Table 30: Emission limit values for plants that use geothermal fluids – Italian regulation

Contaminants	Emission Limit Values[12]
H_2S	70-100 mg/Nm^3 for mass flow equal or higher than 170 kg/h
As[13]	1-1,5 mg/Nm^3 for mass flow equal or higher than 5 g/h
Hg[13]	0,2-0,4 mg/Nm^3 for mass flow equal or higher than 1 g/h

However, the limits indicated for As an Hg are referred only to the salts dissolved in the dragged water, and not to all the emissions of the plant.

The Tuscany region, with DGR 344/2010, in order to integrate the regulatory framework related to the geothermal sector emissions, has established specific requirements and emission limit values for the plants, more restrictive respect to the national regulation. At present, the plants on which the limits established by the Tuscany Region are applied are those built after 2006, or built before 2006 but with authorisation for operation, namely: Chiusdino and Radicondoli (group 2), both built in 2010. For them, it is mandatory to respect the limit values indicated in the following Table 31.

Table 31: Emission limit values – Tuscany regulation

Description	H_2S (kg/h)	Hg (g/h)	SO_2 (g/h)
AMIS outlet	3	2	150
Plant outlet (natural draught, until 20 MW)	10	4	
Plant outlet (natural draught, > 20 MW)	20	8	
Plant outlet (induced draught, until 20 MW)	30	10	
Plant outlet (induced draught, until 20-60 MW)	80	15	
Plant outlet (induced draught, > 60 MW)	100	20	

In addition, considering the importance of the AMIS systems for Tuscan plants, specific requirements have been set on the system itself, to verify its effectiveness. Such requirements are given in Table 32.

Table 32: Minimum operating requirements – Tuscany regulation

Description	Minimum operating requirement
For plants: non-operating hours * 100/8760	< 2 %
For AMIS system: AMIS operating hours*100 / plant operating hours	≥ 98 %

In general, in the absence of regulatory standards for other contaminants, reference values established by international organisations (e.g.: WHO) or other authorities in this field

12 referred to wet gaseous effluents and intended as an hourly average on a monthly basis

13 as salts dissolved in the dragged water

(e.g.: American Conference of Governmental Industrial Hygienists ACGIH) can be taken as good practice by regional authorities.

For certain contaminants, the Directive 2004/107/EC of the European Parliament and of the Council[14] can be used as reference: it specify the limits relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air. Even though the Directive refers to limits for concentration values, it is considered as a relevant reference for the selection of type of emissions to be included in the present study.

Taking into account all the considerations made in the paragraphs above, it is possible to synthetize as per the following. According to the Italian regulations and legislation, which is considered as the most complete and restrictive in the EU framework in terms of obligations and monitoring requirements, the following emissions are to be monitored:

- H_2S;
- Hg;
- As.

If we consider the potential impacts of the different contaminants present within the geothermal gas and the potential environmental concerns in the operation of geothermal power plants, in terms of GHG contribution and toxicity, the following emissions must be taken into account:

- CO_2;
- H_2S;
- CH_4 and the C2-C5 compounds;
- NH_3;
- Hg;
- B;
- Rn.

Cross-checking the two lists above with the typical NCG compositions of the different clusters, the result is the following list, which contains the gaseous emissions that will be included in the analysis of the present study:

- carbon dioxide (CO_2);
- methane (CH_4);

[14] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32004L0107&from=EN

- hydrogen sulphide (H_2S);
- nitrogen (N_2);
- ammonia (NH_3);
- mercury (Hg);
- arsenic (As);
- sulfur dioxide (SO_2).

It is noted that the gas compositions retrieved for these gases in each clusters – as qualitatively reported in tables above - are based on an extensive literature review and on data provided by some plant operators during the data collection phase of the project. The data represent the best of our current knowledge.

10.3.2 Life Cycle Inventory for Operation Phase

Direct gas emissions during production are estimated based on the gas content and compositions of the geothermal fluid and the solubility of the gasses in the fluid:

$$G=max[0,m\_{g}+s\_{0}-s\_i,m\_{g}+s\_{0}-s\_{e}]\times V$$

where s_i stands for the solubility of the gas under the pressure and temperature conditions at the production site and se stands for the solubility of the gas injection or disposal of the geothermal fluid.

Other parameters influencing the calculation of direct emissions are production efficiency, derived from the enthalpy of geothermal fluid entering the unit and depending on the specific type of the plant, as reported in the ANNEX II.

The results of the calculation models are aligned with primary data available. Uncertainties to which such results are associated vary by the type of flow and type of cluster, taking into account also the different configuration in which the plants can operate.

Lifetime for operation for both power and district heating plants is assumed as 30 years, in line with most common hypotheses in the state of the art. Nevertheless, it is acknowledged that also a lifetime of 25 years is often suggested as reasonable, especially for power plants.

During operation, the plant produces the energy outputs it is designed for. To allow this activity, a typical amount of electricity demand, in the order of 5% of the total production is needed. For these LCIs, such demand is considered as a self-consumption and, as such, it is not modelled, but it is taken into account by considering the net energy output of the plant. Water demand for energy production is neglected.

The energy production is a parameter which can be quite robustly retrieved from literature source and primary data, thus, the energy outputs are associated with an uncertainty of 5%.

On the other hand, estimation of direct emissions present variable values of uncertainties, depending on the specific emission and cluster considered.

In addition to potential direct emissions, operation is characterized by ordinary maintantenance auxiliary processes, such as treatments for equipment machines (e.g.: cleaning, greasing), waste disposal (e.g.: filters residues disposal) and prevention of scaling and corrosion or similar chemical treatments dependent on the properties of geothermal fluid circulating in the plant.

In order to represent these processes in the study, proxies applicable to all clusters are derived from primary data available. Specifically, it is assumed that 100 liters of lubricating oil/MW/y are needed to guarantee proper functioning of equipment and that the amount of waste disposed is equal to 63 kg/MW/y.

As the demand of chemicals is concerned, an amount of 800 kg of inorganic chemicals/MW/y is applied to all the clusters for which primary data is not available. Nevertheless, it is worth highlighting that this flow is highly site specific and thus, the uncertainty for its application at cluster level is considerable.

In addition, whenever there is an ORC cycle in the case of binary plants, ORC working fluid losses and leakages occur during normal operation. Based on primary data collected, annual losses are assumed as 0.5% of the total amount of fluid in the cycle. Such losses correspond to an input of chemicals into the cycle, in order to compensate for the losses, and to air emissions generated by the outsourcing fluid.

Lastly, for those systems provided with heat exchangers, an average of 0.6 cleaning treatment/y is considered, generating a demand of water and energy to carry out the operation.

Considering the approximation derived from applying average data to clusters for which primary data is not available, an uncertainty of 50% is taken into account. For clusters where primary data are available, they are associated to an uncertainty of 20%, in order to account for uncertainty of the value itself, possible variations from year to year and to cover the other plants within the cluster.

Full inventories and references for annual operation phase are reported by cluster in ANNEX III.

10.4 Core Processes – Maintenance

10.4.1 Replacement of Surface Equipment

Surface equipment consists of all the machineries used for electricity and heat generation. During the lifetime of the plant, such equipment may need substitution of some components or overall substitution. For a detailed modelling of these LCIs, the specific type of equipment used in each plant, its working conditions and working rates should be taken into account. Nevertheless, considering the complexity of modelling in a reliable way such sub-phase, it has been often excluded from the boundaries.

In this case, a simplified approach is adopted, based on the consideration that according to the proxies developed for equipment, in all the types of plants the sum of steel, stainless steel, copper and aluminum exceeds 75% of the overall amount of materials (w/w). These materials are mainly used for major components of the plant (whenever applicable), such as turbine, generator, heat exchanger, Rankine cycle, characterized by technical lifetimes comparable with the lifetime of the plant. Thus, their entire substitution is excluded, and a replacement rate of 70% is assumed in 30 years of operation. Such replacement rate is extended also to the other materials in the plant.

Considering what previously discussed, this assumption is associated with an uncertainty of 50%.

10.4.2 Testing of the Wells, Drilling of Additional Wells, Wells Workov

Due to difficulties in modelling these aspects at cluster level in a reliable way, applicable to multiple plants, they are considered outside the system boundaries.

10.4.3 Sub-Surface Decomissioning

Sub-surface decommissioning is excluded from the system boundaries. Nevertheless, its contribution to the creadle-to-gate results will be further studied in the sensitivity analysis.

10.4.4 Surface Decomissioning

Surface decommissioning is excluded from the system boundaries.

10.4.5 Overall Data Quality

Data quality is guaranteed as foreseen by the requirements outlined in section 8.3 for generic and specific data.

In order to ensure sufficient data quality at cluster level, solid data quality at plant level is primarily sought.

For upstream processes, such as material and energy production, generic data from international databases are referred to. Specifically, for the selected databases, the most recent available datasets with EU coverage are selected.

For modelling of the core processes, primary data have been collected at plant level in order to model suitable scaled proxies, applicable at cluster level. The proxies developed have been validated against primary data whenever available.

As shown in Section 10, each output from proxies application is associated to a certain value of uncertainty, deriving from multiple factors:

- data variability within a cluster;
- uncertainty about mathematical modelling and input data feeding proxies calculation;
- literature information.

Uncertainty of each value is then taken into account for the implementation of statistical analysis of the results, which aims at estimating quantitatively the reliability of the results generated through the LCA models. In this specific case, a Monte Carlo statistical analysis has been implemented, in order to randomly account for possible deviations from average values implemented in the models within the renges given in the inventories.

Table 33 below show a self-filled data quality assessment. The assessment is provided based on the analysis of data quality for the main factors influencing the calculation of primary data for clusters representation.

Table 33: Data quality assessment

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
1P	High quality data have been collected in the literature and from personal communication with plants owners. *Gas content and composition* which is the critical parameter is of high quality but can vary as a function time. The variability of the composition is reflected by the values collected in the literature from 2006 onwards. Plant owners provided current data available.	*Wells*: High quality as all wells drilled in the geothermal sector are reported in a database managed by OS. The data have been extracted from the database and used in the calculation. Only the drilled depth is used, not the well design as this data was not available at the cluster scale. *Production technology*: High quality data as most plants characteristics are published. Some technical difference exist between plants, especially the eldest ones are quite different compared to the most recent ones, most of them have gone through different stage of retrofitting. Single flash and Double flash plants are accounted for. The collection pipeline: data from the literature have been used as well as data from plants owners. The distance of pipeline estimated by the proxies aligns well with the one in the field.	*Emissions are monitored and reported yearly by plant operators* For this study, emissions during operation are based on the amount of steam that is produced from the field on the gas composition. The amount obtained align well with the data published and communicated by plant owners. *Testing*: this phase is not accounted for as no data was available in the literature. However the emissions related to testing are assumed to be much less than the ones from production.	High

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
1P CHPa	High quality data have been collected in the literature and from personal communication with plants owners. *Gas content and composition* which is the critical parameter is of high quality but can vary as a function time. The variability of the composition is reflected by the values collected in the literature from 2006 onwards. Plant owners provided current data available. It is not excluded that also traces of NH_3, Hg, As are present in the geothermal fluid, based on the gasses encountered in other geothermal plants within the region. However, data about these emissions were not found or reported.	*Wells*: High quality as all wells drilled in the geothermal sector are reported in a database managed by OS. The data have been extracted from the database and used in the calculation. Only the drilled depth is used, not the well design as this data was not available at the cluster scale. *Production technology*: High quality data as most plants characteristics are published. Some technical difference exist between plants, especially the eldest ones are quite different compared to the most recent ones, most of them have gone through different stage of retrofitting. Single flash and Double flash plants are accounted for. The collection pipeline: data from the literature have been used as well as data from plants owners. The distance of pipeline estimated by the proxies aligns well with the one in the field.	*Emissions are monitored and reported yearly by plant operators.* For this study, emissions during operation are based on the amount of steam that is produced from the field on the gas composition and on the efficiency of the abatement system (if present). The amount obtained align well with the data published and communicated by plant owners. *Testing*: this phase is not accounted for as no data was available in the literature. However the emissions related to testing are assumed to be much less than the ones from production.	High

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
1P CHPb	High quality data have been collected in the literature and from personal communication with plants owners. *Gas content and composition* which is the critical parameter is of high quality but can vary as a function time. The variability of the composition is reflected by the values collected in the literature from 2006 onwards. Plant owners provided current data available.	*Wells*: High quality as all wells drilled in the geothermal sector are reported in a database managed by OS. The data have been extracted from the database and used in the calculation. Only the drilled depth is used, not the well design as this data was not available at the cluster scale. *Production technology*: High quality data as most plants characteristics are published. Some technical difference exist between plants, especially the eldest ones are quite different compared to the most recent ones, most of them have gone through different stage of retrofitting. Single flash and Double flash plants are accounted for. The collection pipeline: data from the literature have been used as well as data from plants owners. The distance of pipeline estimated by the proxies aligns well with the one in the field.	*Emissions are monitored and reported yearly by plant operators.* For this study, emissions during operation are based on the amount of steam that is produced from the field on the gas composition and on the efficiency of the abatement system (if present). The amount obtained align well with the data published and communicated by plant owners. *Testing*: this phase is not accounted for as no data was available in the literature. However the emissions related to testing are assumed to be much less than the ones from production.	Medium

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
2P	*Gas composition*: difficult to find useable data about gas content and composition in the literature. Only two datasets have been used, including data from Pico Vermelho and Grande Ribeira plants publicly available from scientific papers. Natural emissions of Hg and As are measured as natural emissions at some locations where there is hydrothermal activity, but they have not been reported in the chamical analysis of the brine or in the vapour phase.	The 3 existing plants belonging to the cluster have been included in the analysis, the main uncertainty is on WHP and T. They operate with the same technology, binary plants where NCGs are degassed and heavy metals are reinjected. The number of wells is reported in the literature. The depth of the wells is also reported for most of them. The installed capacity is reported in the EGEC market report and in published papers.	No data available about actual emissions of the plants. For this study, emissions during operation are based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production).	Low
3P CHP	Data on *steam composition* has been provided by plant operators and evaluated based on data published by the local Regional Agency for Environmental Protection.	Typical plant design has been provided by plsnt operators. All the plants belonging to cluster 3P have been used to estimate the mean running capacity of the reference plant as well as WHT and P. Typical flow rates are based on data provided by plant operatos. *Wells:* number of wells and drilled depth are based on data published in the literature and data provided by plant operator for a typical plant of 20 MWe installed capacity. *Collection pipelines*: length provided by operator for a one of the plant of the cluster, assumed to be representative.	Direct emissions regularly measured by plant managers and regional agencies for operating plants. For this study, emissions during operation are based on volume of steam produced annually, gas composition and efficiency of abatement system. The volume of steam is derived from plant operating parameters and mean annual energy production. The amount obtained align well with the data published and communicated by plant owners.	High

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
4P	Information directly collected from plant managers for the cluster Data on *steam composition* has been provided by plant operators and evaluated based on data published by the local Regional Agency for Environmental Protection.	Information directly collected from plant managers for the cluster	Direct emissions regularly measured by plant managers and regional agencies for operating plants. For this study, direct emissions during operation are based on volume of steam produced annually, gas composition and efficiency of abatement system. The volume of steam is derived from plant operating parameters and mean annual energy production. The amount obtained align well with the data published and communicated by plant owners.	High
4P CHP	Information directly collected from plant managers for the cluster Data on *steam composition* has been provided by plant operators and evaluated based on data published by the local Regional Agency for Environmental Protection.	Information directly collected from plant managers for the cluster	Direct emissions regularly measured by plant managers and regional agencies for operating plants. For this study, emissions during operation are based on volume of steam produced annually, gas composition and efficiency of abatement system. The volume of steam is derived from plant operating parameters and mean annual energy production. The amount obtained align well with the data published and communicated by plant owners.	High

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
5P	*Gas composition and content*: Data have been collected from high quality scientific papers and from pers. Com. With plant owners. Temperature: Data has been collected from the literature and provided by plants owners.	*Wells*: data reported for all the project in the literature. Flow rate: data published for some of the plants but not all of them. Installed capacity and production data: published in EGEC market report.	No data monitoring during testing and operation available. Direct emissions during both phases calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	High
5P CHP	*Gas composition and content*: Data have been collected from high quality scientific papers and from pers. Com. With plant owner.	*Wells*: data about number and characteristics of the wells reported in the literature. Flow rate: data published for some of the plants but not all of them. Installed capacity and production data: published in EGEC market report.	No data monitoring during testing and operation available. Direct emissions during both phases calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	High

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
6P	Gas content and composition based on data found in the literature.	Information based on literature review. Difficult to find information about the actual plant operating parameters. For example, no clear information about the minimum pressure in the surface installation, which can have large impact on the amount of gas that can stay in solution and that can be reinjected. As a consequence the default value of 20 bar is used. If a higher pressure would be set then the direct emissions would decrease drastically.	No data monitored or published on direct emissions. Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	Medium
7P CHP	Information directly collected from plant managers for all the plants of the cluster	Information directly collected from plant managers for all the plants of the cluster	No data monitored or published on direct emissions, as the plant is still not in full operation. Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	High (although plant of this cluster is not yet in full operation)

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
8P	Gas content and composition: mean values found in the literature in scientific papers.	Information collected in literature	Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	Medium
8P CHP	Gas content and composition: mean values found in the literature in scientific papers.	Information collected in literature	Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	Medium
1DHC	Gas content: no data available Gas composition: data provided by research institute	All geothermal applications have different operating parameters. The definition of a cluster is thus not possible.	No data available. However, personal communication with research center highlighted that the emissions are mainly N_2 typically ~ more than 95% of the gases, Argon ~ 1,5% and sometimes very small amount of CH_4	Low

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
2DHC	Information directly collected from plant managers for all the plants of the cluster and from published article.	Information directly collected from plant managers for all the plants of the cluster and from published article.	Information estimated by plant managers is compared to direct emissions calculated from primary data.	High
3DHC	Gas and brine compositions: Publicly available data is difficult to find. Values from literature based on wells in Hungary have been used to derive the cluster value.	At the cluster level all the plants belonging to the cluster have been used to get an averaged production and capacity installed. Abatement system is not accounted for but flaring is a practice in Hungary to abat the CH4 emissions.	Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition. No published data.	Medium
4DHCa	High quality data available for all the plants from the Paris basin. For the other plants belonging to the cluster, less information available. Additionally, information was directly collected from plant managers	All the wells of the Paris basin for which data are available have been used. At the cluster level the mean value of the depth drilled has been used for a doublet.	No data monitored or published on direct emissions. Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	High for plants of the Paris basin, Medium for others

Cluster	Geological Characteristics (e.g.: composition, temperature, pressure, solubility of geothermal fluid)	Technological Characteristics (n of wells, production technology, equipment type, etc.)	Direct emissions to air (e.g.: during operation, testing)	Overall data quality
4DHCb	Data collected from literature.	Data collected from literature.	No data monitored or published on direct emissions. Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	High
5DHC	Gas content and composition: mean values found in the literature in scientific papers. Same as cluster 8P.	Data collected from literature, only available for plants in Austria and Germany.	No data monitored or published on direct emissions. Direct emissions calculated from primary data based on gas content and composition, minimum pressure in the system, volume produced per year. The latter is deduced from operating reference plants input parameters (inlet/outlet enthalpies and pressures, flow rate and mean annual energy production). Emissions during testing are based on the volume produced during the testing phase and gas content and composition.	Medium

11 GHG EMISSIONS INVENTORIES

A GHG inventory focuses on the representation of emissions contributing to the climate change impact category.

The international standard ISO 14067 “Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification” sets an acknowledged and accepted methodology for the transparent communication of the global warming effect of a product.

The inventory is developed by lifecycle phase, i.e.: sub-surface construction, surface construction and core processes, with additional segmentation of respective sub-phases.

GHG emissions factors for each flow are extracted from the software Gabi, considering the latest IPCC GWP100 characterisation factors as adapted within the PEF3.0 framework, which relies on the fifth assessment report of IPCC (2013).

Being the ISO standard 14067 aligned with the methodology, contents and definitions of the ISO standards for LCA studies, pillars references for this study, it can be stated that the goal, scope, boundaries and assumptions already declared for the LCIA are also applied for the development of the inventories, presented at cluster level.

As a first step for GHG emissions representation, the GWP associated with each flow, by phase, is calculated at cluster level and normalized on the appropriate functional unit.

The results of this detailed assessment are reported in the correspondent chapter in ANNEX IV, reporting the ranges based on the minimum and maximum values extrapolated from all the P clusters and DHC clusters respectively. Thus, emissions estimated cover transversally all the clusters (i.e.: minimum limit is the minimum value encountered across all the clusters and maximum limit is the maximum value encountered across all the clusters), expressed as $kgCO_2e/kWh_e$ for the case of P-clusters and as $kgCO_{2e}/kWh_t$ for the case of DHC-clusters. As for the cases of P CHP clusters, the correspondent table are not reported as they are slightly affected by the allocation procedure.

It is highlighted that minimum and maximum values reported in the tables are calculated by single flow and thus, summed up, they are not representative of a cluster, but they rather indicate the limit threshold that can be obtained specifically for a flow, providing a very specifc output.

The proposed high-level representation of results, suitable for all the clusters, is balanced by the thorough analysis performed in the following chapter for all the selected impact categories, and not only limited to GWP.

Hereafter, with the aim of providing a more general output and overview on GWP performane of geothermal plants and application, an analysis focused on a minimum GHG scenario, for the plant representative cluster characterized by the lowest overall emissions and a maximum GHG scenario, characterized by the highest overall emissions.

Correspondent conclusions will be drawn for the case of P-clusters representative plants, as well as P CHP and DHC clusters representative plants.

When looking at the performance at overall reference plant level, average GHG emissions for functional unit range from 0.007 to 0.819 $kgCO_{2e}/kWh_e$ (excluding the results for cluster 6P, considered as an outlier, with an average value of 0.190 $kgCO_{2e}/kWh_e$. The significant variability of this range derives from the intrinsic different features of the clusters, in terms of geothermal reservoirs, plant typology and presence of reinjection or abatement systems for GHG emissions, coupled with uncertainties associated with data estimation.

An interesting analysis is to understand in which phases of the two extreme cases GHG emissions are generated. This focus allows to understand hotspot for the implementation of mitigation measures mainly aimed at the reduction of impacts for the global warming potential category, to which such emissions contribute.

Figure 12 shows the contribution of the different phases to the overall share of emission for the representative plant for the minimum emissions scenario, while Figure 13 provides the same information for the maximum emissions scenario. Clearly, direct emissions generated during the plant operation are the main contributors to the aforementioned aspect and thus they should be the main target when developing climate change mitigation measures in the deep geothermal sector.

On the other hand, in the minimum emissions scenario, these type of emissions are either not present or already mitigated and thus, they do not contribute to GWP category. For such case, contributors are mainly the drilling phase, including, as shown in previous table, a significant share of energy generation from diesel combustion, added to some share deriving from steel and cement manufacturing. Also manufacturing of the equipment materials is not negligible in this scenario, considering the high quantities mainly of steel and cement employed and the high emission factors of some metals and plastics.

In both scenarios, it results that overall the phases of exploration, stimulation and testing do not exceed 10% of the total amount of GHG emissions.

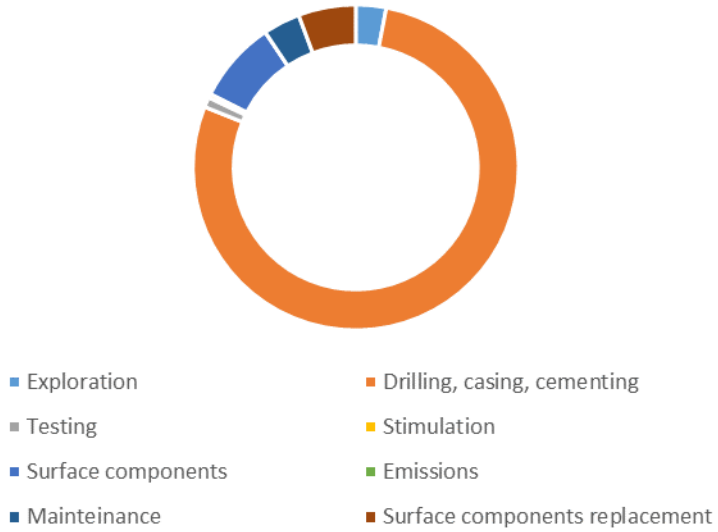


Figure 12: GHG emissions share – minimum direct emissions in operation scenario, P clusters

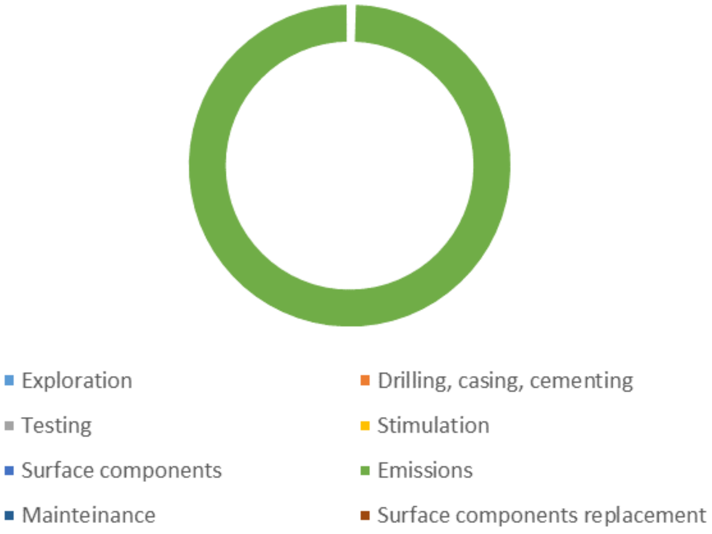


Figure 13: GHG emissions share – maximum direct emissions in operation scenario, P clusters

For the case of electricity generated by P CHP plants, the average electricity emission factor ranges from 0.005 $kgCO_2/kWh_{el}$ to 0.898 $kgCO_2/kWh_{el}$, being slightly lower that the case of P clusters possibly due to the allocation of a share of the impacts also to heat production.

When focusing on the phases relevant to global warming potential in the minimum and maximum emissions scenario, Figure 14 and Figure 15 show the respective results, correspondent to the ones obtained and already commented for the case of P- clusters representative plants.

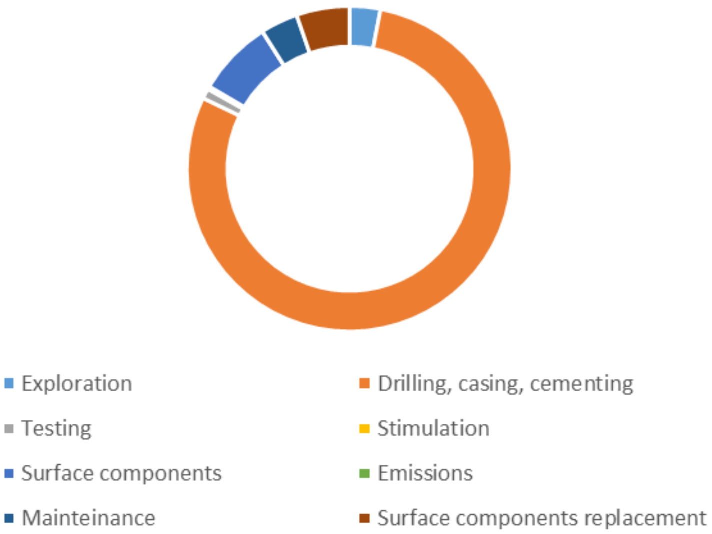


Figure 14: GHG emissions share – maximum direct emissions in operation scenario, P CHP clusters, electricity production

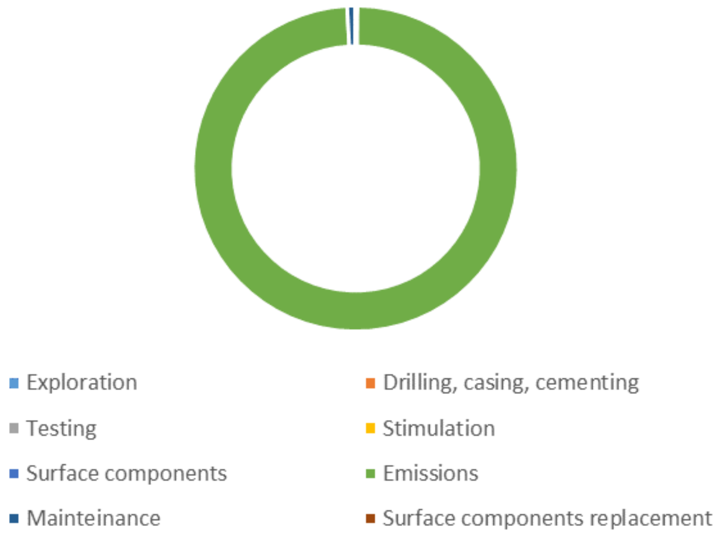


Figure 15: GHG emissions share – maximum direct emissions in operation scenario, P CHP clusters, electricity production

It is highlighted that at overall reference plant level, average emissions range from 0.008 $kgCO_{2e}/kWh_{th}$ to 0.220 $kgCO_{2e}/kWh_{th}$, representative of a minumim emission scenario and maximum emission scenario, respectively.

For the mimimum emission scenario, as represented in Figure 16 the major contributor to GHG emissions is associated to electricity consumed deuring operation phase for pumping the geothermal fluid along the circuit within the plant, followed by a significant share releated to drilling operations.

For the maximum emissions scenario, as already obtained for the previous configurations, direct emissions represent the predominats contributor, while the other phases can be considered negligible, as it can be observed in Figure 17.

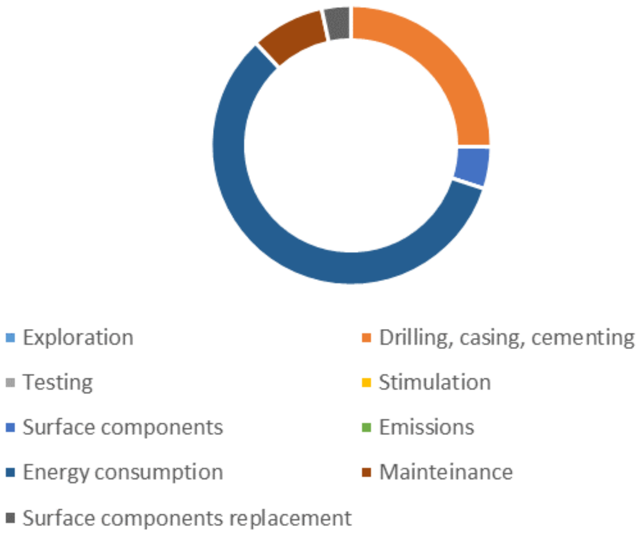


Figure 16: GHG emissions share – minimum direct emissions in operation scenario, DHC clusters

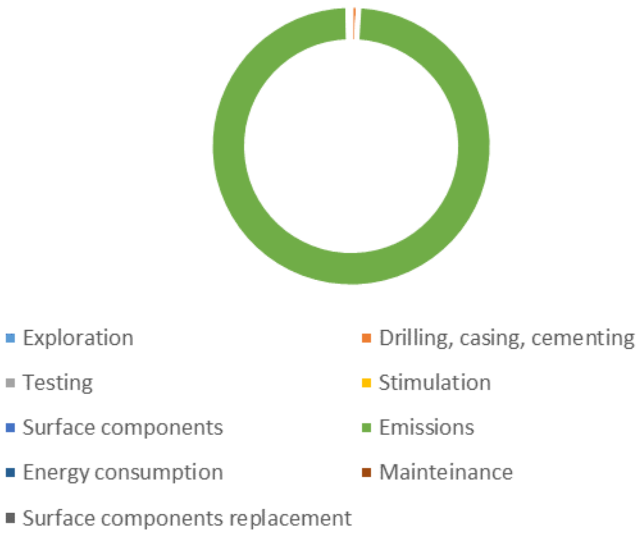


Figure 17: GHG emissions share – maximum direct emissions in operation scenario, DHC clusters

Finally, the production of thermal energy in P CHP representative plants leads to GHG emissions ranging from 0.003 $kgCO_2e/kWh_{th}$ to 0.723 $kgCO_2e/kWh_{th}$. The share of GHG emissions for the minimum emissions scenario and the maximum emissions scenario is illustrated in Figure 18 and Figure 19 respectively. As for the former, similarly to the case of the plants of P clusters, drlling represents the phase of major concern, as in this configuration, electricity consumption during production is accounted implicitily as a self-consumption and thus it is not associated to any emissions. Finally, considering the maximum emissions scenario, the trend already encountered in all the correspondeednt cases is confirmed: direct emissions play a key role in generating GHG emissions and, in comparison, all the other phases become negligible.

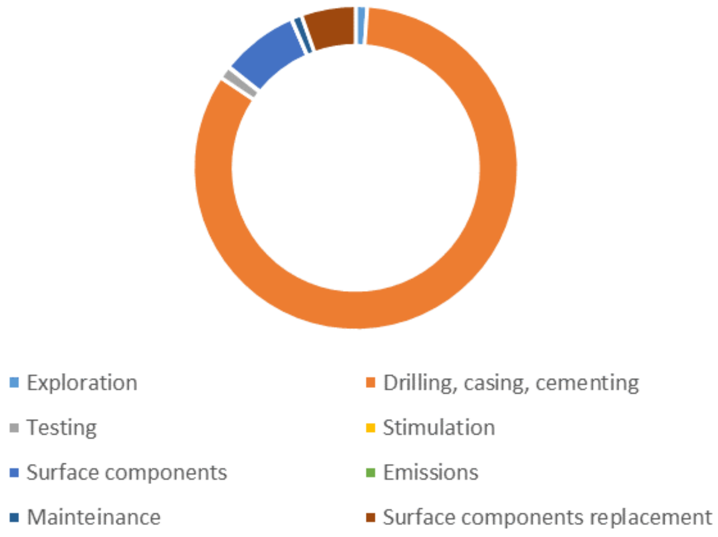


Figure 18: GHG emissions share – maximum direct emissions in operation scenario, DHC clusters, heat production

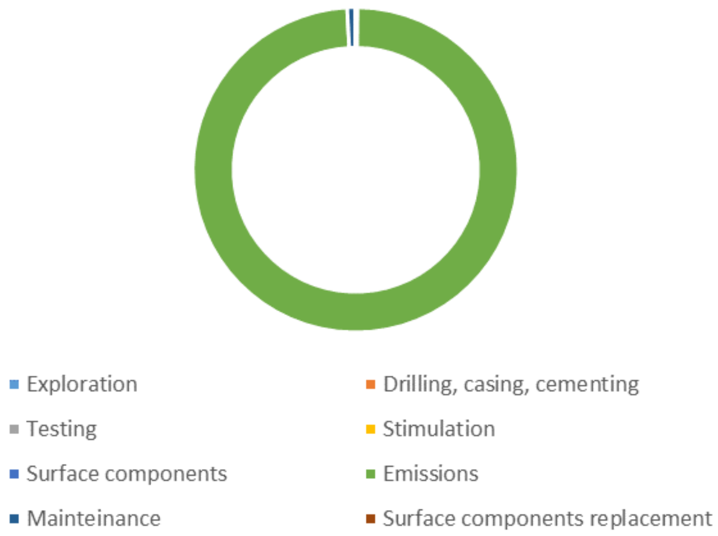


Figure 19: GHG emissions share – maximum direct emissions in operation scenario, DHC clusters, heat production

12 LCIA RESULTS

12.1 Global Results

This chapter reports the global LCA results of the study, for all the clusters analyzed, considering the impact categories selected within the SCR. In tables below, the results are provided per declared unit, i.e. 1 kWh net of electricity generated and/or 1 kWh of steam or hot water generated.

Specifically, Table 34, Table 35, Table 36, Table 37 and Table 38include the results for LCA studies of P clusters, including also the results derived from allocation of impacts of CHP plants for electricity production. Moreover, Table 39, Table 40 and Table 41 show results for P CHP plants considering the impacts allocated to heat production.

Table 34: LCIA results for P clusters (for 1 KWhe)

Flow	UoM	1P		1P CHPa		1P CHPb	
		min	max	min	max	min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	6.0E-05	8.8E-05	1.1E-05	1.9E-05	6.9E-06	9.9E-06
Cancer human health effects	CTUh	2.7E-11	4.2E-11	2.8E-11	4.2E-11	3.3E-11	4.9E-11
Climate Change	kg CO2 eq.	1.5E-02	5.2E-02	9.0E-03	1.5E-02	9.6E-03	1.3E-02
Ecotoxicity freshwater	CTUe	5.1E+01	6.5E+01	4.0E-01	5.1E-01	3.9E+01	7.7E+01
Eutrophication freshwater	kg P eq	1.6E-07	2.8E-07	1.2E-07	2.1E-07	6.1E-08	1.3E-07
Eutrophication marine	kg N eq	5.3E-06	8.5E-06	2.9E-06	5.9E-06	1.9E-06	2.6E-06
Eutrophication terrestrial	Mole of N eq	2.4E-04	3.9E-04	3.0E-05	6.3E-05	2.0E-05	2.8E-05
Non-cancer human health effects	CTUh	1.4E-09	2.2E-09	1.3E-09	2.0E-09	1.4E-09	1.9E-09
Ozone depletion	kg CFC-11 eq	1.1E-10	1.8E-10	7.4E-11	1.5E-10	3.9E-11	8.0E-11
Photochemical ozone formation - human health	kg NMVOC eq.	1.2E-05	1.9E-05	8.8E-06	1.7E-05	5.6E-06	8.0E-06
Respiratory inorganics	Disease incidences	5.8E-10	9.8E-10	1.8E-10	4.2E-10	1.2E-10	2.0E-10

Table 35: LCIA results for P clusters (for 1 KWhe)

Flow	UoM	2P		3P CHP		4P	
		min	max	min	max	min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	2.8E-03	5.6E-03	2.2E-05	1.6E-03	4.5E-04	9.7E-04
Cancer human health effects	CTUh	1.2E-10	1.9E-10	6.3E-11	1.1E-10	5.7E-11	3.5E-10
Climate Change	kg CO2 eq.	9.9E-02	3.7E-01	1.8E-01	5.2E-01	5.1E-01	1.1E+00
Ecotoxicity freshwater	CTUe	4.5E+02	5.4E+02	4.7E+00	1.6E+01	5.7E+00	1.2E+01
Eutrophication freshwater	kg P eq	2.1E-07	3.5E-07	8.0E-08	5.1E-07	2.2E-07	3.4E-07
Eutrophication marine	kg N eq	7.2E-05	2.0E-04	2.3E-05	1.1E-04	2.1E-05	4.1E-05
Eutrophication terrestrial	Mole of N eq	1.0E-02	2.8E-02	0.0E+00	7.5E-03	2.0E-03	4.3E-03
Non-cancer human health effects	CTUh	1.3E-08	2.1E-08	5.0E-09	1.0E-08	4.2E-09	4.0E-08
Ozone depletion	kg CFC-11 eq	1.0E-10	2.6E-10	1.2E-10	6.5E-10	1.6E-10	3.9E-10
Photochemical ozone formation - human health	kg NMVOC eq.	1.1E-05	2.8E-05	7.4E-05	2.0E-04	7.5E-05	1.5E-04
Respiratory inorganics	Disease incidences	1.5E-08	4.4E-08	1.1E-09	1.4E-08	3.6E-09	7.5E-09

Table 36: LCIA results for P clusters (for 1 KWhe)

Flow	UoM	4P CHP		5P		5P CHP	
		min	max	min	max	min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	1.7E-03	2.5E-03	5.6E-05	8.4E-05	4.7E-05	5.9E-05
Cancer human health effects	CTUh	1.5E-10	1.6E-10	3.7E-11	5.9E-11	3.9E-11	4.7E-11
Climate Change	kg CO2 eq.	8.8E-01	9.1E-01	6.2E-03	8.3E-03	5.0E-03	5.9E-03
Ecotoxicity freshwater	CTUe	1.3E+00	4.9E+00	2.0E+00	2.5E+00	1.1E+00	2.2E+00
Eutrophication freshwater	kg P eq	1.0E-07	6.2E-07	5.2E-07	6.5E-07	2.5E-07	6.4E-07
Eutrophication marine	kg N eq	5.6E-05	8.1E-05	2.2E-05	3.3E-05	2.0E-05	2.2E-05
Eutrophication terrestrial	Mole of N eq	7.5E-03	1.1E-02	2.3E-04	3.6E-04	2.1E-04	2.4E-04
Non-cancer human health effects	CTUh	1.6E-08	1.7E-08	3.2E-09	5.3E-09	2.8E-09	3.7E-09
Ozone depletion	kg CFC-11 eq	5.8E-11	2.9E-10	5.6E-10	8.5E-10	4.4E-10	6.4E-10
Photochemical ozone formation - human health	kg NMVOC eq.	1.4E-04	1.6E-04	6.3E-05	9.6E-05	5.7E-05	6.4E-05
Respiratory inorganics	Disease incidences	1.2E-08	1.8E-08	1.7E-09	2.6E-09	1.5E-09	1.8E-09

Table 37: LCIA results for P clusters (for 1 KWhe)

Flow	UoM	6P		7P CHP		8P	
		min	max	min	max	min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	2.6E-05	5.3E-05	7.2E-05	1.1E-04	7.4E-05	1.3E-04
Cancer human health effects	CTUh	8.1E-11	1.3E-10	7.7E-11	9.1E-11	5.2E-11	8.5E-11
Climate Change	kg CO2 eq.	2.6E+00	3.1E+00	7.5E-03	1.0E-02	6.6E-03	1.2E-02
Ecotoxicity freshwater	CTUe	1.5E+00	1.9E+00	2.0E+00	2.6E+00	1.6E+00	2.7E+00
Eutrophication freshwater	kg P eq	4.0E-07	6.8E-07	5.3E-07	6.4E-07	4.7E-07	8.6E-07
Eutrophication marine	kg N eq	7.1E-06	1.9E-05	2.8E-05	4.4E-05	3.0E-05	5.0E-05
Eutrophication terrestrial	Mole of N eq	7.6E-05	2.0E-04	3.0E-04	4.8E-04	3.2E-04	5.5E-04
Non-cancer human health effects	CTUh	7.0E-09	1.1E-08	3.1E-09	3.7E-09	4.7E-09	7.5E-09
Ozone depletion	kg CFC-11 eq	2.2E-10	5.2E-10	7.0E-10	1.1E-09	7.4E-10	1.3E-09
Photochemical ozone formation - human health	kg NMVOC eq.	2.1E-05	5.4E-05	8.1E-05	1.3E-04	8.6E-05	1.5E-04
Respiratory inorganics	Disease incidences	5.0E-10	1.4E-09	2.2E-09	3.5E-09	2.4E-09	3.9E-09

Table 38: LCIA results for P clusters (for 1 KWhe)

Flow	UoM	8P CHP	
		min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	3.7E-05	8.5E-05
Cancer human health effects	CTUh	6.5E-11	1.0E-10
Climate Change	kg CO_2 eq.	4.5E-03	8.1E-03
Ecotoxicity freshwater	CTUe	6.7E-01	1.8E+00
Eutrophication freshwater	kg P eq	3.1E-07	4.3E-07
Eutrophication marine	kg N eq	1.3E-05	3.4E-05
Eutrophication terrestrial	Mole of N eq	1.4E-04	3.7E-04
Non-cancer human health effects	CTUh	3.4E-09	5.3E-09
Ozone depletion	kg CFC-11 eq	3.3E-10	8.4E-10
Photochemical ozone formation - human health	kg NMVOC eq.	3.8E-05	9.8E-05
Respiratory inorganics	Disease incidences	1.0E-09	2.7E-09

Table 39: LCIA results for P CHP clusters (for 1 kWhth)

Flow	UoM	1P CHPa		1P CHPb		3P CHP	
		Min	max	Min	max	Min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	8.6E-06	1.4E-05	4.5E-06	6.4E-06	1.7E-05	1.3E-03
Cancer human health effects	CTUh	2.1E-11	3.2E-11	2.2E-11	3.2E-11	5.0E-11	9.0E-11
Climate Change	kg CO2 eq.	6.7E-03	1.1E-02	6.2E-03	8.6E-03	1.4E-01	4.1E-01
Ecotoxicity freshwater	CTUe	3.0E-01	3.8E-01	2.5E+01	5.0E+01	3.8E+00	1.3E+01
Eutrophication freshwater	kg P eq	9.2E-08	1.6E-07	4.0E-08	8.7E-08	6.3E-08	4.0E-07
Eutrophication marine	kg N eq	2.2E-06	4.4E-06	1.2E-06	1.7E-06	1.8E-05	9.0E-05
Eutrophication terrestrial	Mole of N eq	2.3E-05	4.7E-05	1.3E-05	1.8E-05	2.0E-04	5.5E-03
Non-cancer human health effects	CTUh	9.9E-10	1.5E-09	8.8E-10	1.2E-09	4.0E-09	8.1E-09
Ozone depletion	kg CFC-11 eq	5.6E-11	1.1E-10	2.5E-11	5.2E-11	9.5E-11	5.2E-10
Photochemical ozone formation - human health	kg NMVOC eq.	6.6E-06	1.3E-05	3.6E-06	5.2E-06	5.8E-05	1.6E-04
Respiratory inorganics	Disease incidences	1.4E-10	3.2E-10	7.7E-11	1.3E-10	8.7E-10	1.1E-08

Table 40: LCIA results for P CHP clusters (for 1 kWhth)

Flow	UoM	4P CHP		5P CHP		7P CHP	
		Min	max	Min	max	Min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	1.4E-03	2.0E-03	3.6E-05	4.4E-05	2.8E-05	4.3E-05
Cancer human health effects	CTUh	1.2E-10	1.3E-10	2.9E-11	3.6E-11	3.0E-11	3.6E-11
Climate Change	kg CO2 eq.	7.1E-01	7.3E-01	3.7E-03	4.4E-03	2.9E-03	4.1E-03
Ecotoxicity freshwater	CTUe	1.0E+00	3.9E+00	8.3E-01	1.6E+00	8.0E-01	1.0E+00
Eutrophication freshwater	kg P eq	8.2E-08	5.0E-07	1.8E-07	4.8E-07	2.1E-07	2.5E-07
Eutrophication marine	kg N eq	4.5E-05	6.5E-05	1.5E-05	1.7E-05	1.1E-05	1.8E-05
Eutrophication terrestrial	Mole of N eq	6.0E-03	8.7E-03	1.6E-04	1.8E-04	1.2E-04	1.9E-04
Non-cancer human health effects	CTUh	1.3E-08	1.3E-08	2.1E-09	2.8E-09	1.2E-09	1.4E-09
Ozone depletion	kg CFC-11 eq	4.7E-11	2.3E-10	3.3E-10	4.8E-10	2.8E-10	4.4E-10
Photochemical ozone formation - human health	kg NMVOC eq.	1.1E-04	1.3E-04	4.2E-05	4.8E-05	3.2E-05	5.1E-05
Respiratory inorganics	Disease incidences	9.8E-09	1.4E-08	1.1E-09	1.3E-09	8.7E-10	1.4E-09

Table 41: LCIA results for P CHP clusters (for 1 kWhth)

Flow	UoM	8P CHP	
		min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	2.3E-05	5.3E-05
Cancer human health effects	CTUh	4.1E-11	6.3E-11
Climate Change	kg CO_2 eq.	2.8E-03	5.0E-03
Ecotoxicity freshwater	CTUe	4.2E-01	1.1E+00
Eutrophication freshwater	kg P eq	1.9E-07	2.7E-07
Eutrophication marine	kg N eq	8.2E-06	2.1E-05
Eutrophication terrestrial	Mole of N eq	8.8E-05	2.3E-04
Non-cancer human health effects	CTUh	2.1E-09	3.3E-09
Ozone depletion	kg CFC-11 eq	2.1E-10	5.2E-10
Photochemical ozone formation - human health	kg NMVOC eq.	2.4E-05	6.1E-05
Respiratory inorganics	Disease incidences	2.3E-05	5.3E-05

Table 42: LCIA results for DHC clusters (for 1 kWhth)

Impact category	Unit	2DHC		3DHC		4DHCa	
		min	max	min	min	min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	3.5E-05	6.4E-05	1.2E-04	1.2E-04	1.5E-05	3.9E-05
Cancer human health effects	CTUh	1.8E-11	3.0E-11	4.5E-11	4.5E-11	4.6E-11	6.2E-11
Climate Change	kg CO_2 eq.	1.1E-02	1.7E-02	4.2E-02	4.2E-02	0.0E00	4.6E-01
Ecotoxicity freshwater	CTUe	3.2E-01	4.9E-01	1.1E+00	1.1E+00	5.4E-01	1.6E+00
Eutrophication freshwater	kg P eq	9.4E-08	2.6E-07	3.3E-07	3.3E-07	1.8E-07	8.2E-07
Eutrophication marine	kg N eq	6.7E-06	1.4E-05	1.9E-05	1.9E-05	5.6E-06	1.1E-05
Eutrophication terrestrial	Mole of N eq	7.2E-05	1.5E-04	2.1E-04	2.1E-04	6.0E-05	1.2E-04
Non-cancer human health effects	CTUh	4.8E-10	8.6E-10	1.2E-09	1.2E-09	1.5E-09	2.4E-09
Ozone depletion	kg CFC-11 eq	5.8E-11	1.2E-10	1.3E-10	1.3E-10	1.3E-10	4.4E-10
Photochemical ozone formation - human health	kg NMVOC eq.	1.9E-05	4.0E-05	5.4E-05	5.4E-05	5.5E-05	1.1E-04
Respiratory inorganics	Disease incidences	3.4E-10	7.5E-10	9.1E-10	9.1E-10	6.5E-10	6.5E-10

Table 43: LCIA results for DHC clusters (for 1 kWhth)

Impact category	Unit	4DHCb		5DHC	
		min	max	min	max
Acidification terrestrial and freshwater	Mole of H+ eq.	2.8E-05	5.6E-05	2.8E-05	5.6E-05
Cancer human health effects	CTUh	4.3E-11	6.7E-11	4.3E-11	6.7E-11
Climate Change	kg CO_2 eq.	6.1E-03	9.5E-03	6.1E-03	9.5E-03
Ecotoxicity freshwater	CTUe	1.1E+00	1.4E+00	1.1E+00	1.4E+00
Eutrophication freshwater	kg P eq	3.2E-07	6.4E-07	3.2E-07	6.4E-07
Eutrophication marine	kg N eq	6.6E-06	1.6E-05	6.6E-06	1.6E-05
Eutrophication terrestrial	Mole of N eq	7.2E-05	1.8E-04	7.2E-05	1.8E-04
Non-cancer human health effects	CTUh	1.3E-09	2.1E-09	1.3E-09	2.1E-09
Ozone depletion	kg CFC-11 eq	1.9E-10	4.0E-10	1.9E-10	4.0E-10
Photochemical ozone formation - human health	kg NMVOC eq.	1.9E-05	4.7E-05	1.9E-05	4.7E-05
Respiratory inorganics	Disease incidences	4.6E-10	1.2E-09	4.6E-10	1.2E-09

12.1.1 Overall Analysis of Results

This section presents a high level analysis of the results in terms of global warming potential indicator, in order to provide a full overview of the current situation at Europen level.

Table 44 shows an overview of GWP results for P clusters and P-CHP clusters (impacts of electricity production only) – cluster 6P is however excluded for the evaluation as the result for the low reliability of global warming potential results. In detail, the table provides the number of plants and the total installed capacity for three ranges of global warming potential values:

- lower than 100 gCO_{2e}/kWh_e;
- between 100 gCO_{2e}/kWh_e and 500 gCO_{2e}/kWh_e;
- higher than 500 gCO_{2e}/kWh_e.

The threshold of 100 gCO_{2e} is selected as it represents the threshold proposed by the in the technical annex of the Taxonomy Report (EU Technical Expert Group on Sustainable Finance, 2020) for assessment of electricity generation from geothermal plants. Conversely, the threshold of 500 gCO_{2e} is arbitrary, but representative of the average impact of the European electricity grid mix.

Table 44: GWP results overview – P clusters and P CHP clusters

Range [gCO_{2e}/kWh_e]	N° of Representative Plants	Share of Representative Plants [%]	Electrical installed capacity [MW_e]	Share of electrical installed capacity [%]
<100	18	32%	779	45%
between 100 and 500	33	58%	827	48%
>500	6	11%	121	7%

In correspondence to the previous paragraph, Table 45 shows an overview of GWP results for DHC-clusters and P CHP clusters (impacts of heat production only) – excluding cluster 1DHC for which results could not be calculated. The same thresholds used for the previous assessment are used, with reference to themal energy.

Table 45: GWP results overview – DHC-clusters and P CHP clusters

Range [gCO_{2e}/kWh_{th}]	N° of Representative Plants	Share of Representative Plants [%]	Electrical installed capacity [MW_{th}]	Share of electrical installed capacity [%]
<100	155	60%	1784	74%
between 100 and 500	101	39%	590	25%
>500	3	1%	21	1%

12.1.2 Results Grouped per Technology

This chapter reports the results of the study, in terms of GHG emissions, grouped per technology. Indeed, from an analysis of data of gas composition and direct emissions, such emissions, typically CO_2 and in some cases CH_4, are the only ones present in all the clusters and, in addition, they are commonly and reliably characterized emissions for the geothermal sector, being among the most aboundant in mass flow.

To facilitate the interpretation of the grouped results, a summary of the correlation among technologies and clusters is reported in the table below.

Table 46: Technology per cluster

Cluster	Technology			
	Flash steam	Binary	Dry steam	Hybrid flash steam/ binary
1P	X			
1P CHPa	X			
1P CHPb	X			
2P		X		
3P CHP			X	
4P	X			
4P CHP				X
5P		X		
5P CHP		X		
6P		X		
7P CHP		X		
8P		X		
8P CHP		X		

In Figure 20, the GHG emissions (in kilograms of carbon dioxide equivalent per kilowatt-hour generated [kg CO2eq/kWh]) from the different technologies are reported. The figure shows a high variability for the flash steam technology, which ranges from 0.011 to 0.819 kg $CO_{2\ eq}$/ kWh_{el}. Binary technology presents lower impacts, ranging from 0.005 to 0.234 kg $CO_{2\ eq}$/ kWh_{el} (from this range, the results associated to the cluster 6P have been excluded, since they highly deviate from the other results for binary clusters but at the same time the data quality for this cluster is less robust than in the other cases). Dry steam technologies and hybrid flash steam/ binary are characterized by 0.351 and 0.898 kg $CO_{2\ eq}$/ kWh_{el}, respectively.

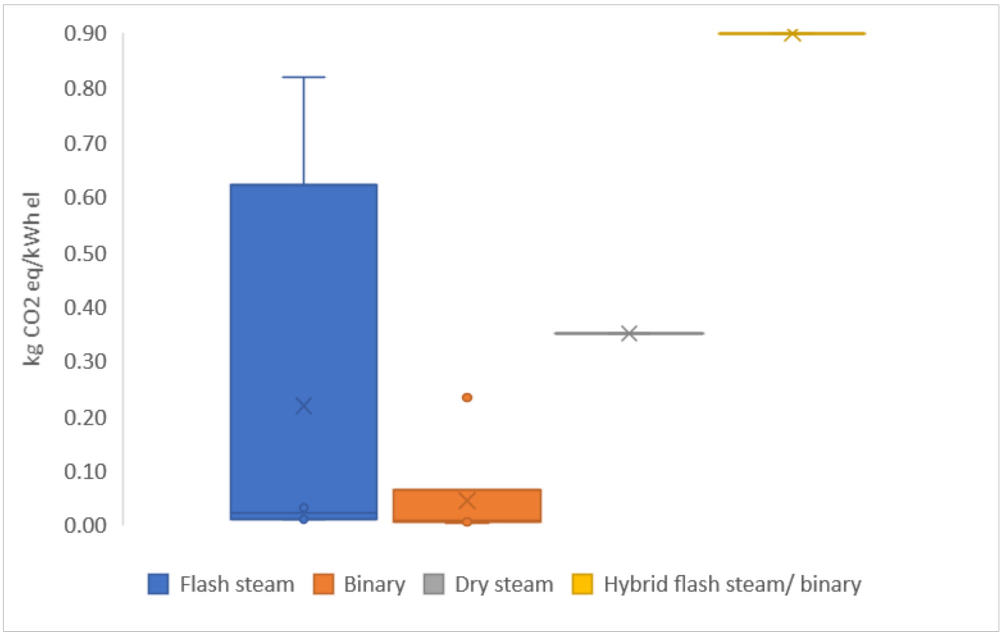


Figure 20: GHG emissions per kWh el – grouping by technology

Analogoulsy, the results associated with heat production are reported, grouper by technology: for flash steam, the results range from 0.007 to 0.009 kg $CO_{2\ eq}$/ kWh_{th}, for binary they range from 0.003 to 0.004 kg CO_2 eq/ kWh_{th}, for hybrid flash steam/binary they are equal to 0.723 kg $CO_{2\,eq}$/ kWh_{th}, while for DHC the emissions of CO_2 associated to each kWh_{th} range from 0.014 to 0.224.

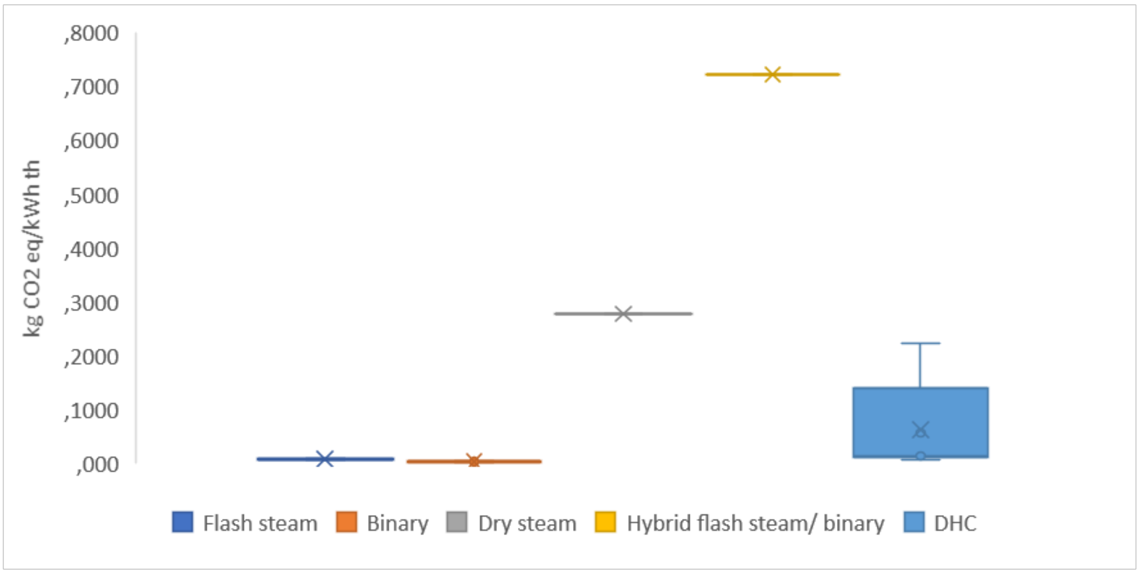


Figure 21: GHG emissions per kWh th – grouping by technology

12.1.3 Results Grouped per Geological Play

This chapter reports the global LCA results of the study, in terms of GHG emissions, grouped per geological play. To facilitate the interpretation of the grouped results, a summary of the correlation among geological play and clusters is reported in the table below. Indeed, from an analysis of data of gas composition and direct emissions, such emissions, typically CO_2 and in some cases CH_4, are the only ones present in all the clusters and, in addition, they are commonly and reliably characterized emissions for the geothermal sector, being among the most aboundant in mass flow.

Table 47: Geological play per cluster

Cluster	Geological play				
	Volcanic	Magmatic intrusive	Extensional, fault controlled	Intracratonic	Orogenic
1P	x				
1P CHPa	x				
1P CHPb	x				
2P	x				
3P CHP		x			
4P		x			
4P CHP		x			
5P			x		
5P CHP			x		
6P			x		
7P CHP				x	
8P					x
8P CHP					x
1DHC	x				
2DHC			x		
3DHC			x		

Cluster	Geological play				
	Volcanic	Magmatic intrusive	Extensional, fault controlled	Intracratonic	Orogenic
4DHCa				x	
4DHCb				x	
5DHC					x

For the electricity production, the results for volcanic geological play range from 0.011 to 0.234 kg $CO_{2\ eq}$/ kWh_{el}, those for magmatic intrusive range from 0.351 to 0.898 kg $CO_{2\ eq}$/ kWh_{el} . The results for the other geological plays range from 0.006 to 0.009 kg $CO_{2\ eq}$/ kWh_{el}, however the contribution from cluster 6P is excluded, due to the high uncertainty related to the data for this cluster. Including also cluster 6P contribution, the results associated with extensional, fault controlled geological phase would be up to 2.81 kg $CO_{2\ eq}$/ kWh_{el}.

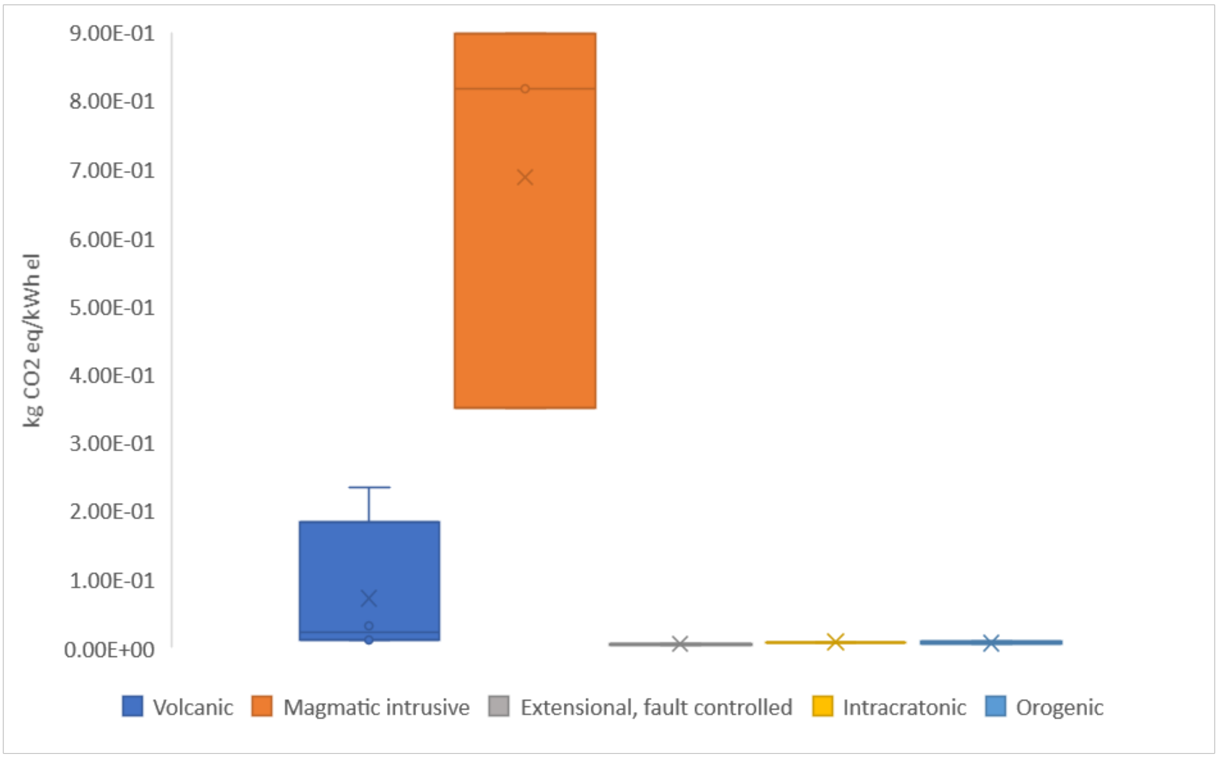


Figure 22: GHG emissions per kWh el – grouping by geological play

Analogoulsy, the results associated with heat production are reported, grouper by geological play: for volcanic they range from 0.007 to 0.009 kg $CO_{2\ eq}$/ kWh_{th}, for magmatic intrusive, they range from 0.278 to 0.723 kg $CO_{2\ eq}$/ kWh_{th}, for extensional, fault controlled from 0.004 to 0.224, for intracratonic from 0.003 to 0.058 and for orogenic up to 0.004 kg $CO_{2\ eq}$/ kWh_{th}.

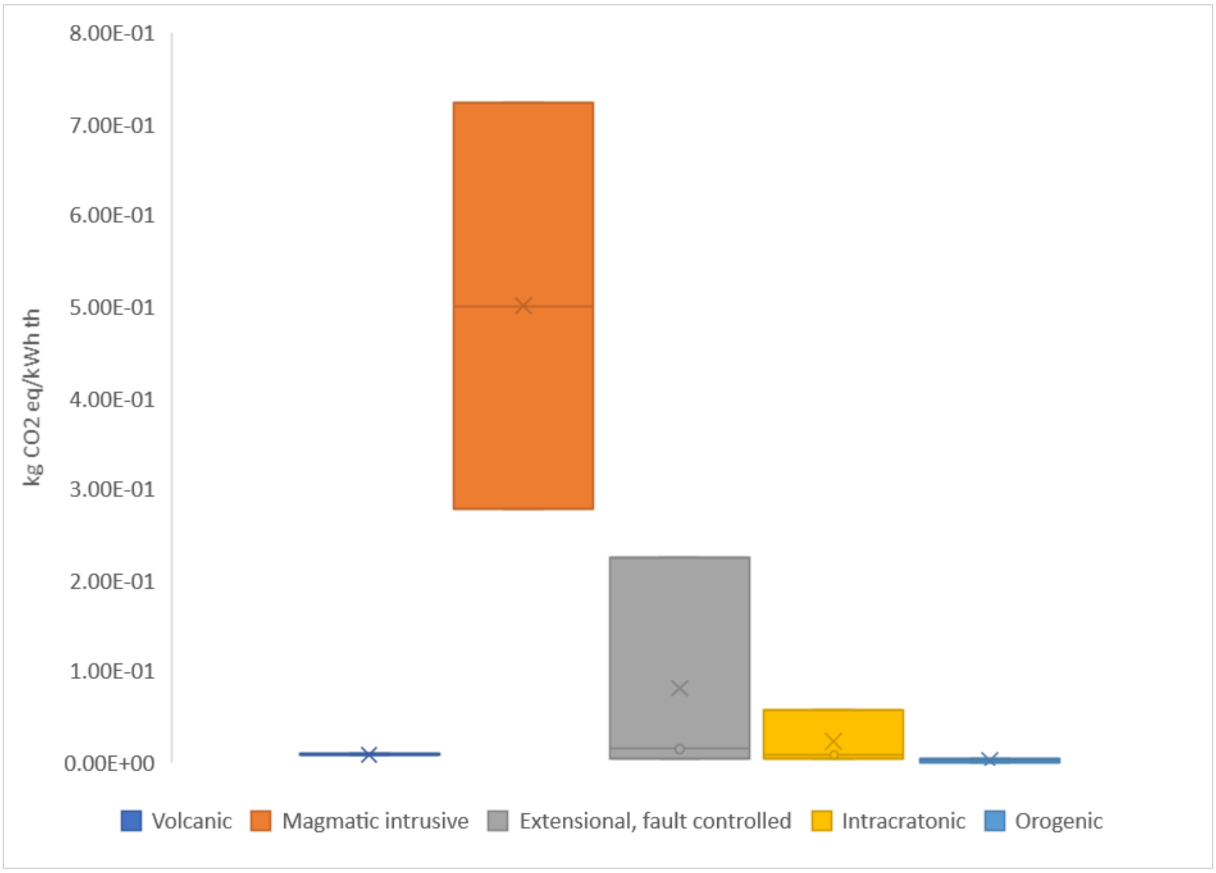


Figure 23: GHG emissions per kWh th – grouping by geological play

12.2 Contribution Analysis: Phases and Direct/ Indirect Emissions

With reference to the impacts reported in the previous chapter, a contribution analysis has been performed, to highlight the split between the different phases and between direct and indirect emissions respectively, for all the clusters and the impacts categories considered.

The aim of this analysis, in line with the Guidelines for Interpretation published by JRC (Zampori et al., 2016) is to identify – cluster by cluster - the most relevant phases, which for each impact category are responsible for the main share of impacts and thus should be primarily targeted when aiming at improving the performance of the system. In detail, the Guidelines suggest to consider as relevant the phases exceeding the percentage of 80% of any impact category, considering the entire life cycle. Even though this definition is not systematically applied in this context, it may support the reader to gain higher sensitivity about the importance and menaning of the proposed results. On the other hand, the analysis supports the identification of the phases which are not crucial for the extrapolation of the final results and conclusions.

For the contribution analysis along the life cycle, the terminology used is aligned with the terminology used for the presentation of the Life Cycle Inventories.

Below, the definition of the phases is recalled:

- exploration: exploration activities carried out before the beginning of construction works to characterize soil properties;
- drilling, casing and cementing: on-site activities for wells construction;

- testing: preliminary activities for the operation of the wells;
- stimulation: injection of fluids into a reservoir to increase permeablity and/or connectivity;
- surface components: materials used for construction of surface components (power and heat equipment), collection pipeline (when applicable) and plant structure;
- operation: air emissions during operation of the plant for P-clusters and air emissions and electricity consumption during operation of the plant for DHC clusters;
- maintenance: operation auxiliary activities (i.e.: scaling and corrosion control, fluid treatment, cleaning, leakages);
- surface components replacement.

In addition, direct emissions are to be intended as those associated with fuel combustions and air emissions of the geothermal plant, while indirect emissions are those related to the manufacturing of raw materials.

P Clusters

Figure 24 presents the breakdown of cluster 1P by phase and by impact categories, while Figure 25 shows the share of direct and indirect emissions for the same clusters.

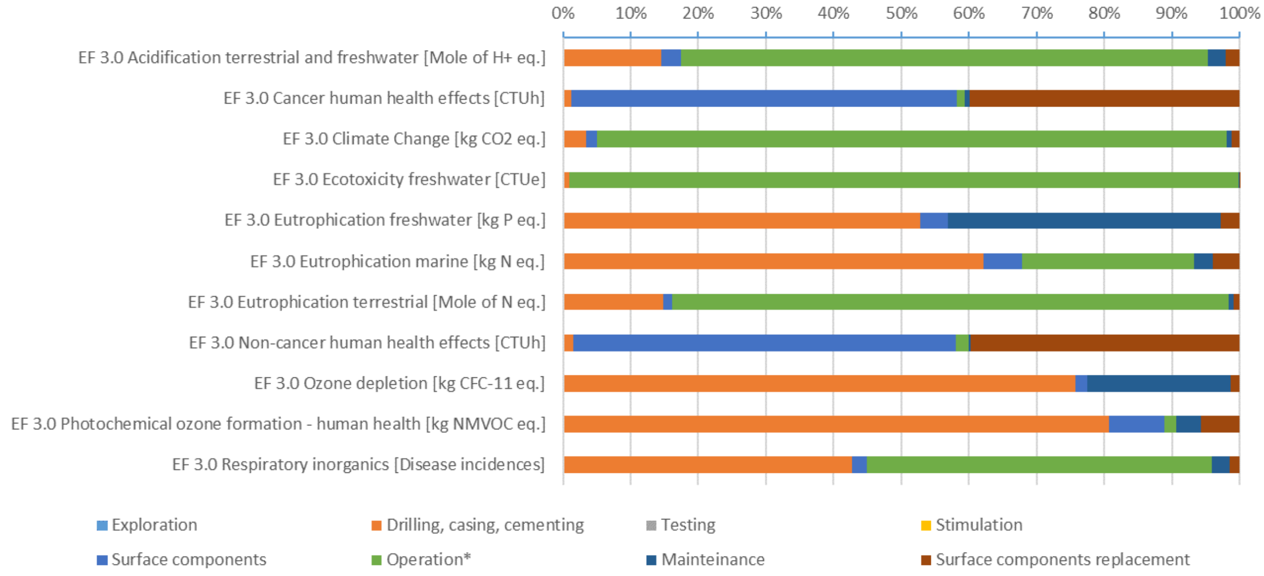
It can be noticed that the drilling phase is responsible of the largest part of impacts for eutrophication (marine and freshawater), as well as ozone depletion, photochemical ozone formation (human health) and respiratory inorganics. Its contribution – here and in the other clusters where the same situation is encountered - relates mainly to direct emissions generated by drilling muds and residues after excavation for ecotoxicity freshwater and diesel combustion, in terms of the other potential impacts.

Conversely, the operation phase is predominant on acidification, climate change, ecotoxicity freshwater, terrestrial eutrophication and minorly on respiratory disease.in the first four categories mentioned, the share associated to the operation, constituted by direct emissions to air, is over 80%. The most significant flows causing these potential impacts are ammonia, for acidification, carbon dioxide and methane for global warming, hydrogen sulphide for ecotoxicity freshwater and eutrophication marine, as well as – in less significant share – heavy metals. This situation results from the moderate NCGs content in the geothermal fluid and, in turn, degassed to the atmosphere.

The maintenance phase, characterized mainly by production of chemicals, affects in a non-negligible way both eutrophication freshwater and ozone depletion.

Finally, cancer and non-cancer human health effects are dominated by the manufacturing and replacement of construction materials, mainly copper and plastics and only slightly affected by the low share of direct air emissions of heavy metals during operation.

The representation of the shares of direct and indirect emissions reflects the aforementioned findings, showing that all the categories expect for cancer and non-cancer effects and eutrophication freshwater are related to direct emissions from drilling or operation.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 24: Cluster 1P – Breakdown of impact by phase

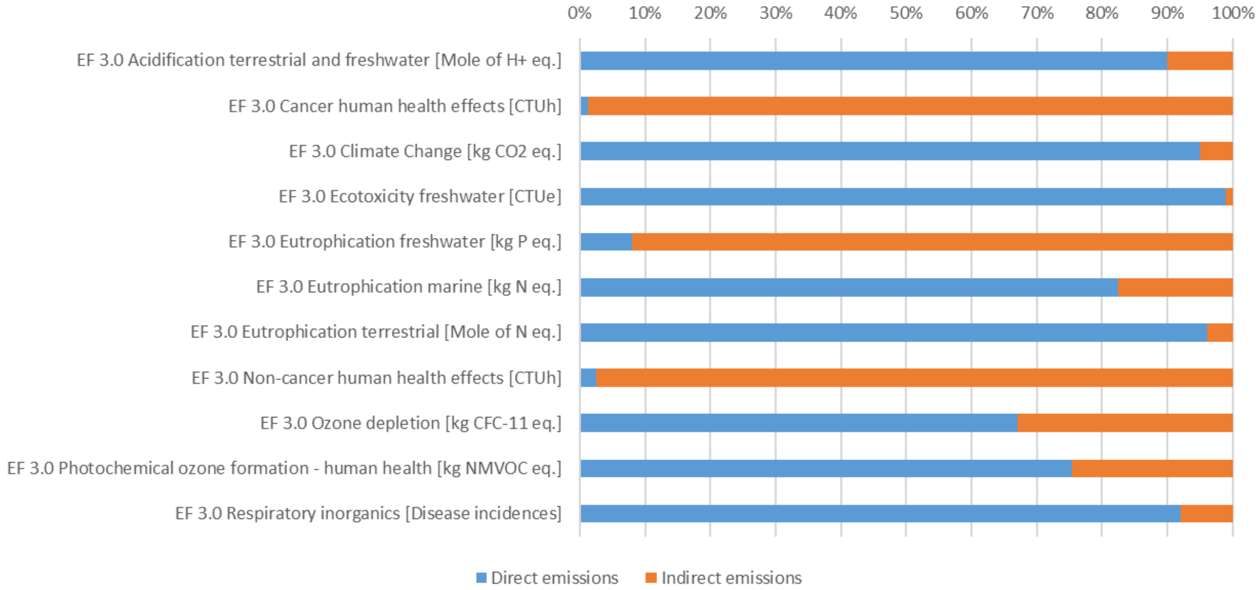


Figure 25: Cluster 1P – Breakdown of impact by direct/indirect emissions

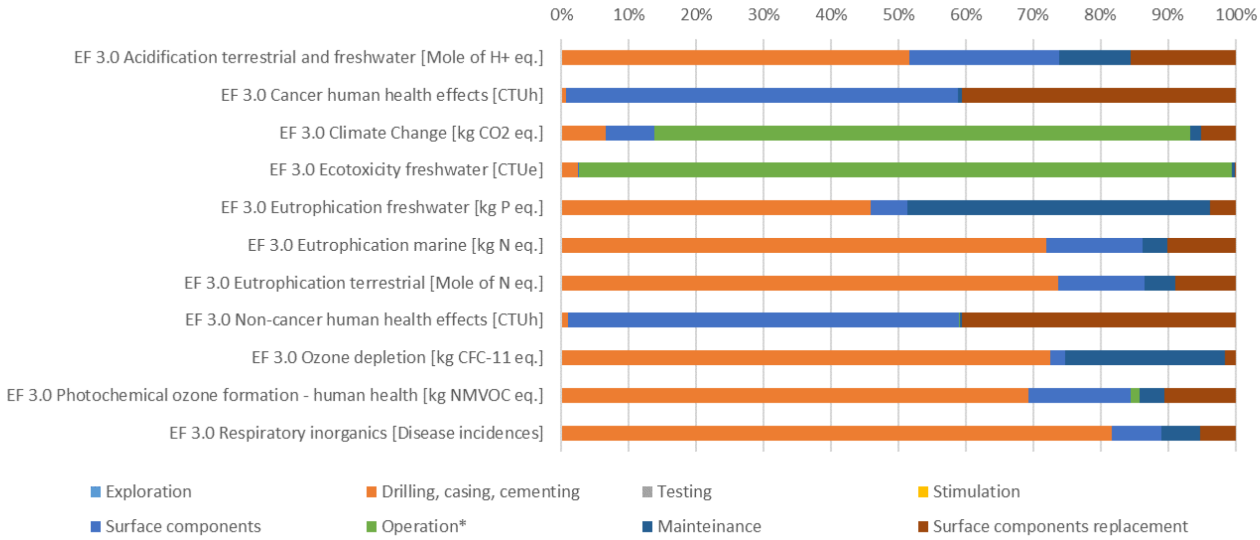
Figure 26 presents the breakdown of cluster 1P CHPa by phase and by impact categories, while Figure 27 shows the share of direct and indirect emissions for the same clusters.

It can be noticed that the drilling phase is responsible of the largest part of impacts acidification, for eutrophication (marine and freshawater), as well as ozone depletion, photochemical ozone formation (human health) and respiratory inorganics, with shares over 70% except for the case of freshwater autrophication and acidification.

The operation phase is predominant on climate change and ecotoxicity, with shares over 90%. This result is caused by the type and amount of air emissions present in the geothermal fluid, influencing in turn their degassment to the atmosphere. In detail, climate change is affected by methane and carbon dioxide emissions and ecotoxicity freshwater is affected by hydrogen suplhide emissions.

The maintenance phase, characterized mainly by production of chemicals, affects in a non-negligible way the eutrophication freshwater impact category. As in previous case, cancer and non-cancer human health effects are dominated by the manufacturing and replacement of construction materials, mainly copper and plastics.

The representation of the shares of direct and indirect emissions reflects the aforementioned findings, showing that all the categories expect for cancer and non-cancer effects and eutrophication freshwater are related to direct emissions from drilling or operation.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 26: Cluster 1P CHPa – Breakdown of impact by phase

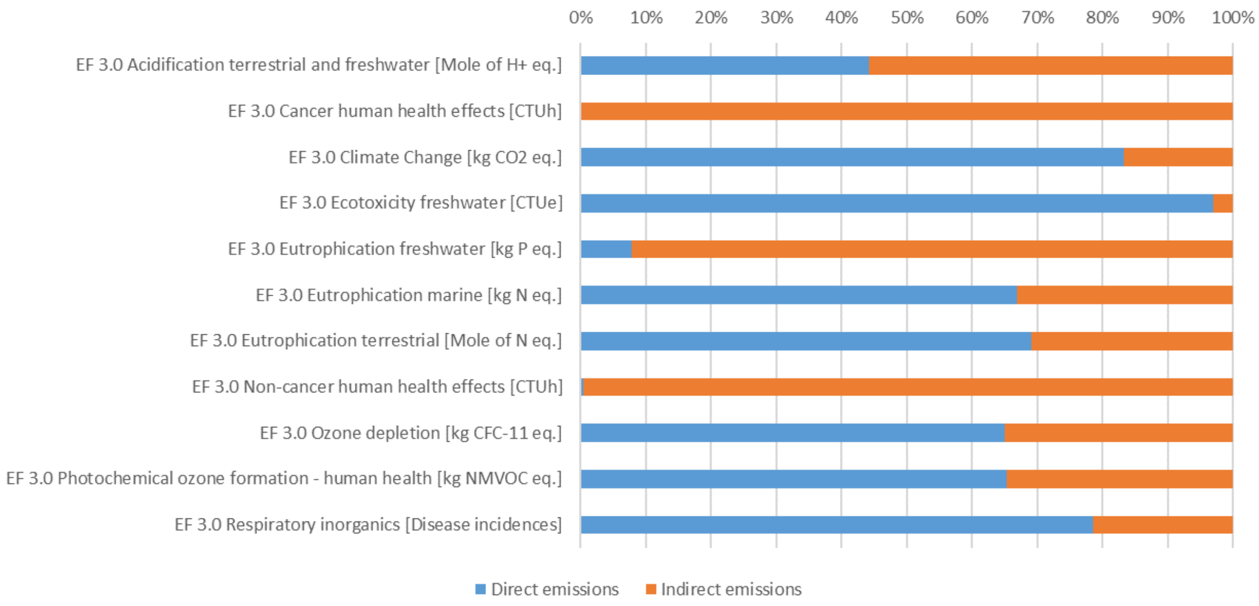
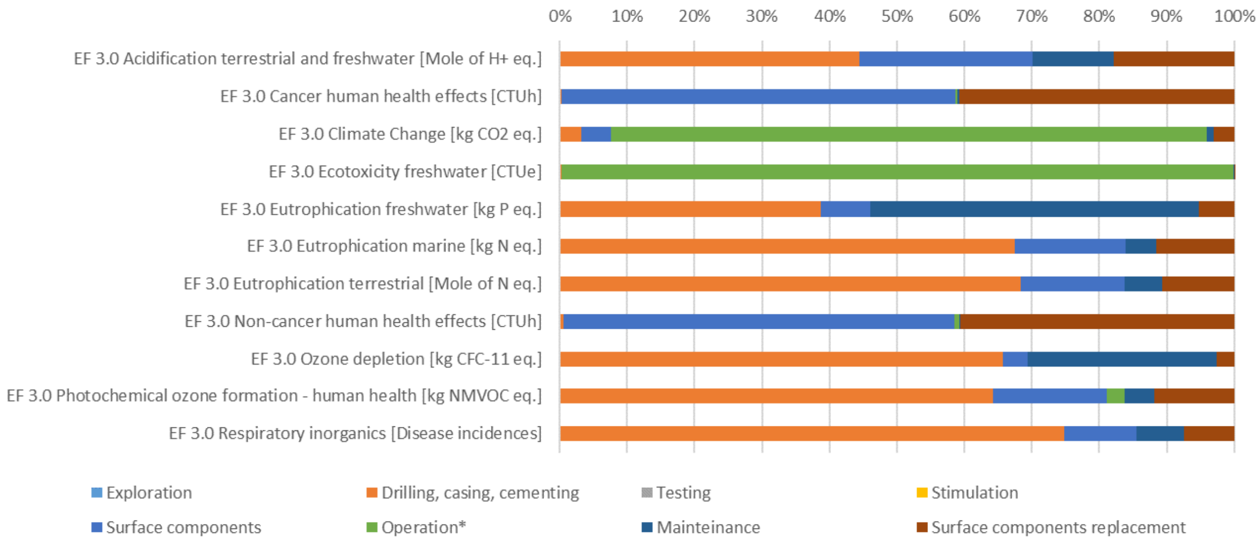


Figure 27: Cluster 1P CHPa – Breakdown of impact by direct/indirect emissions

Figure 28 presents the breakdown of cluster 1P CHPb by phase and by impact categories, while Figure 29 shows the share of direct and indirect emissions for the same clusters.

The pattern of the results is correspondent to the one obtained for cluster 1P CHPa, considering the similarities of the two clusters. Thus, the same conclusions hold true and are not repeated.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 28: Cluster 1P CHPb – Breakdown of impact by phase

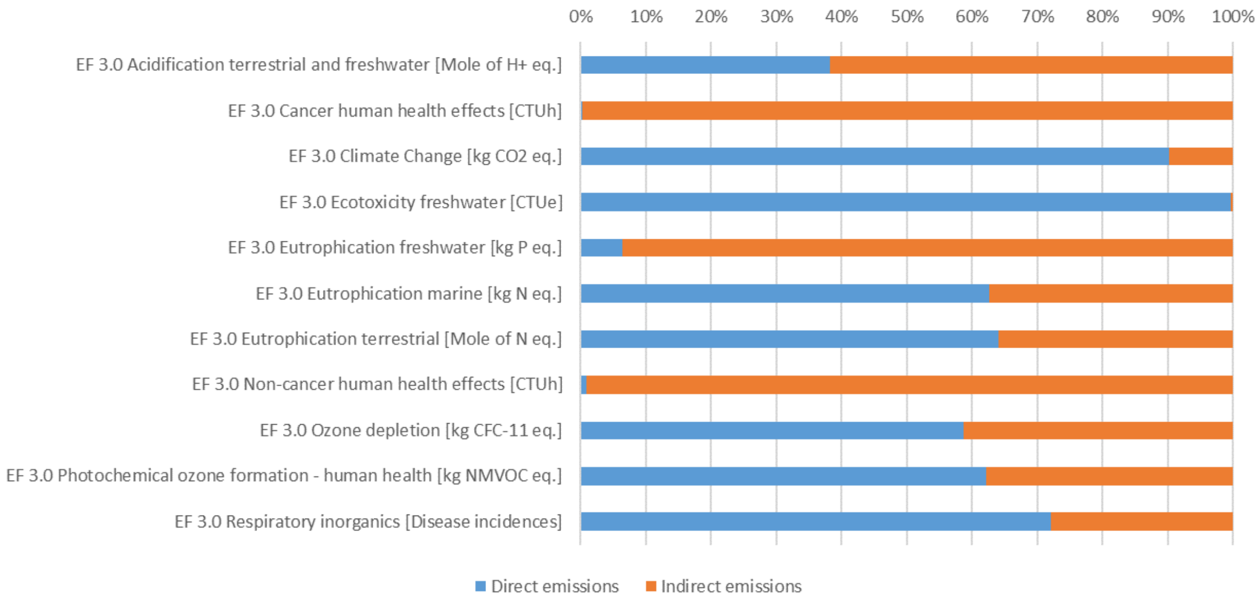


Figure 29: Cluster 1P CHPb – Breakdown of impact by direct/indirect emissions

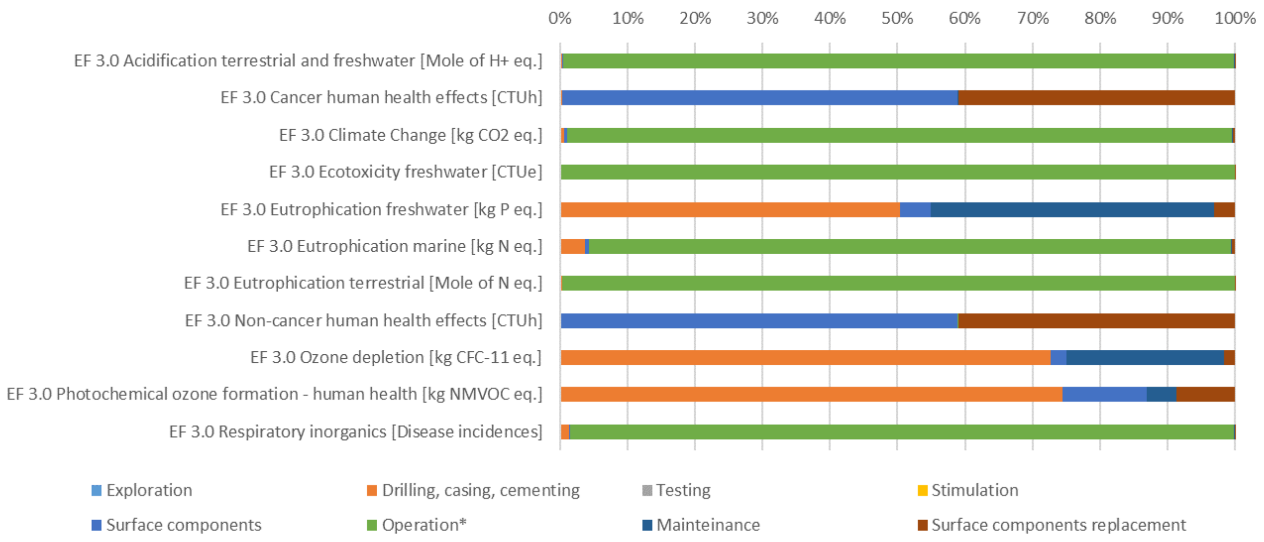
Figure 30 presents the breakdown of cluster 2P by phase and by impact categories, while Figure 31 shows the share of direct and indirect emissions for the same clusters.

The pattern of the results is typical of the clusters characterized by H_2S and ammonia emissions, along with the most common GHG emissions: the potential impacts generated in operation phase dominate acidification, climate change, ecotoxicity freshwater, eutrophication (marine and terrestrial) and respiratory inorganics. Indeed, despite the binary technology of the plant, degassing of NCGs, present in moderate quantities in the geothermal fluid, is perfomed to prevent corrosion.

As for drilling, it largely affects eutrophication freshwater, due to the chemicals used for the drilling muds and their disposal and ozone depletion and photochemical human health for diesel combustion.

Finally, cancer and non-cancer human health impact categories are dominated – as in the other cases – by the manufacturing and replacement of construction materials.

The representation of the shares of direct and indirect emissions reflects the aforementioned findings, showing that all the categories expect for cancer and non-cancer effects and eutrophication freshwater are related to direct emissions from drilling or operation.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 30: Cluster 2P – Breakdown of impact by phase

Figure 31: Cluster 2P – Breakdown of impact by direct/indirect emissions

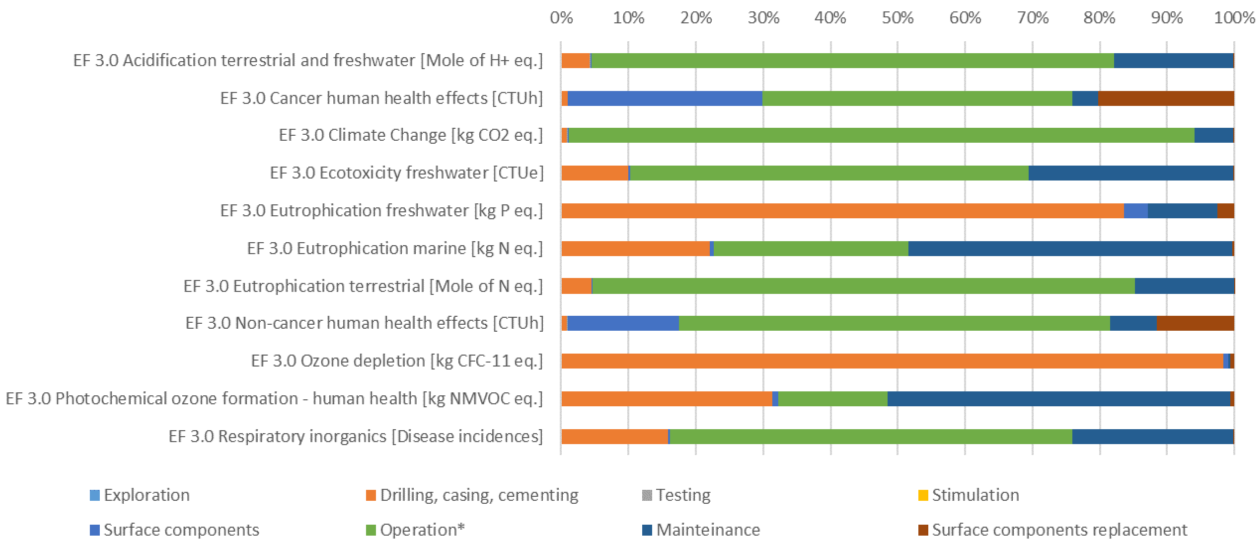
Figure 32 presents the breakdown of cluster 3P CHP by phase and by impact categories, while Figure 33 shows the share of direct and indirect emissions for the same clusters.

It can be observed that the operation phase, associated with ammonia, hydrogen sulphide and heavy metals emissions along with the most common GHG emissions degassed to the atmosphere to the high amount of NGCs in the geothermal fluid, is predominant for acidification, climate change, ecotoxicity freshwater eutrophication terrestrial, non-cancer human health effects and respiratory inorganics, with shares over 60%, but it is also present – in minor amount – in the cancer human health effects, the eutrophication marine and the photochemical ozone formation impact categories. In this scenario, the most significant flows are ammonia, for acidification and marine eutrophication, carbon dioxide and methane for global warming, hydrogen sulphide for ecotoxicity freshwater, and heavy metals for cancer and non-cancer human health effects.

The drilling phases exceeds the share of 80% for the eutrophication freshwater and ozone depletion impact categories, due to the use and disposal of drilling muds and diesel combustion respectively.

In addition, also non-negligible shares of impacts associated with chemicals used for fluid treatment encountered in the maintenance phase are present across multiple impact categories, and eutrophication amrine and photochemical ozone formation in particular, being in these cases in the order of 50% of the overall impact.

The breakdown between direct and indirect emissions reflects the aforementioned findings, showing a non-negligible contribution of direct emissions in all the impact categories, in most cases affected by indirect emissions especially in association with use of chemicals during drilling and for fluid treatment.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 32: Cluster 3P CHP – Breakdown of impact by phase

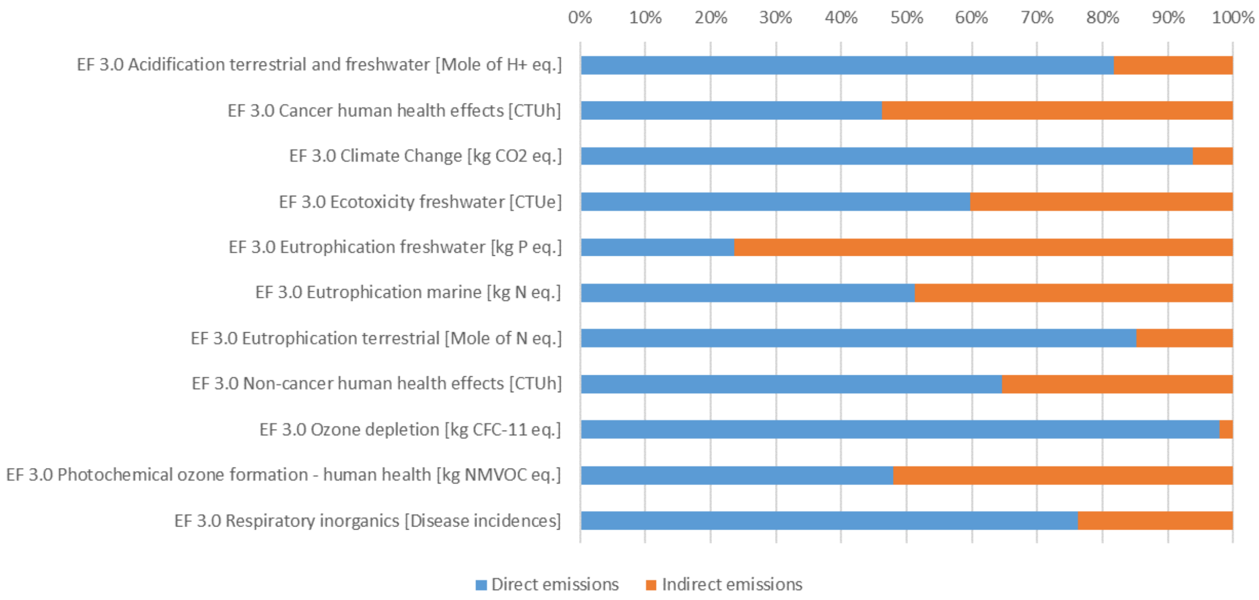


Figure 33: Cluster 3P CHP – Breakdown of impact by direct/indirect emissions

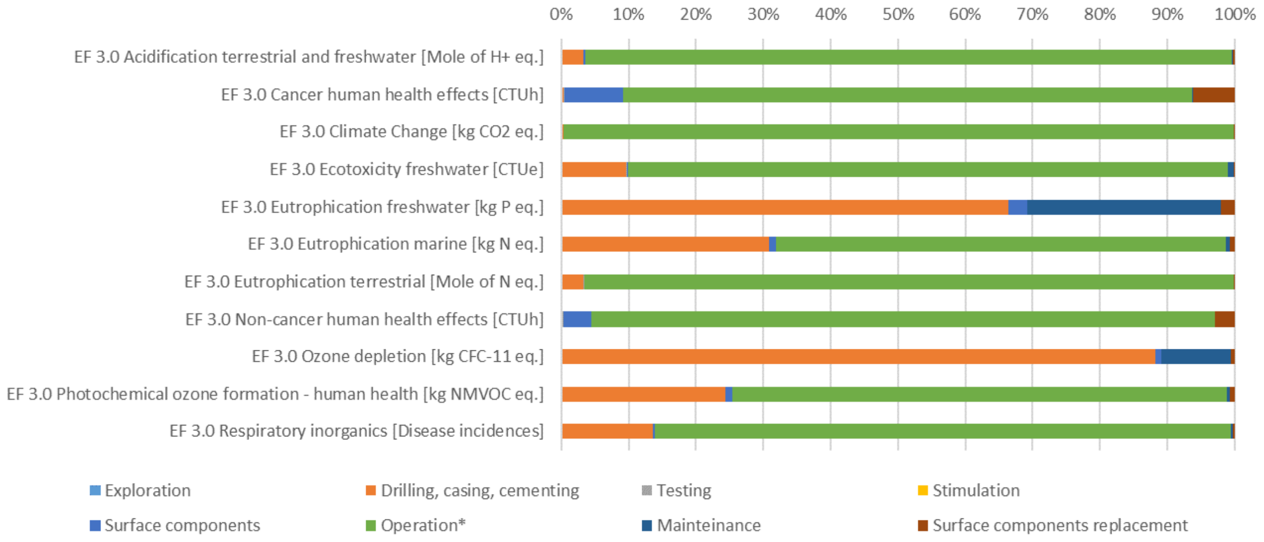
Figure 34 presents the breakdown of cluster 4P by phase and by impact categories, while Figure 35 shows the share of direct and indirect emissions for the same clusters.

It is observed that the contribution of the operation phase, characterized by direct emissions to air, exceeds 60% - and mostly 80% - in all the impact categories excepts for euthropication freshwater and ozone depletion. This results is caused by the fact that the operation phase is associated with ammonia, hydrogen sulphide and heavy metals emissions along with the most common GHG emissions degassed to the atmosphere to the high amount of NGCs in the geothermal fluid. Also in this case, the most significant flows are ammonia, for acidification and marine eutrophication, carbon dioxide and methane for global warming, hydrogen sulphide for ecotoxicity freshwater, and heavy metals for cancer and non-cancer human health effects.

The drilling phase contributes for over 60% to the eutrophication freshwater impact category and to the ozone depletion impact category, due to the use and disposal of drilling mud and diesel combustion respectively.

Finally, non-negligible shares are associated with the maintenance phase, and chemicals production in particular, for the eutrophication freshwater and ozone depletion impact categories.

The breakdown between direct and indirect emissions reflects the aforementioned findings, showing a clearly predominant contribution of indirect emissions in all impact cateogires, except for the case of eutrophication freshwater, characterizaed by chemicals manufacturing and use for both drilling and maintenance purposes.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 34: Cluster 4P – Breakdown of impact by phase

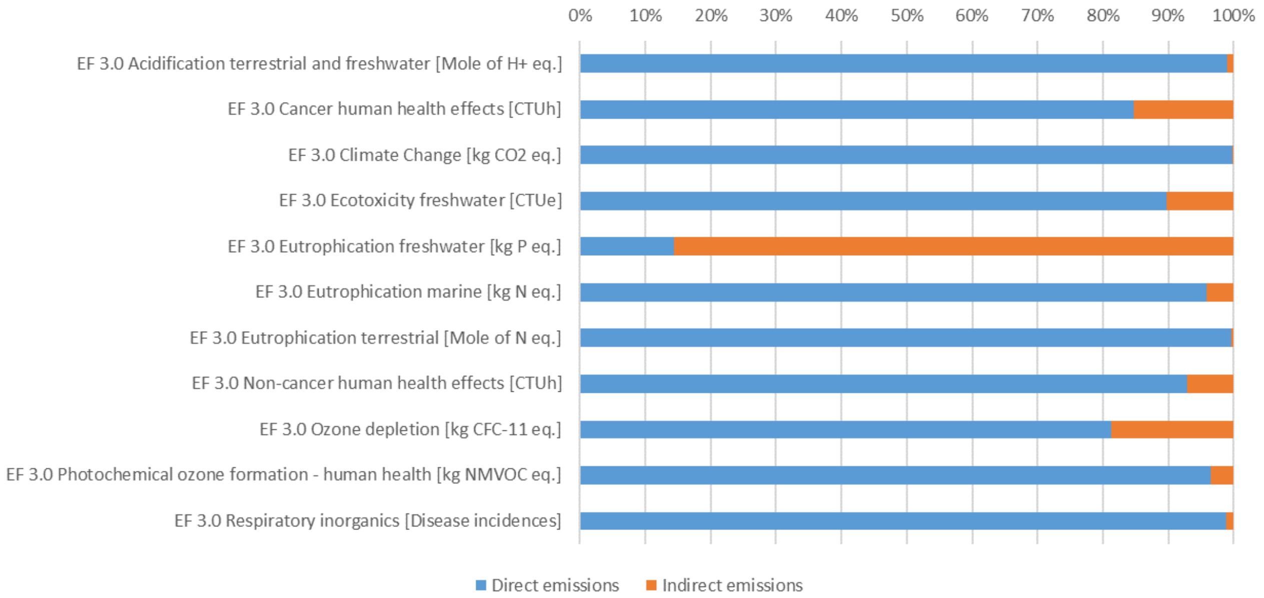
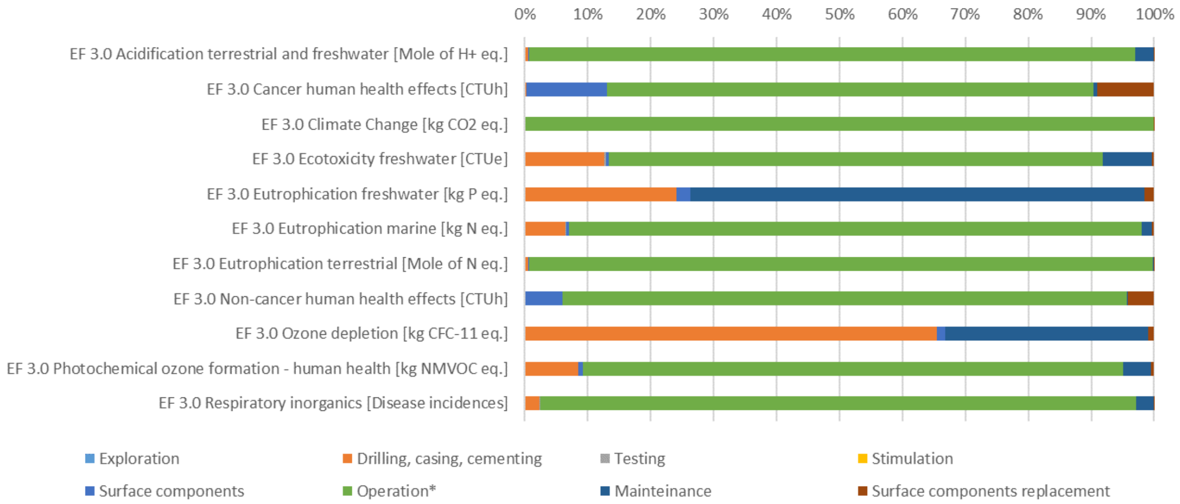


Figure 35: Cluster 4P – Breakdown of impact by direct/indirect emissions

Figure 36 presents the breakdown of cluster 4P CHP by phase and by impact categories, while Figure 37 shows the share of direct and indirect emissions for the same clusters.

The pattern of the results is correspondent to the one obtained for cluster 4P, considering the similarities of the two clusters. Thus, the same conclusions hold true and are not repeated.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 36: Cluster 4P CHP – Breakdown of impact by phase

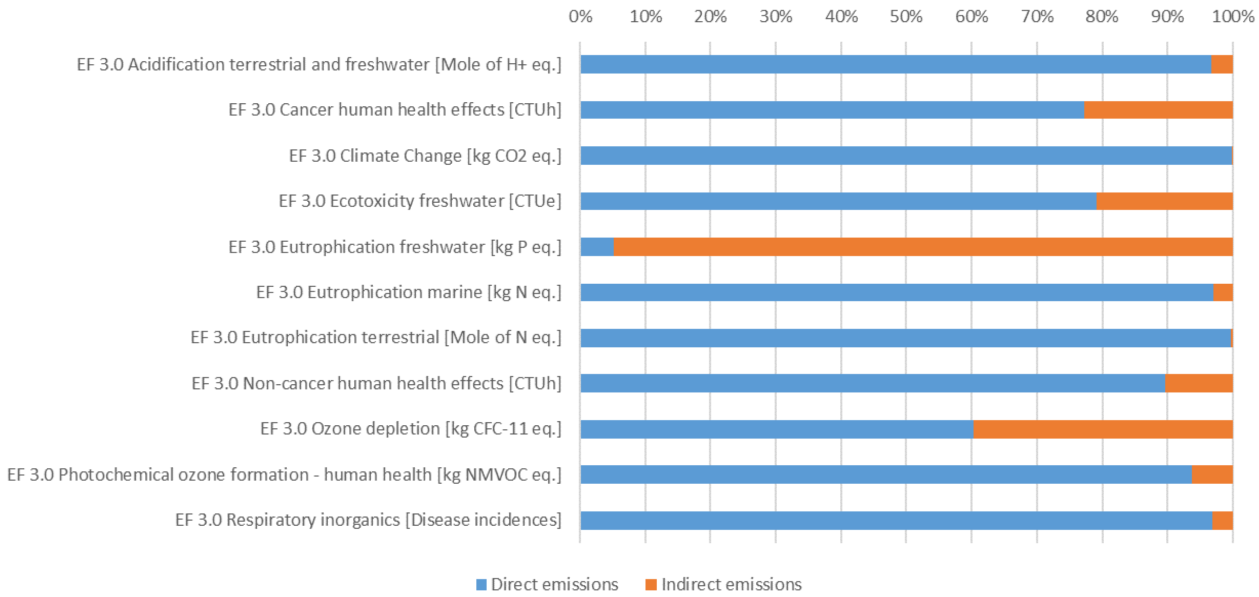


Figure 37: Cluster 4P CHP – Breakdown of impact by direct/indirect emissions

Figure 38 presents the breakdown of cluster 5P by phase and by impact categories, while Figure 39 shows the share of direct and indirect emissions for the same clusters.

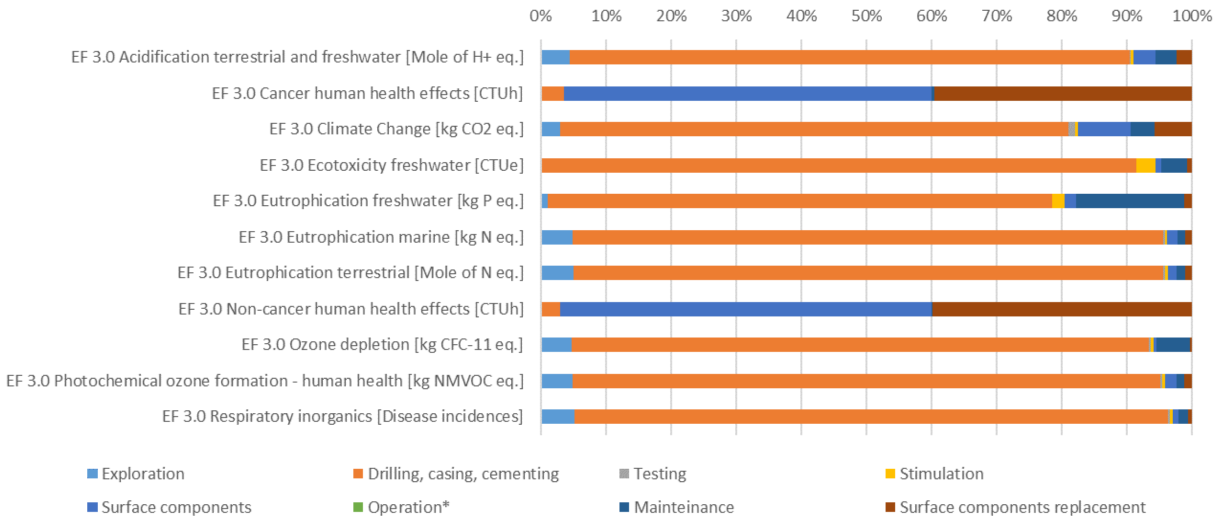
It appears that the predominant contributors for all the impact categories, except for cancer and non-cancer human health effects – is the drilling phase, with shares exceeding 75%. As already mentioned for other cases, this results is given by the presence of direct emissions from diesel combustion for electricity generation for the construction equipment engines, affecting acidification, global warming, eutrophication (marine and terrestrial), ozone depletion, photochemical ozone formation, and respiratory inorganics. On the other hand, the use of drilling fluids and the disposal of drilling muds are responsible for indirect emissions affecting ecotoxicity and eutrophication freshwater impact categories.

It is highlighted that the use of chemicals for ordinary maintenance, such as fluid treatment, anti-corrosion or anti-scaling may lead to non-negligible effects on the ecotoxicity freshwater impact category.

Finally, the most relevant phases for cancer and non-cancer human health effects are the construction of surface components and their replacement, both characterized by the manufacturing of construction materials. In deeper detail, the most relevant flows for this cases are copper and plastics manufacturing.

It is worth noticing that the features of this cluster allow to avoid air emissions of NCGs during the operation phase, thus not influencing the overall impacts.

The breakdown between direct and indirect emissions reflects the aforementioned findings, showing a clearly predominant contribution of indirect emissions in all impact cateogires, except for the case of eutrophication and ecotoxicity freshwater and cancer and non-cancer human health effects.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 38: Cluster 5P – Breakdown of impact by phase

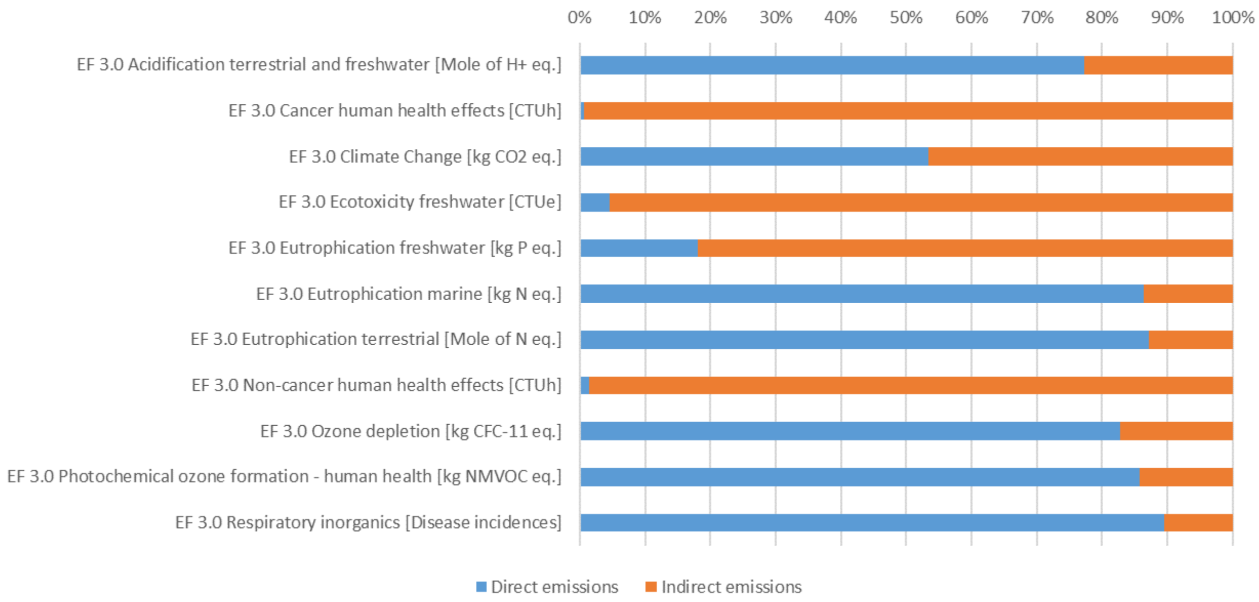
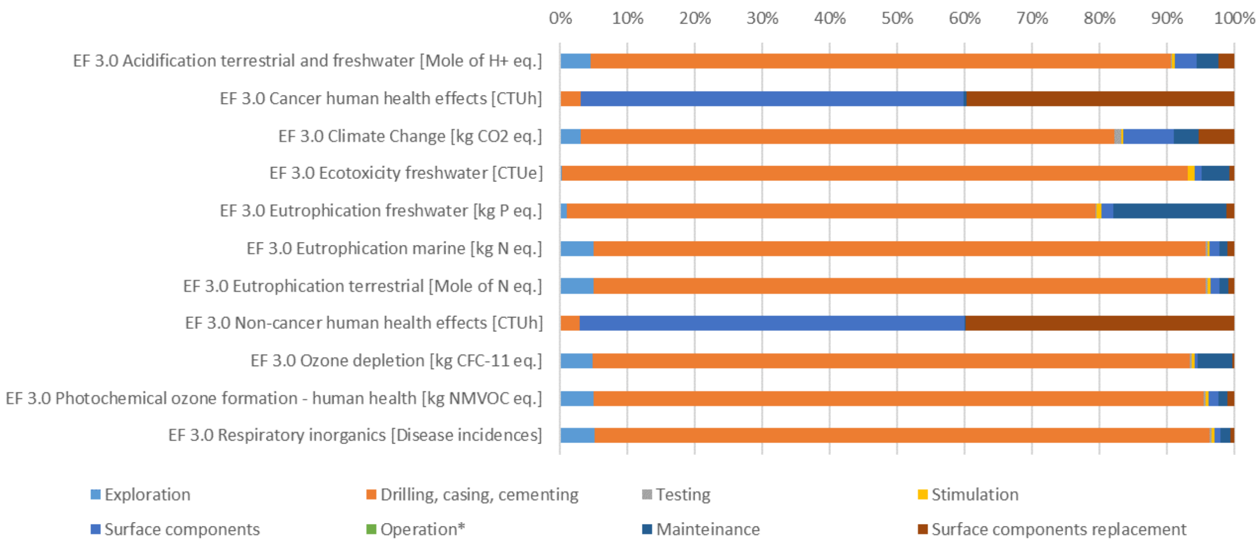


Figure 39: Cluster 5P – Breakdown of impact by direct/indirect emissions

Figure 40 presents the breakdown of cluster 5P CHP by phase and by impact categories, while Figure 41 shows the share of direct and indirect emissions for the same clusters.

The pattern of the results is correspondent to the one obtained for cluster 5P, considering the similarities of the two clusters. Thus, the same conclusions hold true and are not repeated.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 40: Cluster 5P CHP – Breakdown of impact by phase

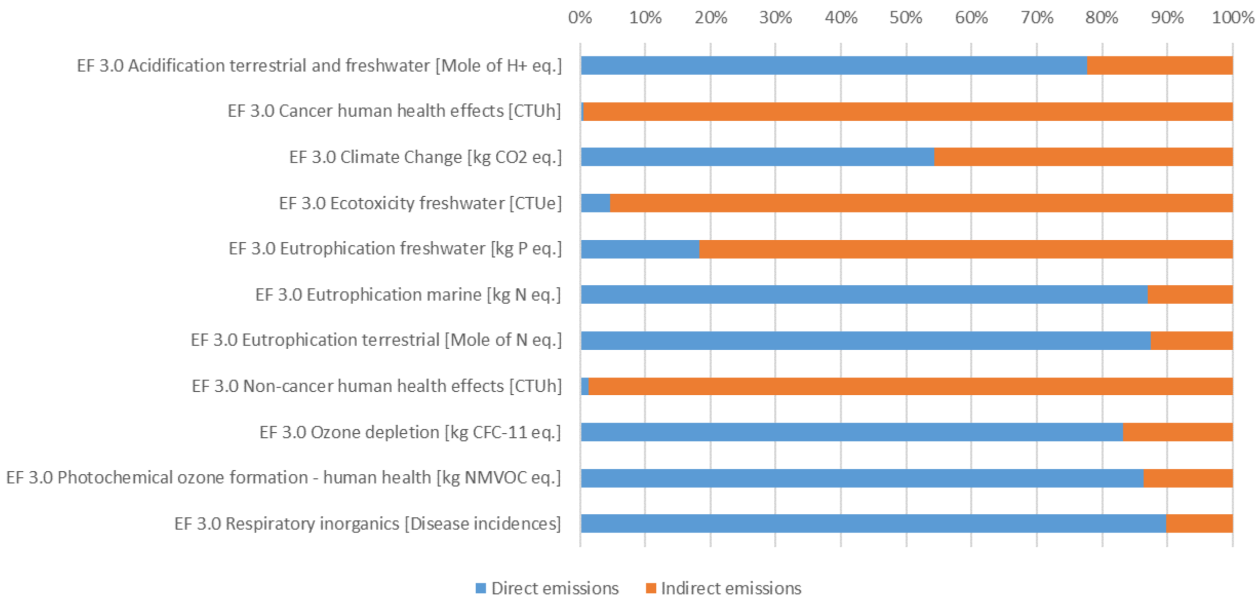


Figure 41: Cluster 5P CHP – Breakdown of impact by direct/indirect emissions

Figure 42 presents the breakdown of cluster 6P by phase and by impact categories, while Figure 43 shows the share of direct and indirect emissions for the same clusters.

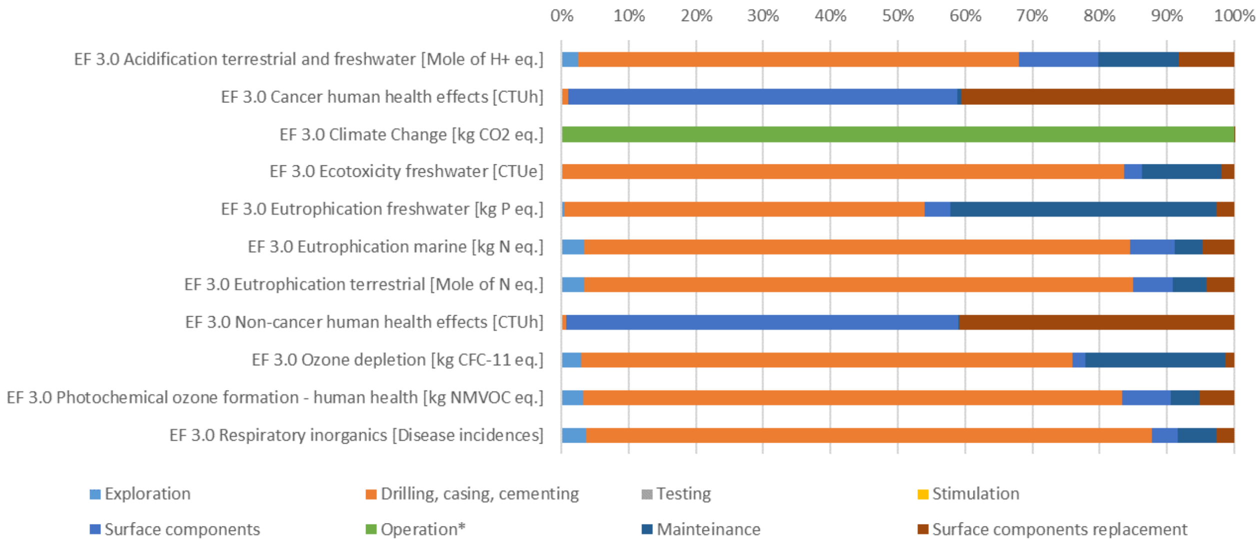
Coherently with the type of NCGs emissions associated with the operation of this cluster's typical plant, the operation phase is almost the unique contributors to the climate change impact category[15].

The drilling phase significantly contributes to acidification, ecotoxicity freshwater, eutrophication (freshwater, marine and terrestrial), ozone depletion, photochemical ozone formation, and respiratory inorganics, due to diesel combustion and use of drilling fluids and disposal of muds, depending on each specific impact category. The shares of total impact vary from about 50% to almost 90%. Morevoer, the use of chemicals for ordinary maintenance, such as fluid treatment, anti-corrosion or anti-scaling may lead to non-negligible effects on the ecotoxicity freshwater impact category.

As already observed in other cases, the most relevant phases for cancer and non-cancer human health effects are the construction of surface components and their replacement, both characterized by the manufacturing of construction materials. In deeper detail, the most relevant flows for this cases are copper and plastics manufacturing.

The breakdown between direct and indirect emissions reflects the aforementioned findings, showing acidification, global warming, eutrophication (marine and terrestrial), ozone depletion, photochemical ozone formation and respiratory inorganics as impact categories dominated by direct emissions from diesel combustion for electricity supply to drilling equipment and air emissions during operation. The other categories are dominated by indirect emissions.

[15] Despite the absolute impact result for this category is affected by poor data quality, the results of the contributional analysis are consistent and representative



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 42: Cluster 6P - Breakdown of impact by phase

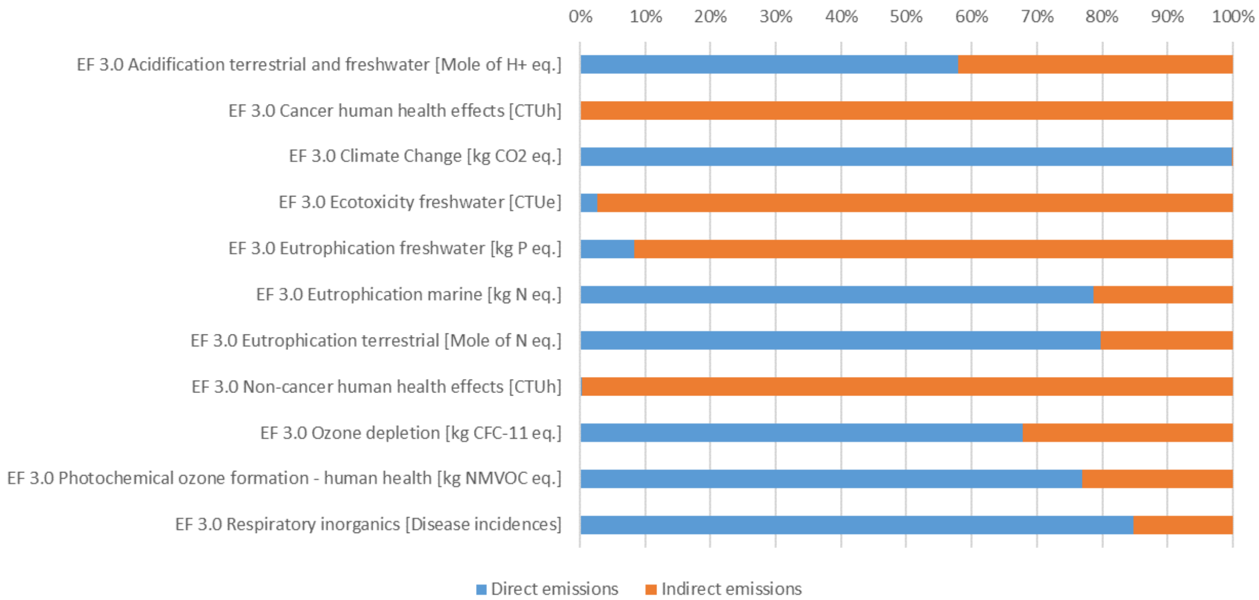
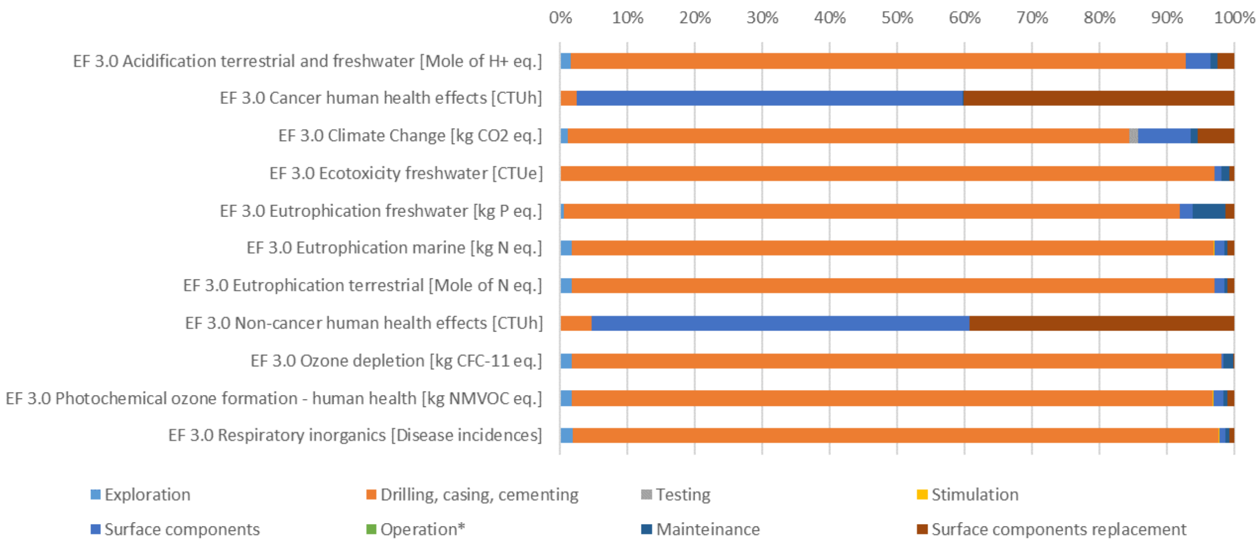


Figure 43: Cluster 6P - Breakdown of impact by direct/indirect emissions

Figure 44 presents the breakdown of cluster 7P CHP by phase and by impact categories, while Figure 45 shows the share of direct and indirect emissions for the same clusters.

The pattern of the results is correspondent to the one described for cluster 5P, considering the similarities of the two clusters, which are not associated with any direct air emissions during the operation phase. Thus, the same conclusions hold true and are not repeated.

The same situation is also obtained for cluster 8P, for which the breakdown of impact by phase is reported in Figure 46 and the breakdown between direct and indirect emissions is reported in Figure 47 and for cluster 8P CHP, for which the breakdown of impact by phase is reported in Figure 48and the breakdown between direct and indirect emissions is reported in Figure 49. The main motivation for these findings is that also these clusters are are not associated with any direct air emissions during the operation phase.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 44: Cluster 7P CHP – Breakdown of impact by phase

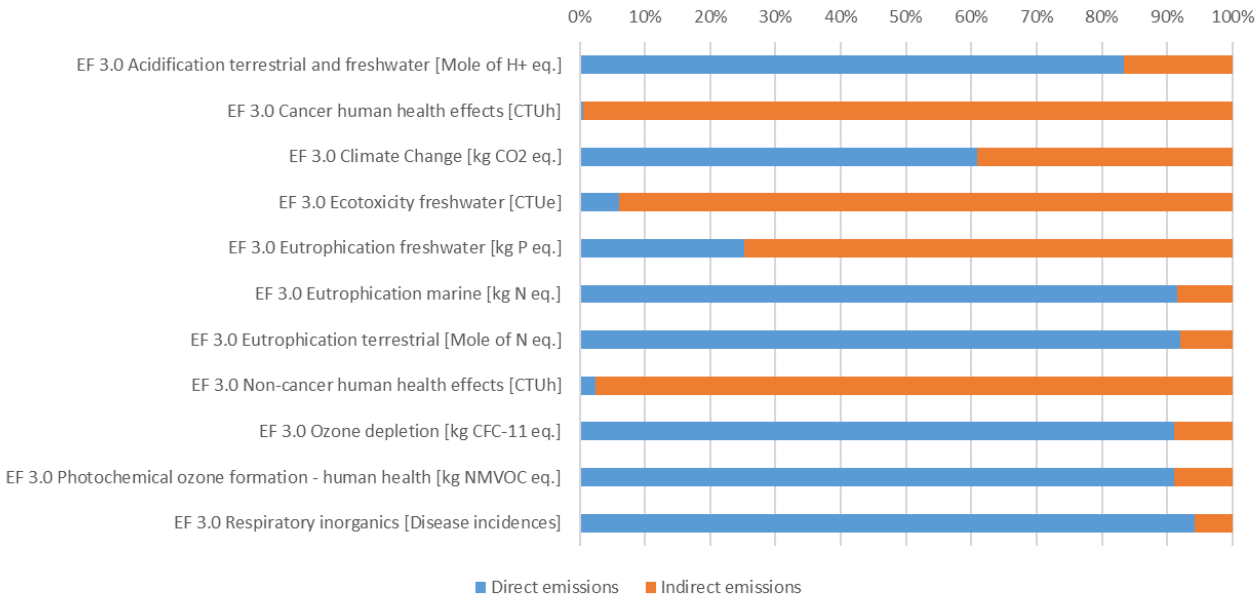
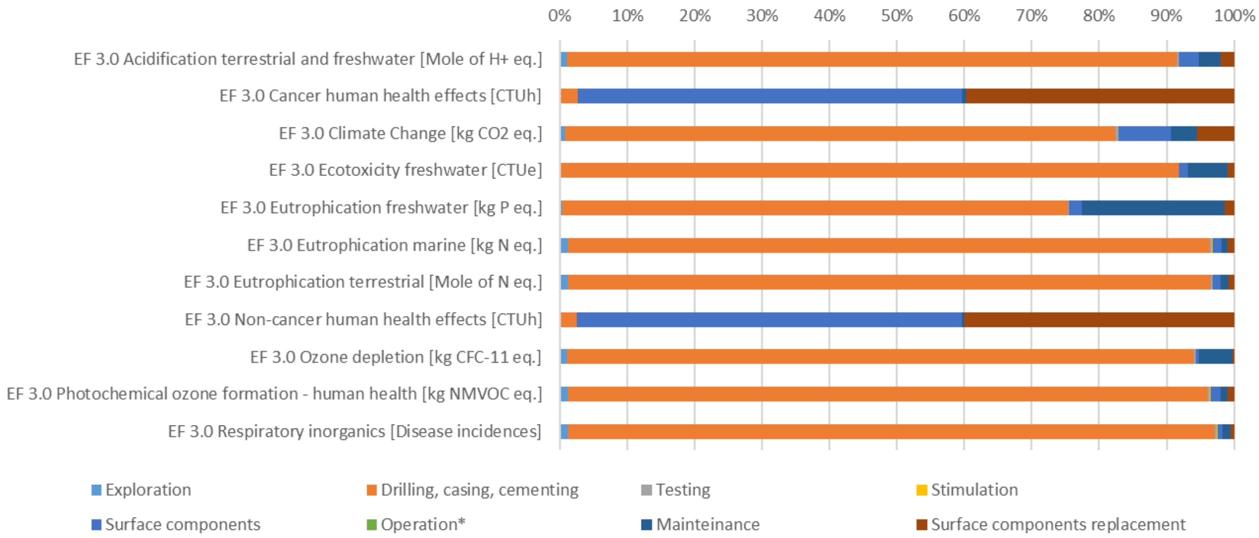


Figure 45: Cluster 7P CHP – Breakdown of impact by direct/indirect emissions



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 46: Cluster 8P – Breakdown of impact by phase

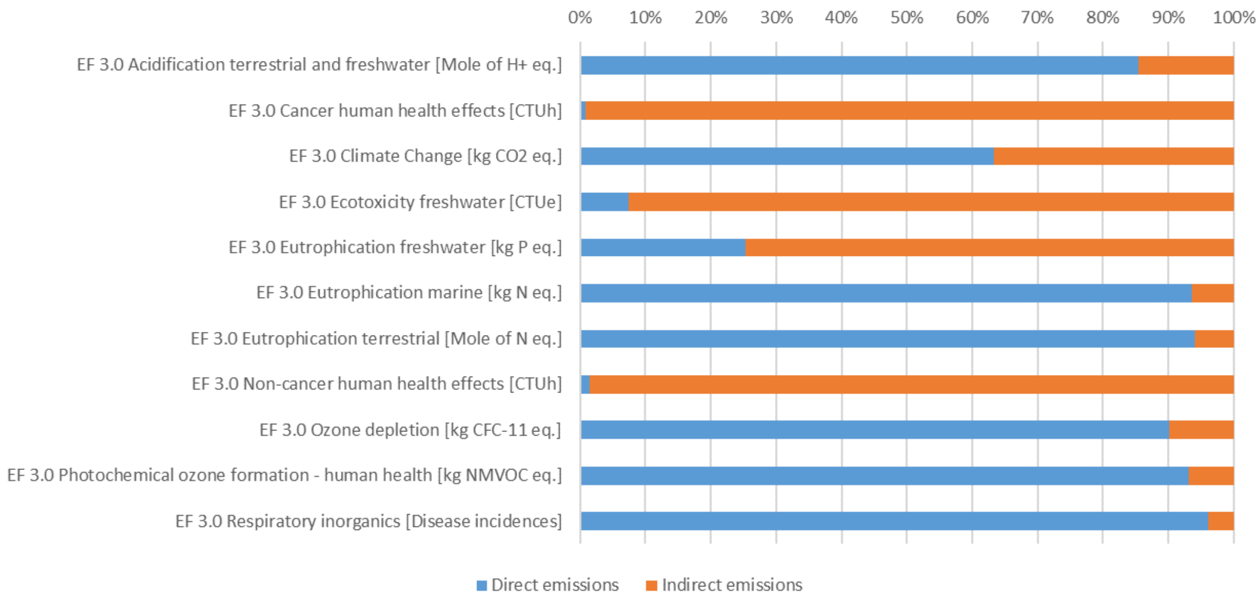
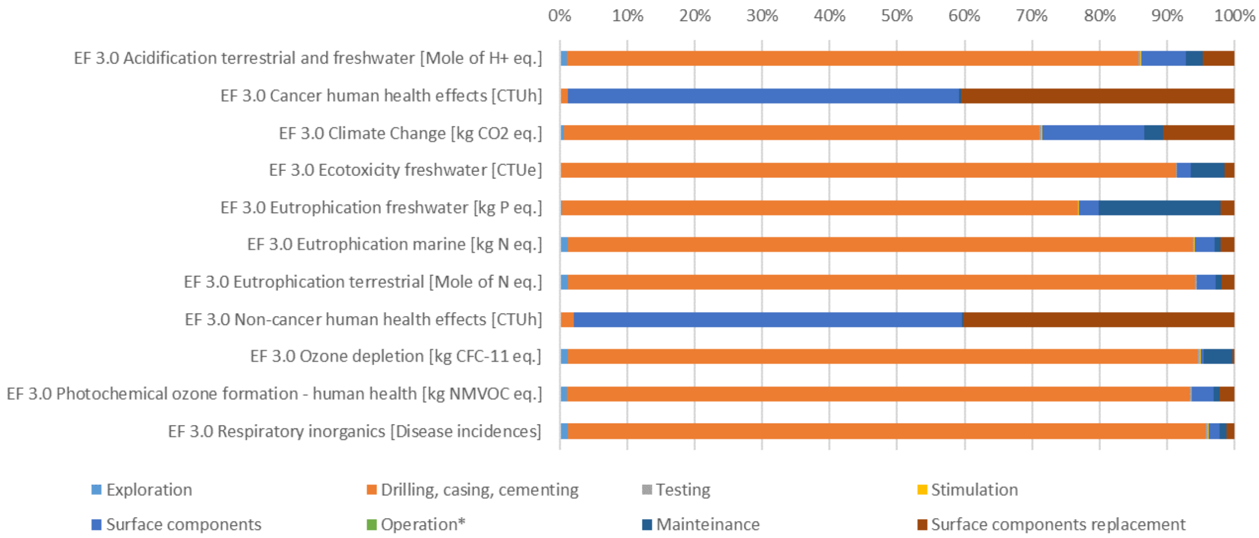


Figure 47: Cluster 8P – Breakdown of impact by direct/indirect emissions



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 48: Cluster 8P CHP – Breakdown of impact by phase

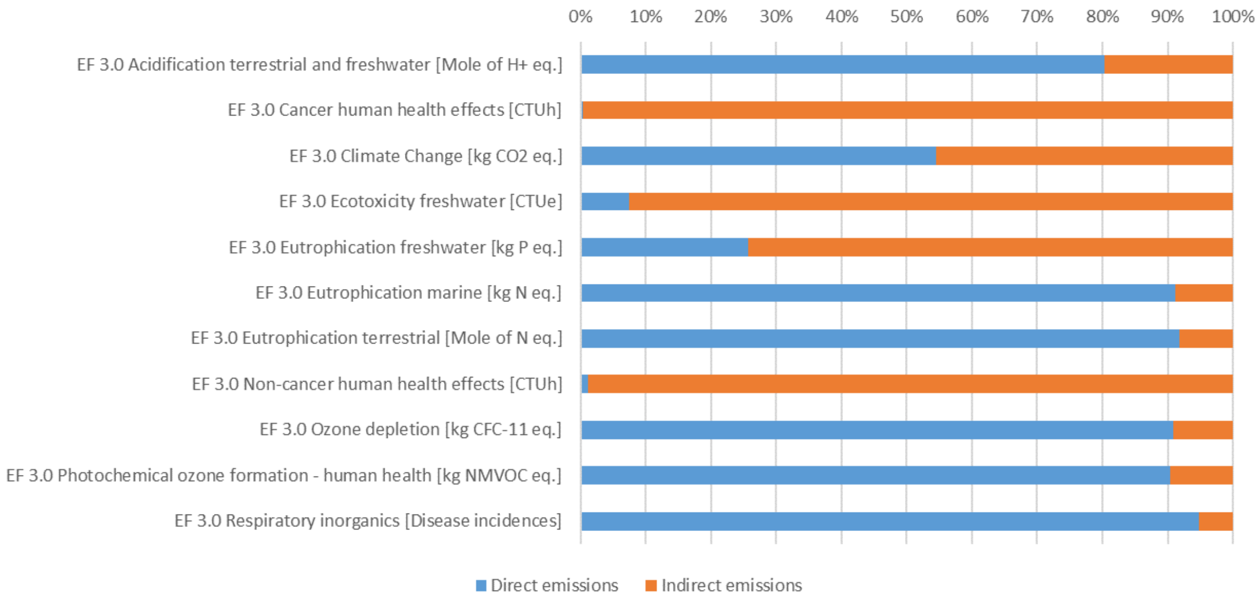
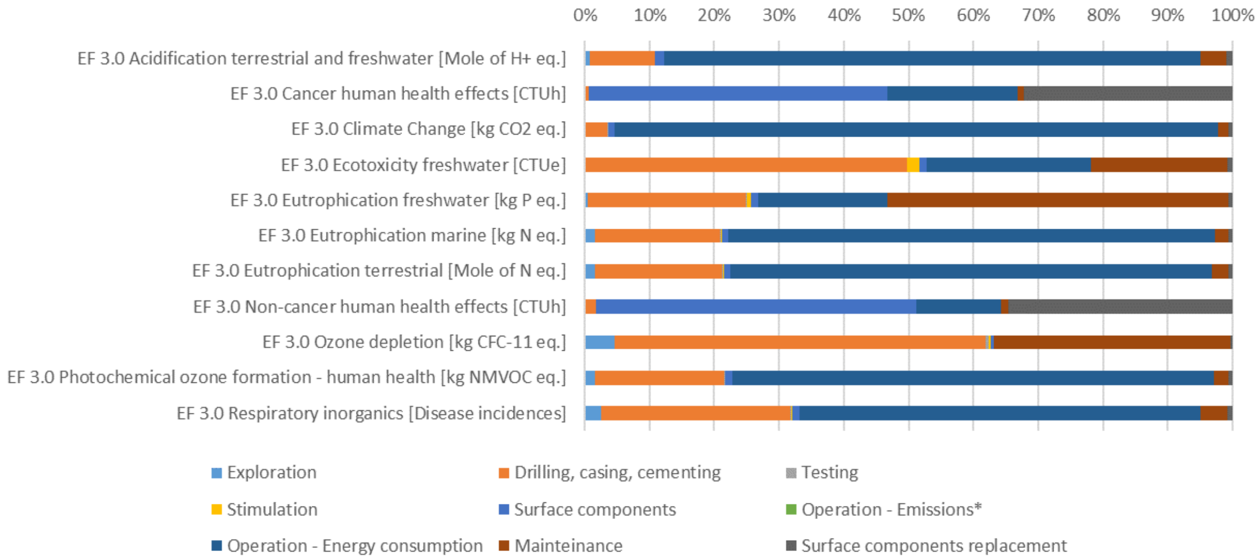


Figure 49: Cluster 8P CHP – Breakdown of impact by direct/indirect emissions

DHC clusters

Analogously, the same contribution analysis has been performed for DHC clusters, to highlight the split between the different phases and between direct and indirect emissions respectively, for the impacts categories considered.

Figure 50 presents the breakdown of cluster 2DHC by phase, while Figure 51 shows the share of direct and indirect emissions for the same cluster; it can be noticed that the energy consumption of operational phase is responsible of the largest part of the impacts for almost all indicators, especially Acidification, Climate change, Euthropication marine and terrestrial, Photochemical ozone formation and Respiatoy inorganics. This reflects on the breakdown of impacts between direct and indirect emissions: in this case, the indirect emissions contribution is linked to the electricity production (from grid mix). The drilling phase affects some impact categories, especially Ecotoxicity freshwater and Ozone depletion, due to the diesel combustion. Another non-negligible contribution is represented by the mainteinance phase, due to the lubrificat oil and chemicals used. Finally, cancer and non-cancer human health effects are dominated by the manufacturing and replacement of construction materials.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 50: Cluster 2DHC – Breakdown of impact by phase

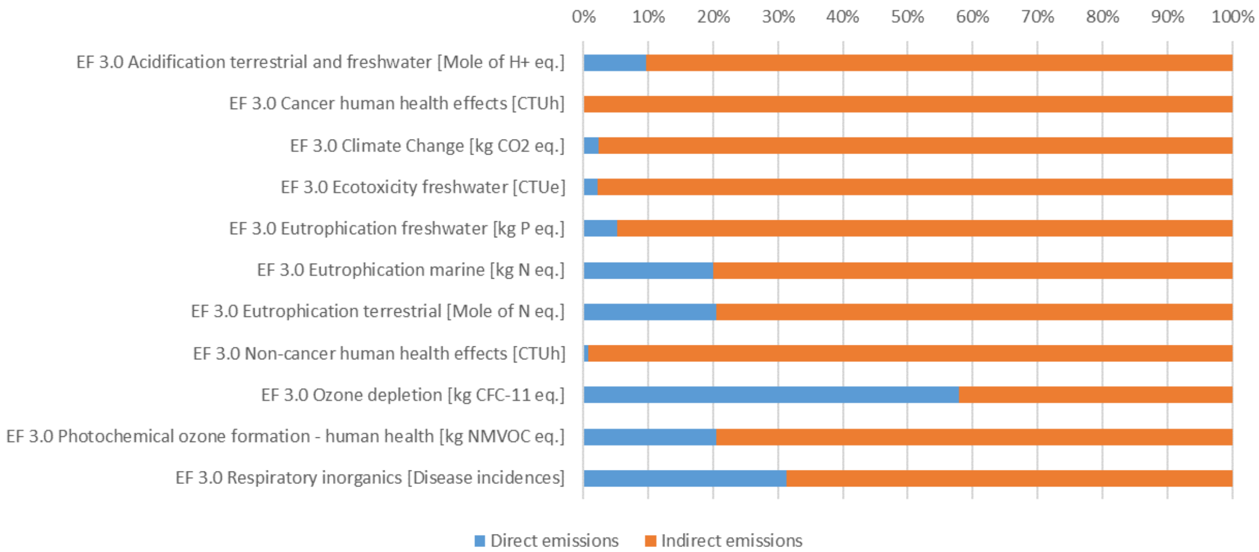
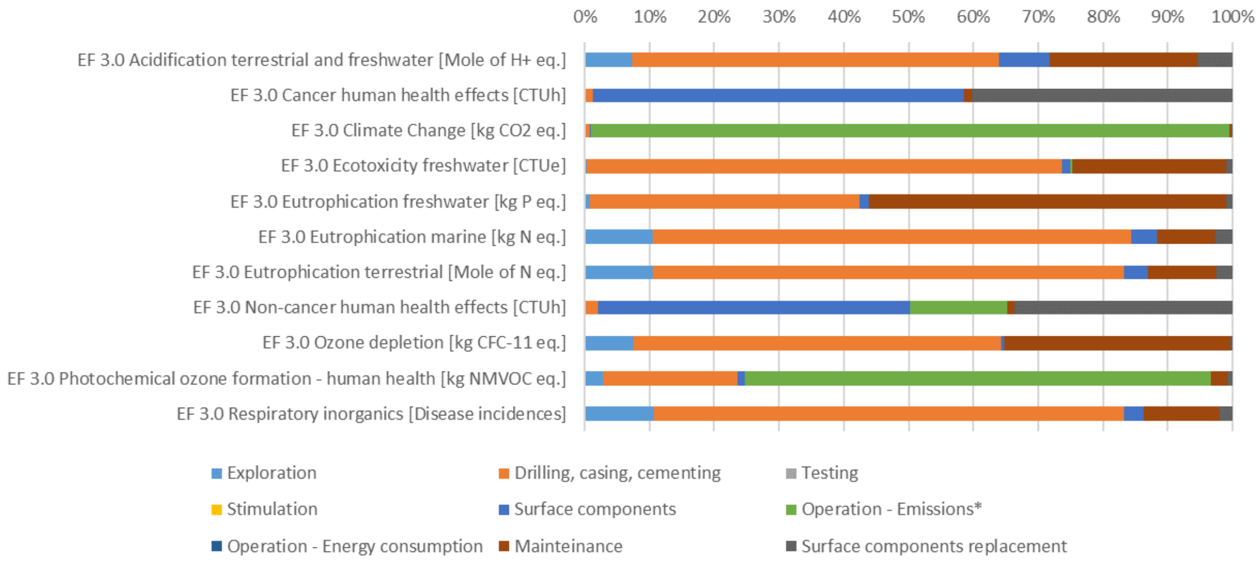


Figure 51: Cluster 2DHC – Breakdown of impact by direct/indirect emissions

Regarding cluster 3DHC, the breakdown of impact by phase is presented in Figure 52.

In this case, since the cluster is self-flowing, it does not consume electricity for the pumps, and therea are no impacts associated to the energy consumption. For this cluster it can be noticed that, for the majority of indicators, the drilling phase is the major responsible of impacts. This is associated to a significant share of direct emissions generated from the diesel combustion, as shown in Figure 53. For the Climate change impact category, the predominant contribution is associated to the CH_4 emissions released during operation phase, which strongly influence this indicator, as well as Photochemical ozone formation one. Also the mainteinance phase, due to the lubrificat oil and chemicals used, impacts on different indicators, especially Euthropication freshwater. The manufacturing and replacement of construction materials have an impact on cancer and non-cancer human health effects indicators.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 52: Cluster 3DHC – Breakdown of impact by phase

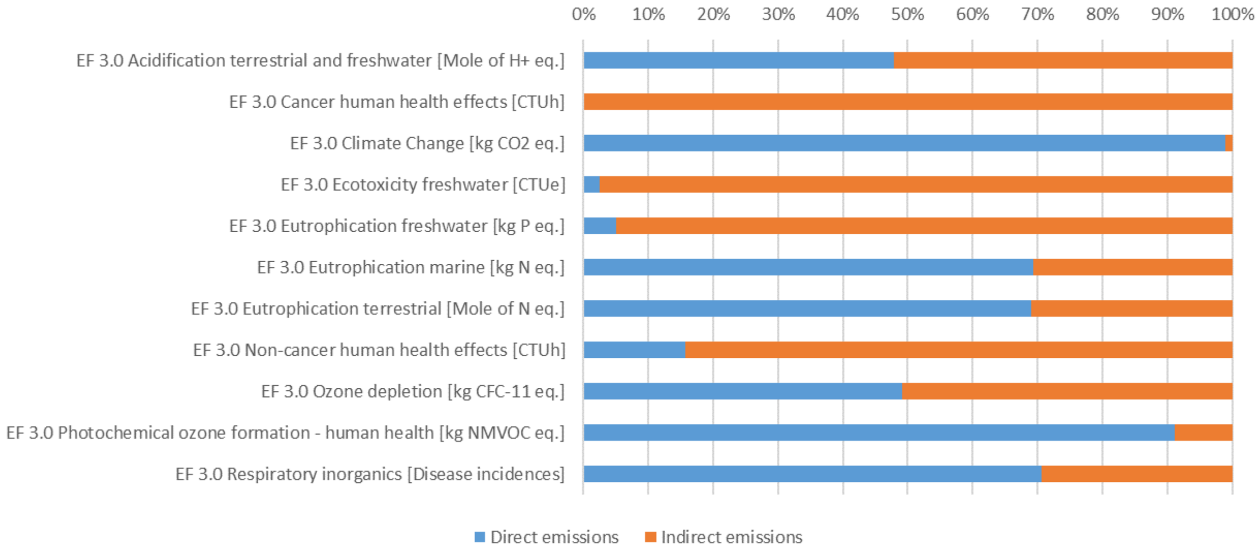
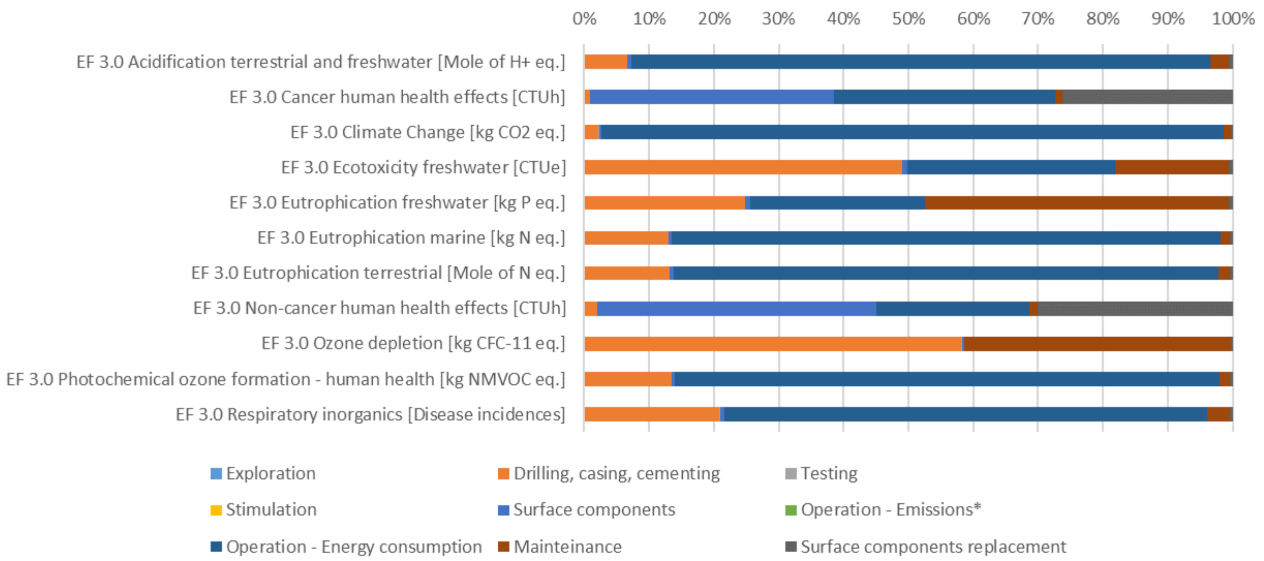


Figure 53: Cluster 3DHC – Breakdown of impact by direct/indirect emissions

As concerns cluster 4DHCa, Figure 54 indicates that the most relevant contributions are associated with the energy consumption during operation. The energy consumption is mainly linked to indirect emissions, are reported within Figure 55. Drilling operation plays a role for some categories, such as Ecotoxicity freshwater and Ozone depletion; for this last indicator, the diesel burned during drilling operation is responsible also for a relevant share of direct emissions. The mainteinance phase affects some indicators due to the lubrificat oil and chemicals used.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 54: Cluster 4DHCa – Breakdown of impact by phase

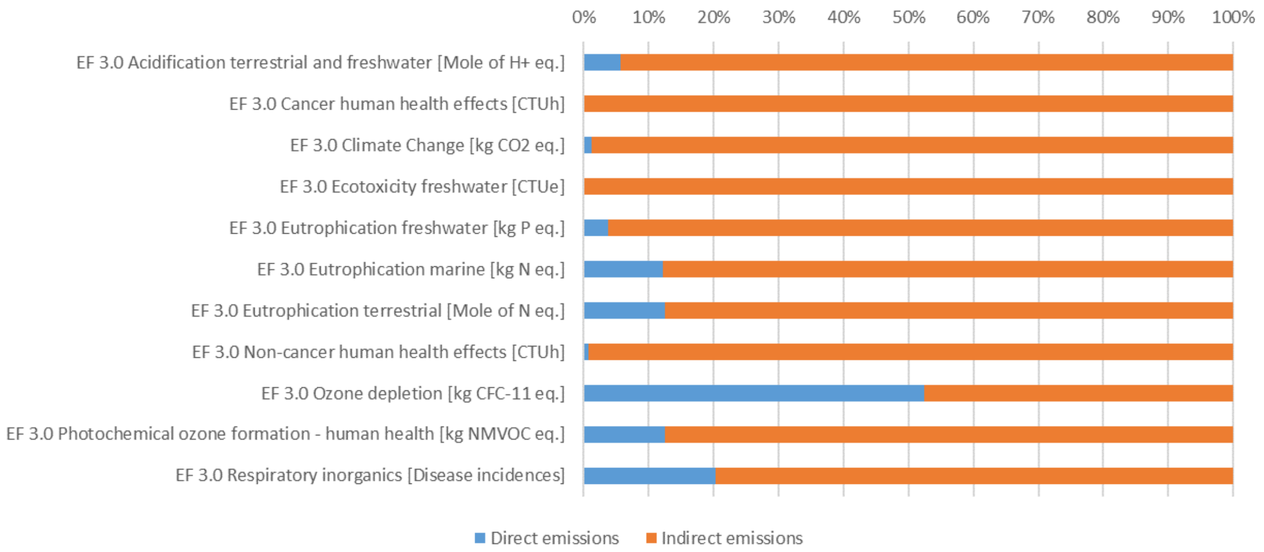
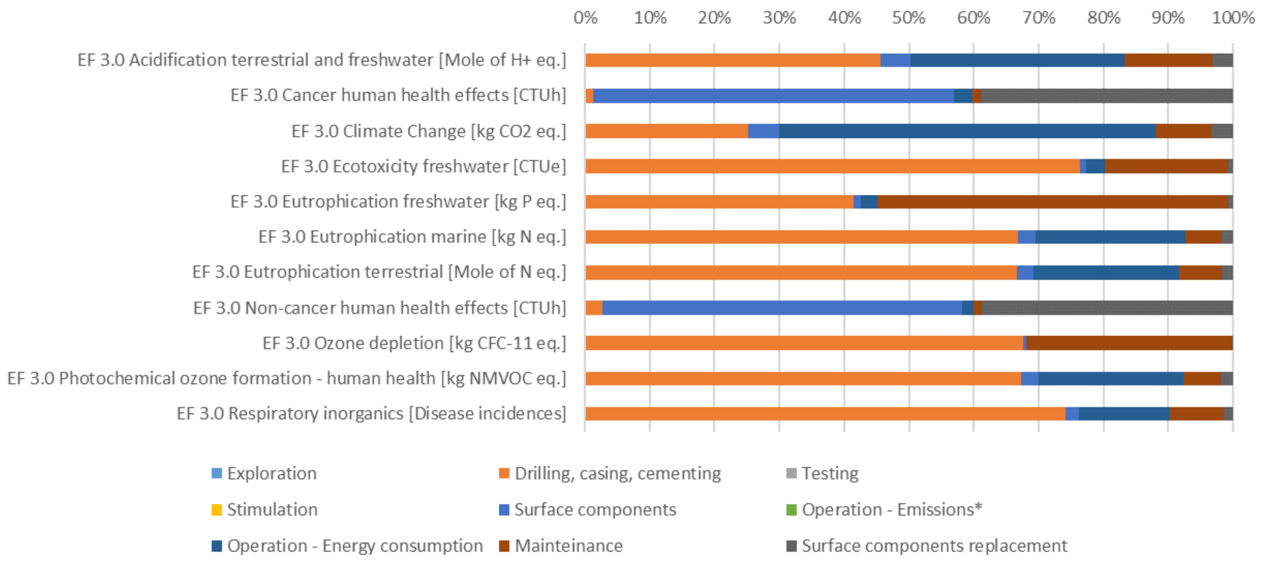


Figure 55: Cluster 4DHCa – Breakdown of impact by direct/indirect emissions

Figure 56 shows the breakdown of impact by phase for cluster 4DHCb. The most impacting contributions are associated with the drilling phase, for almost all indicators, except Cancer and Non-cancer human effects, which are mainly influenced by the manufacturing and the replacement of construction materials. The contribution of the drilling operation is associated with direct emissions, as reported in Figure 57, which reports the share of direct and indirect emissions for the cluster. The energy consumption influences some impact categories, especially Climate change, while some indicators are affected by the mainteinace phase, especially Euthorpication freshwater indicator.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 56: Cluster 4DHCb – Breakdown of impact by phase

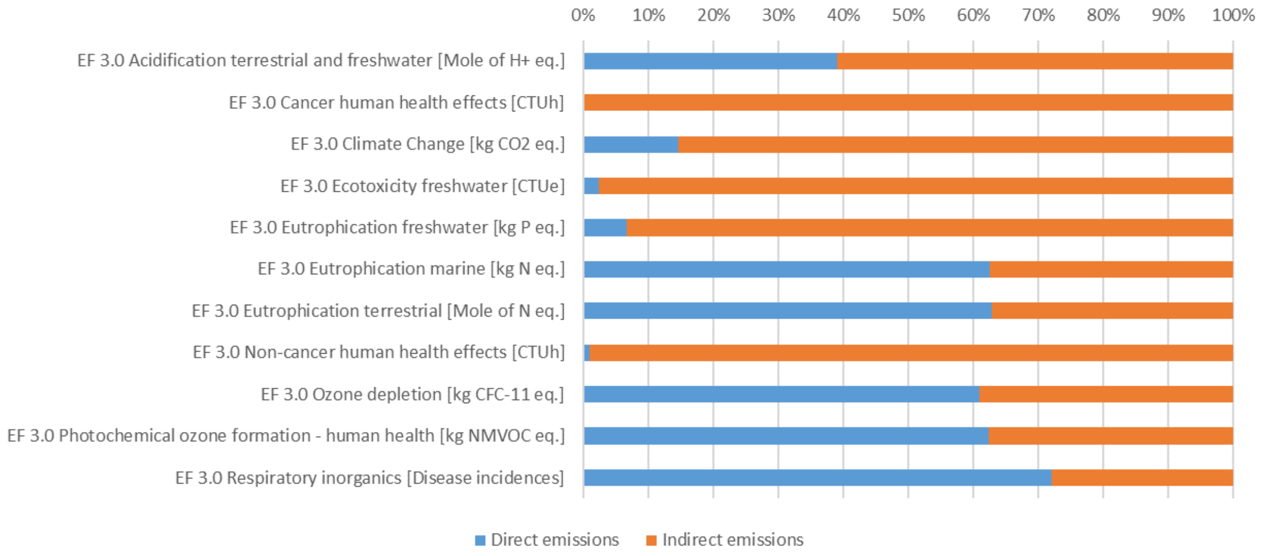
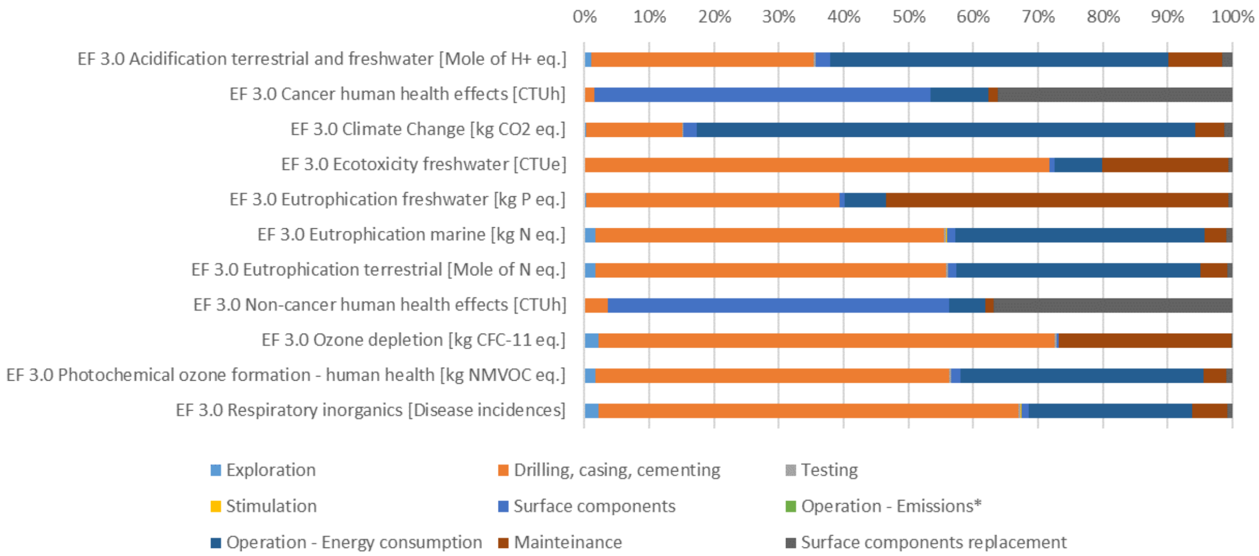


Figure 57: Cluster 4DHCb – Breakdown of impact by direct/indirect emissions

With reference to cluster 5DHC, the breakdown of impact by phase is reported in Figure 58, while the share of direct and indirect emissions for the same clusters is reported in Figure 59. The predominant contributors for this cluster are the drilling operations and the energy consumptions, associated with direct and indirect emissions, respectively. Similarly to the other clusters presented above, other contributions are represented by the mainteinance operations, while the manufacturing and replacement of construction materials have an impact on cancer and non-cancer human health effects indicators.



*see section "Core Processes – Operation" and section "Natural Emissions" for details on specific cases

Figure 58: Cluster 5DHC – Breakdown of impact by phase

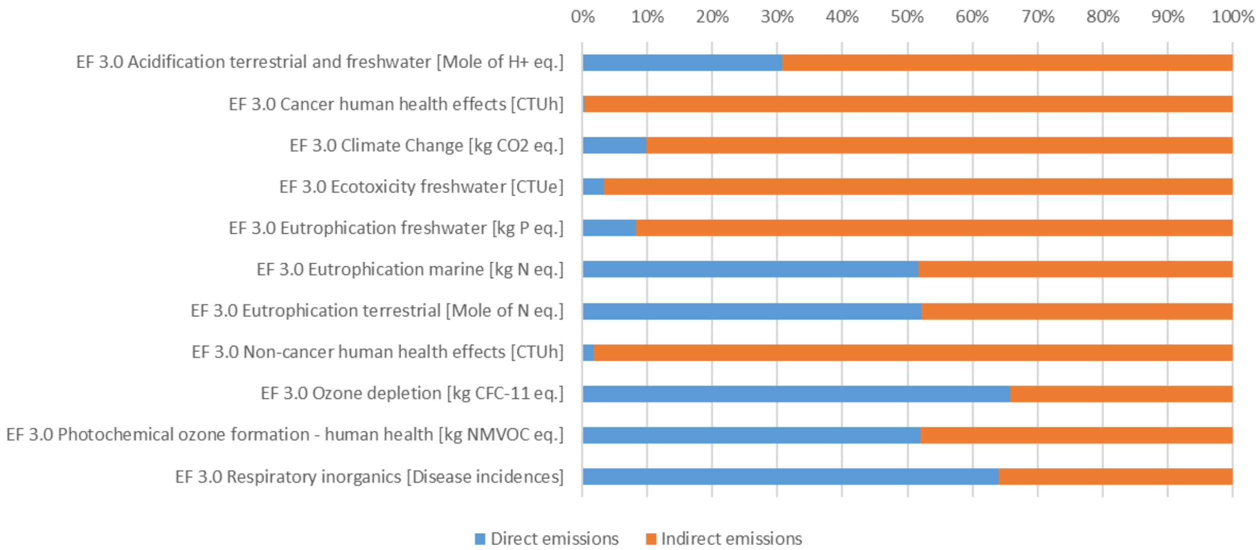


Figure 59: Cluster 5DHC– Breakdown of impact by direct/indirect emissions

13 RESULTS INTERPRETATION

In the previous paragraphs, the LCA results are analyzed from various perspective. This section brings further discussion on the robustness of the results. In detail, the main results are compared with LCA results retrivable in literature and a sensitivity analysis is carried out.

13.1 Results Validation

With the aim of assuring a sufficient level of quality for the outputs of the LCA models, the results calculated are compared with already available LCA studies which are representative in general for the geothermal sector and also more specifically at cluster level whenever sufficient literature data are available. Specific attention is given to GWP impact category, which is the most widely .

Nevertheless, it is highlighted that the comparability between different available LCA studies is a delicate matter. Indeed, considering that methodological harmonisation of approaches for the life cycle assessment of geothermal systems is missing in the state of the art sources, results available in literature are calculated with different boundary conditions mainly with respect to: functional unit, life cycle phases included in system boundaries, data accuracy, geographical location, impact categories, characterisation methods, secondary databases.

From this perspective, the outcome of the comparison should be treated with proper expert judgement.Table 48 summarizes the outcomes of the data and results validation analysis at cluster level for P-clusters. The main focus of the validation is the GWP impact category and only the clusters for which specific references could be retrieved are reported.

Table 48: Results validation at cluster level

Cluster	Reference Literature	Comments
1P **1P CHPa** **1P CHPb**	Paulillo (2019)	Ranges about gas concentration in different geothermal areas are given. Validation covers impacts from emissions during operation.
3P CHP **4P** **4P CHP**	Buonocore et al. (2015) Parisi et al. (2019)	Validation covers inventory data for direct emissions during operation andand also general conclusions are anylized. Where available for comparison, also LCIA results are taken into account.
5P **5P CHP**	Lacirignola and Blanc (2012), Martin-Gamboa et al. (2015), Pratiwi (2018)	Validation covers GWP impact category. It results that impacts from reservoir stimulation may be an underestimation, but still in the range of literature sources available.
8P **8P CHP**	Martin Gamboa et al. (2015), Lacirignola (2017)	Validation covers GWP impact category. It results that impacts from reservoir stimulation may be an underestimation, but still in the range of literature sources available.

Furthermore, an additional data collection is performed to map existing data about GWP for electricity generation from various geothermal plants. Thus, Figure 60 shows the alignement between results available from a selection of literature sources (either review or specific studies) and the results obtained in the present study (grouped per technology and per geological play), with the aim of validating the outcomes of the present study.

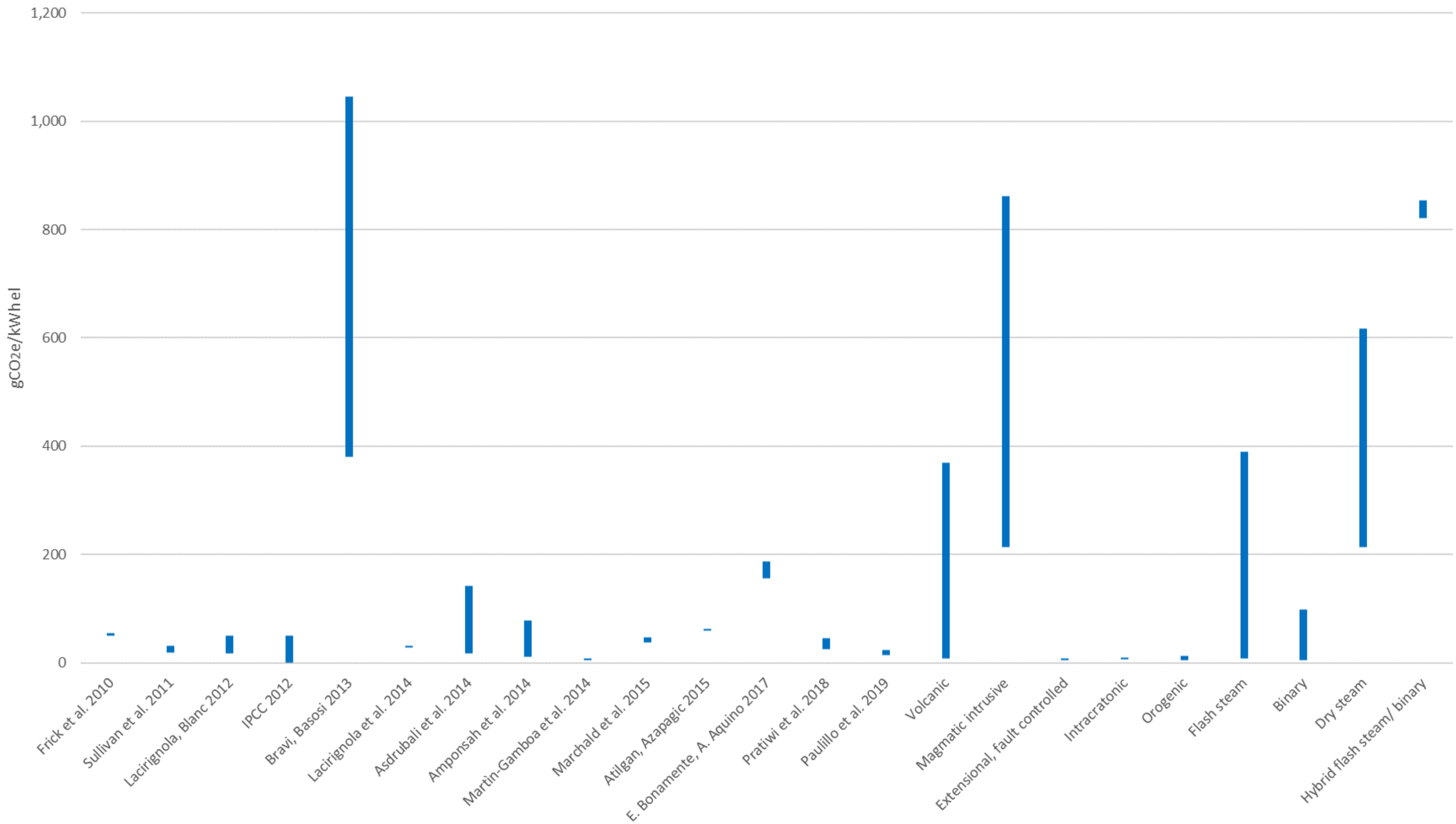


Figure 60: Results validation – GWP

It appears that the results of the study are overall aligned with available information from literature and confirm the high variability of potential impacts in terms of greenhouse effect.

For the case of DHC-clusters, a similar assessment could not be performed due to the limited number of studies addressing the environmental impacts of thermal energy production from geothermal resources from a life cycle perspective.

Available sources provides an estimate of GWP equal to 5.8 gCO_2e/kWh_{th} (Karlsdottir, 2014) and 8 gCO_2e/kWh_{th} (Pratiwi, 2018). Morevoer, the IPCC report (Goldstein et al., 2011) indicates a potential impact between 14 gCO_2e/kWh_{th} and 202 gCO_2e/kWh_{th} for district heating systems and ground source heat pumps.

Calculated GWP results for clusters without emissions during operation, as the case of the scenarios considered in literature studies, range in average between 8 gCO_{2e}/kWh_{th} and 58 gCO_{2e}/kWh_{th}. For all these cases, electricity appears as the major contributor for the potential impacts and thus, the selection of the energy mix play a crucial role in the validation of the results.

For example, in the literature LCA perfomed in (Pratiwi, 2018), the electricity mix presents an extremely low GWP value, because it is characterized primarily by nuclear and solar energy sources. This consideration is relevant for a consistent comparison.

Similarly to what has been done at cluster level, the results grouped by technology and by geological play are compared with already available with already available literature information.

Wiht reference to the geothermal technologies that generate electricity, a comparison is made with the systematic review of the LCA literature performed by (Eberle et al., 2017), who examinated three electricity generation technologies (i.e., EGS binary, HT binary, and HT flash) in detail and compiled published estimates for life cycle GHG emissions. They did not analyze published GHG emission estimates for hybrid systems and dry steam, so the comparison is limited to the HT binary and HT flash.

They found that the median estimate of life cycle GHG emissions (in grams of carbon dioxide equivalent per kilowatt-hour generated [g CO2eq/kWh]) reported by the studies analyzed are 47 and 11.3 for HT flash and HT binary, respectively. However they also pointed out that operational emissions from geothermal flash plants vary widely and may be up to ten times than the median values reported: the range for total emissions HT flash is 15.0–245 g CO2 eq/kWh, as reported in Figure 61.

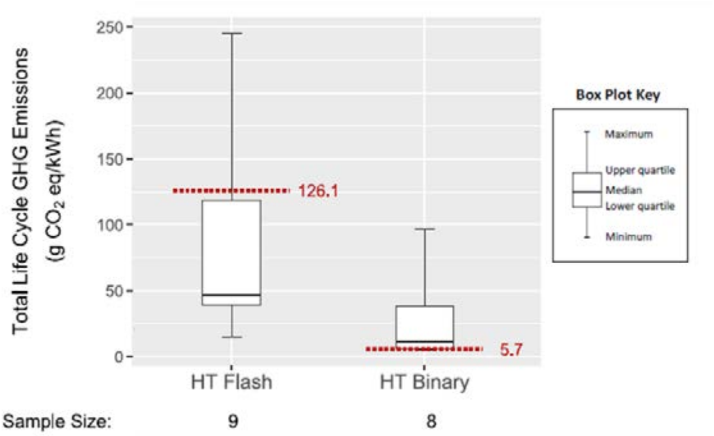


Figure 61: GHG emissions from hydrothermal (HT) flash and HT binary (Eberle et al., 2017)

In addition, within this article, they examined also the large variability associated with the operational emissions from HT flash plants; they mentioned four studies (compiled from Bertani and Thain 2002, Holm et al. 2012, Sullivan and Wang 2013, and Bravi and Basosi 2014) reporting operational emissions of carbon dioxide (CO2) from actual power plants are compared to the GHG emissions computed from life cycle assessments (LCAs). This comparison is reported in Figure 62.

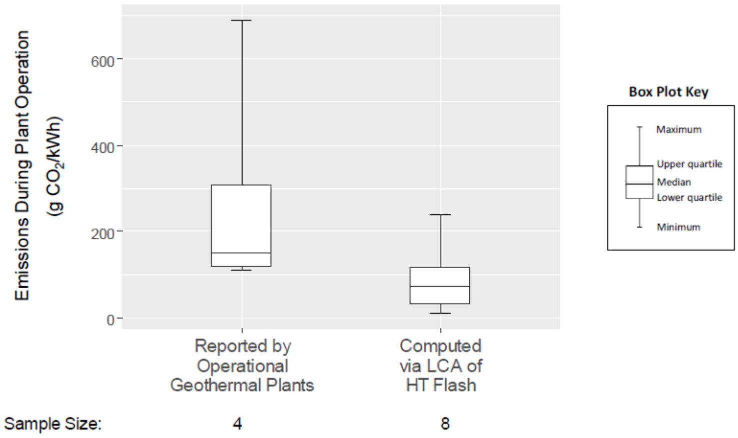


Figure 62: Comparison of carbon dioxide (CO2) emissions reported by operational geothermal plants versus GHG emissions computed from life cycle assessments (LCAs) of electricity generated by hydrothermal (HT) flash plants (Eberle et al., 2017)

13.2 Sensitivity Analysis

The results obtained with the sectoral LCA procedure can be affected by different sources of uncertainty, mainly realted to methodological choices, initial assumption and quality of the available data. Essentially, uncertainty derives from missing knowledge on the exact value of a quantity, but it is possible to distinguish different types uncertainty:

- parameter uncertainty, due to imprecise, incomplete, outdated or missing values of data needed in the inventory analysis or in the impact analysis;
- models uncertainty, often due to the adoption of linear models to describe the relationships among environmental phenomena and of aggregate data regarding spatial and temporal features;
- uncertainty due to unavoidable methodological choices in sectoral LCA procedure, such as allocation methods, functional unit, system boundaries, cut-off rules, data collection methods.

Below, a selection of sensitivity analyses is presented, in order to provide quantitative investigation about allocation method, electricity supply for drilling operations, contribution of well abandonment and presence of natural emissions.

Such areas of investigation have been selected based on the state-of-art practice for LCA studies (for the case of analaysis of assumptions for allocation, inclusion of end-of-life) and also based on assumptions specifically relevant for the geothermal sector (electricity supply during drilling phase). Their selection is also consistent with the overall level of detail of the study.

13.2.1 Allocation Method

With reference to the last point, uncertainty due to unavoidable methodological choices in sectoral LCA procedure, it has been decided to evaluate how the choice of the allocation method can influence the results. Different options indeed have been evaluated (and described within the SCR, in the Chapter dedicated to the allocation procedures). For this assessment, it has been decided to use the exergy allocation method, since it has been considered one of the most suitable. However, other approaches could be used.

In this sub-chapter, a comparison among the exergy allocation approach and the alternative generation approach is reported. The allocation factors for both methods are reported in figure below, per each CHP plant considered. To calculate the allocation factors of the alternative generation method, the default values of efficiency defined within Annex B of EN 15316-4-5:2017 have been used (i.e. $\eta_{E,ref}$ =0,4 and $\eta_{Q,ref}$=0.9). The comparison among the two methods underline that the results obtained applying the alternative generation allocation method would be similar to those obtained with the exergy method, since no remarkable difference arise among the allocation factors.

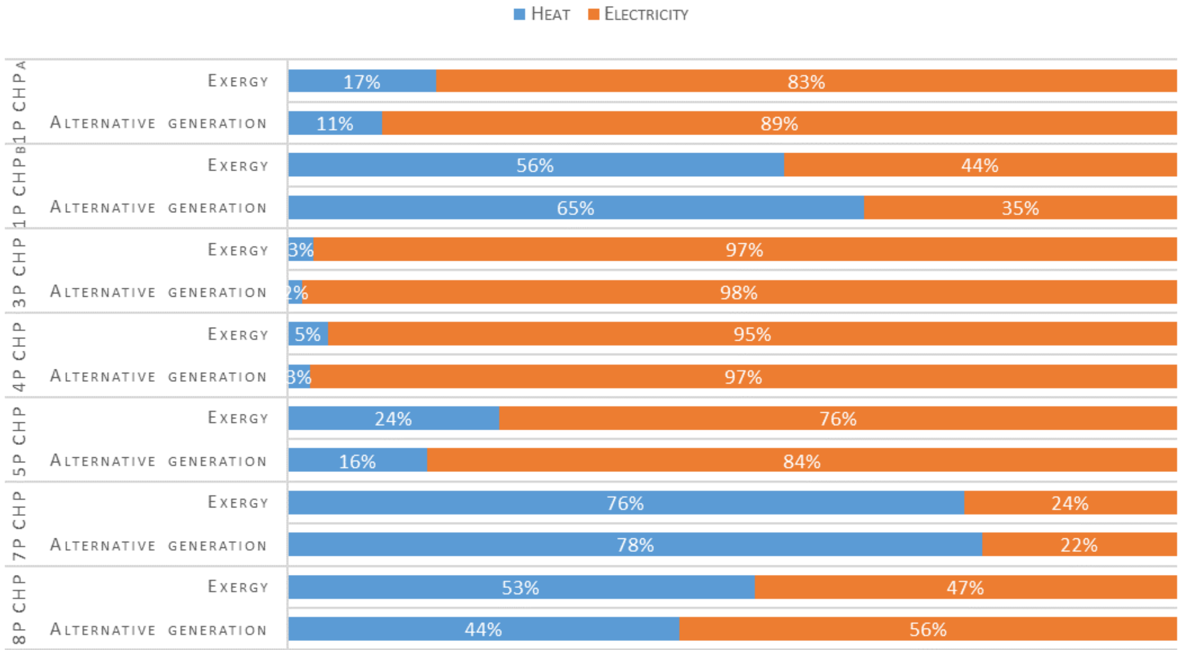


Figure 63: Comparison among allocation factors

13.2.2 Electricity Supply for Drilling Operations

It appears from the analysis of the above-presented results that for the clusters where direct emissions during operations are not registered, the drilling phase acquires high significance on the results of the LCA.

Flows contributing to this phase are material flows (i.e.: cement and steel), drilling mud and associated treatment after-use and electricity produced by burning diesel in standard electric generators. It results, and it has been already investigated in literature, that the substitution of electricity from diesel with electricity from national grid may lead to non-negligible overall benefits.

In order to investigate the effects of this measure, two limit case studies are derived from the previously shown results, considering on one side a representative plant where influence of drilling operation is negligible in comparison with the emissions during the operation phase and, on the other side the representative plant which shows the highest contribution of the drilling phase for the GWP impact category and also the highest share of direct emissions for the same category. It is highlighted that the analysis is dedicated to the set of P-clusters' representative plants, which have resulted in higher overall impacts than the DHC cluster's representative plants.

The first limit case study represents the scenario in which the impacts of substituting diesel-generated electricity with electricity from the national grid leads to mimimum changes in the overall performance of the plant, while the second limit case represents the case in which the highest benefits are achievable, in relative terms.

Specifically, Table 49 illustrates the variation of the contribution of the drilling phase to the life cycle phases considered and of the share of direct and indirect emissions, for the global warming potential impact category. For the analysis, the average European electricity mix is used.

As expected, it is observed that when direct emissions during operation are present (negligible drilling phase), electricity grid supply does not substantially affect the overall performance of the power plant in relative terms, which is mostly characterized by the type and amount of direct emissions during operation only. A slight reduction of 1% is however observed I the contribution of the drilling phase to life cycle impacts for GWP, while the share of direct emissions over total emissions is not affected.

In those cases where direct emissions are not generated during operation, the drilling phase is a relevant phase of the life cycle (significant drilling phase) and thus the sensitivity to any change is such phase increases. In this scenario, the use of grid electricity leads to clear reduction of the contribution of the drilling phase to overall lifecycle phases, moving from 82% to only 1% of contribution and, in addition, it causes the decrease of the share of direct emissions from 63% to 7%.

Table 49: Sensitivity analysis – Effect of electricity supply on GWP

Parameter	Scenario			
	Negligible drilling phase - diesel	Negligible drilling phase - grid	Significant drilling phase - diesel	Significant drilling phase - grid
Drilling phase contribution to life cycle	1%	0%	82%	1%
Share of direct emissions on total emissions	99%	99%	63%	7%

It is concluded that, in any scenario, the substitution of electicity from diesel generators with electricity from the grid is beneficial towards mitigation of global warming potential and towards reduction of direct emissions. In relative terms, such benefits are more evident when the drilling phase is dominant over the lifecycle in terms of impacts calculated, but is also achieved whenever drilling is not the predominant phase over the lifecycle.

13.2.3 Sub-surface Decommissioning

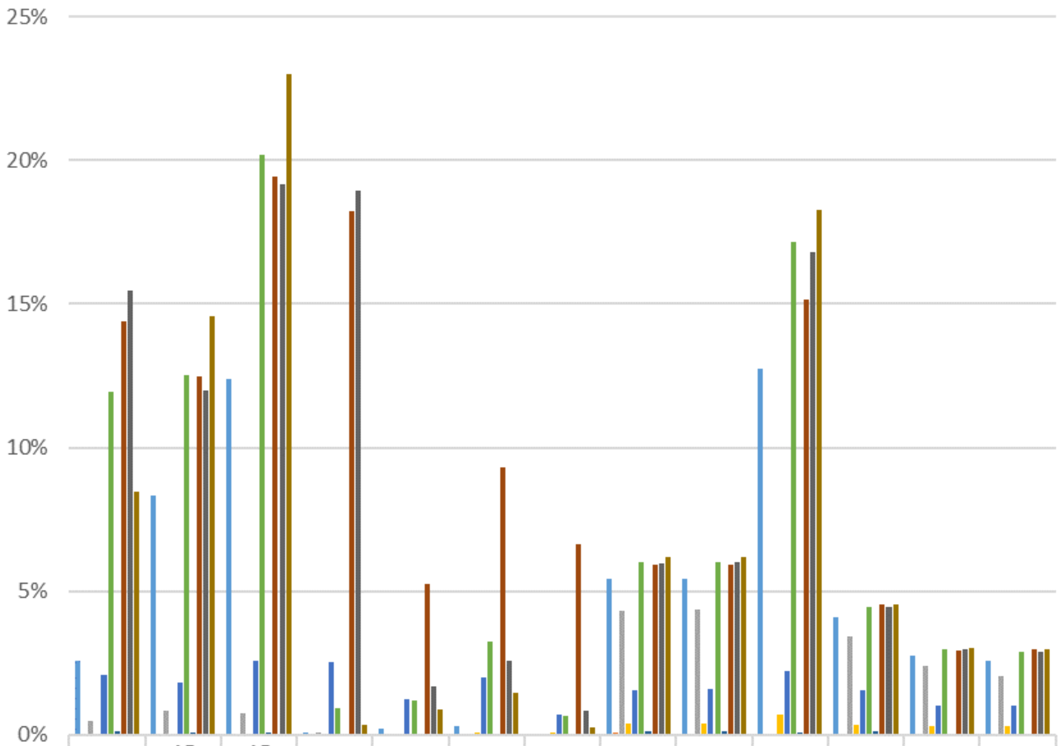
Among the sources of uncertainty that affect LCA results, it is worth mentioning the exclusion of the sub-surface decommissioning phase from system boundaries

Sub-surface decommissioning refers to the operations necessary for the abandonment of wells, consisting in the filling of borehole with cement. Despite being not included within the system boundaries, the potential impact of this sub-phase is analyzed in this section, considering only well abandonment operations.

Assumptions for quantification of well abandonment are derived from primary data available at well scale.

The impact of decommissioning sub-phase on LCA results are shown in Figure 64 for all the clusters' representative plants and all the considered impact categories.

Looking at the values in the chart, it can be noticed that as outlined in section Figure 64, the impact of this assumption is negligible, i.e. below 5%, on GWP as well as on other impact categories (CE, TOX, EP_f, NCE). However, for other impact categories the relative impact is significant: AP, EP_m, ODP, POF, RI can increase by up to 6-23% due to the emissions correlated to the well abandonment sub-phase. This is particularly important for the plants which have a significant number of wells and therefore a significant high impact related to their decommissioning, considering the assumptions set for this analysis.



	1P	1P CHPa	1P CHPb	2P	3P CHP	4P	4P CHP	5P	5P CHP	6P	7P CHP	8P	8P CHP
AP	3%	8%	12%	0%	0%	0%	0%	5%	5%	13%	4%	3%	3%
CE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
GWP	0%	1%	1%	0%	0%	0%	0%	4%	4%	0%	3%	2%	2%
TOX	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	0%	0%	0%
EP_f	2%	2%	3%	3%	1%	2%	1%	2%	2%	2%	2%	1%	1%
EP_m	12%	13%	20%	1%	1%	3%	1%	6%	6%	17%	4%	3%	3%
NCE	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
ODP	14%	12%	19%	18%	5%	9%	7%	6%	6%	15%	5%	3%	3%
POF	15%	12%	19%	19%	2%	3%	1%	6%	6%	17%	4%	3%	3%
RI	8%	15%	23%	0%	1%	1%	0%	6%	6%	18%	5%	3%	3%

Figure 64: SensitivityaAnalysis – Effect of decommissioning phase exclusion

13.2.4 Natural Emissions

During the validation workshop and the final workshop, the importance of the topic of "natural" gas emissions was stressed. It is an important topic especially in regions were high (and often visible) natural emissions of gases take place, such as in Italy and Iceland. A thorough search of the existing literature has been performed to evaluate the possible ways to discriminate between (diverted) natural emissions and anthropogenic emissions over the life-time of a plant.

In geothermal areas with natural emissions of the same gases as the ones present in the geothermal fluid, the contribution of geothermal installations to the impact on nature can be assessed with difficulty. This is, however, an important point of attention for public acceptance as well as for plant developers as Bravi et al. (2014) mention that emissions of geothermal gases may have an impact on global warming, acidification and human toxicology.

Below, a clear focus on the topic is presented, with the aim of justifying the assumption of excluding natural emissions from the core of the analysis on one hand, but also of including potential natural emissions scenarios on a sensitivity level on the other.

Naturally Emitted Gases

It is not easy to differentiate between anthropogenically and naturally emitted gases from geothermal systems. For most geothermal systems data on naturally emitted gases present without human interaction, thus prior to the development of the geothermal power plant, are not available. Furthermore, due to the natural site-specific character of the geothermal resources, data on natural emissions from one geothermal site cannot be transferred to other sites or cannot be generalized. Originally none of the gases present in the geothermal fluid are anthropogenic. The dominant non-condensable gas in geothermal fluids is carbon dioxide, typically constituting more than 95 percent of the total non-condensable gas content. For this reason, the following text will focus mainly on carbon dioxide emissions.

Carbon dioxide within the geothermal system may have different sources, but they are all part of the carbon dioxide degassing of the earth. Volcanic activity (in active and quiescent volcanoes) is the best known way through which gases can escape from depth and end up in the geothermal reservoir where they may be dissolved in the thermal fluid. But this can also take place through non-volcanic degassing with escape of gases from the upper mantle, from carbonate bearing rocks (metamorphic decarbonation), from hydrocarbon reservoirs in sedimentary beds, from surface deposits and through surface processes (Oladottir & Fridriksson, 2015). The three main sources for carbon dioxide in geothermal reservoirs are:

1. carbon dioxide dissolved in fluids that recharge the geothermal system, i.e. meteoric water and/or sea water. (Carbon dioxide from surface level);
2. carbon dioxide derived from the reservoir rock of the geothermal system through dissolution, especially in the case of carbonate bearing rocks and to a lesser extent in the case of volcanic rocks. (Carbon dioxide from reservoir level);
3. carbon dioxide from degassing of a mantel source or a deep magma intrusion (Carbon dioxide from deeper levels).

Carbon dioxide is the most widely emitted gas by geothermal systems. Even without human interaction geothermal systems will exhaust carbon dioxide to the atmosphere. This usually happens through craters, crater lakes, fumaroles, thermal springs, cold springs, groundwater, mud pots, geysers and diffuse soil degassing or diffuse degassing structures such as fractures, faults and fissures (Chiodini et al., 2001). However in some places these gases accumulate at depth in crustal traps, generate (overpressurized) carbon dioxide reservoirs and may never reach the earth’s surface (Chiodini et al., 2004), thus creating natural analogues for the geological storage of anthropogenic carbon dioxide.

In Europe, data on natural emissions of carbon dioxide are available for a couple of regions (Italy, Iceland, Greece, Spain (Canary Islands) and Portugal (Azores)), mainly linked to volcanic activity.

Papers from **Italy** deal with natural emissions of the Somma-Vesuvius volcanic complex (Aiuppa et al., 2004), the Etna (Allard et al., 1991), Monte Amiata (Barelli et al., 2010), Vulcano Island (Baubron et al., 1990), central Italy (Chiodini et al., 1995), Volcano Island and Solfatara of Pozzuoli (Chiodini et al., 1998), Manziana Caldera and Poggio dell'Ollivio (Chiodini et al., 1999), central Apennine (Chiodini et al., 2000), Solfatara volcano (Chiodini et al., 2001), central and southern Italy (Chiodini et al., 2004), Solfatara, Donna Rachele, Vesuvio, Volcano Porto di Levante, Volcano crater, Favara Grande and Favara Piccola (Chiodini et al., 2005), the Latera caldera (Chiodini et al., 2007), Pantellaria Island (Favara et al., 2001), Vesuvio (Frondini et al., 2004), Monte Amiata (Frondini et al., 2008), Tuscany and northern Latium (Frondini et al., 2009), central southern Italy (Gambardella et al., 2004), La Fossa crater (Granieri et al., 2006) and Vulcano Island (Inguaggiato et al., 2012).

Papers from **Iceland** deal with natural emissions of Krafla (Dereinda, 2008; Fridriksson, 2009), Reykjanes (Fridriksson et al., 2006; Fridriksson et al., 2009; Fridriksson et al., 2010; Oladottir., 2012; Oladottir et al., 2015) and Katla (Ilyinskaya et al., 2018).

Papers from Greece deal with natural emissions of the Nea Kameni Islet (Santorini Volcano) (Chiodini et al., 1998), Nisyros (Brombach et al., 2001), Stefanos, Kaminakia, Polybotes Micros and Nisyros volcanic systems (Chiodini et al., 2005).

Papers from **Portugal** deal with natural emissions on Sao Miguel Island (Cruz et al., 1999; Andrade et al., 2019).

Papers from **Spain** deal with natural emissions of the Teide volcano on Tenerife (Hernandez et al., 1998).

Monitoring of CO_2 Degassing

Carbon dioxide from geothermal systems exhausted through craters, crater lakes, fumaroles, geysers, mud pots and diffuse degassing structures can be measured. However, it should be kept in mind that a certain amount of carbon dioxide escaping from the reservoir may dissolve in groundwater on its way up and may seep into the biosphere through springs and rivers not necessarily within the vicinity of the geothermal system and possibly accompanied by travertine deposition. On the other hand, carbon dioxide may lead to precipitation of carbonate minerals (mainly calcite) in relatively cool aquifers at shallow depths (Armannsson, 2017) or forming a calcite cap-rock overlying basaltic geothermal reservoirs (Aradottir et al., 2015). Unambiguously quantifying the total amount of carbon dioxide released from a geothermal reservoir into the atmosphere through natural pathways can become somewhat problematic.

Gases Emissions during Production of Geothermal Power Plants

Although none of the gases emitted during power generation are anthropogenic in origin, over time geothermal power plants may have an impact on the amount of carbon dioxide released into the atmosphere. Extraction of geothermal fluids for power production will disturb the natural balance between the amount of carbon dioxide dissolved in the geothermal fluid, the amount of carbon dioxide that gradually escapes to the surface in a natural way and the natural replenishment of carbon dioxide through generation from the different sources mentioned. Not only the rate at which carbon dioxide is discharged into the biosphere will change, but also the place where it is released.

With the construction of a geothermal power plant at first carbon dioxide may escape more rapidly and more concentrated into the atmosphere. As the rate, at which carbon dioxide is emitted, is increased with regard to the natural state of the geothermal system, the concentration of carbon dioxide dissolved in the geothermal fluid may gradually decline, resulting in a decrease in carbon dioxide discharge over time, not only from the power plant itself but also through the natural pathways. For reasons of sustainability, as it helps to maintain the pressure in the reservoir and the influx of geothermal fluid, reinjection of waste brine and injection of surface water (Kaya et al., 2011) has become standard practice. Both fluids are depleted in non-condensable gases, thus further decreasing the concentration of carbon dioxide dissolved in the geothermal fluid and again resulting in a decrease of both the natural carbon dioxide discharge and the discharge from the power plant. The depleted geothermal fluid will tend to absorb free carbon dioxide that enters the reservoir through natural replenishment, preventing it from seeping to the surface along natural pathways. So enhanced discharge of gas in the early stages of the energy production of the geothermal power plant may be followed by times of overall (natural and power plant) low carbon dioxide emission.

This however needs to be nuanced. Injection of surface water or reinjection of waste brine should be carefully managed, as the optimum (re)injection strategy depends on the type of geothermal system (Kaya et al., 2011). In flash steam power plants which are liquid dominated, (re)injection of carbon dioxide depleted fluids into the reservoir may lead to a gradual decrease of gas concentrations in the geothermal fluid and to a decline of gas emissions with time. In steam dominated reservoirs no such straightforward relationship between (re)injection of carbon dioxide depleted fluids and gas concentrations in the steam seems to exist. Steam produced from different parts of the geothermal reservoir of the Geysers field in California may show an increase, a decrease or a steady state of carbon dioxide concentration in response to the injection of surface waters into the reservoir. (Re)injection however seems necessary as withdrawal of large volumes of geothermal fluids may lead to a pressure drop in the reservoir, resulting in the formation of a steam cap. As dissolved gases partition preferentially to the vapor phase, the liquid in the reservoir will become (relatively) depleted of carbon dioxide and the gas concentrations in the steam cap will increase. Production from the steam cap thus will result in (relatively) higher carbon dioxide emissions than production from the liquid phase deeper in the reservoir. Gas concentration in the steam cap may change with time according to changes in production and (re)injection. Where the geothermal reservoir is connected to the surface increased boiling in response to production with the formation of a steam cap may result in increased heat flow and carbon dioxide emissions into the biosphere. Surface activity increases as shown by increased steam flow in fumaroles and geysers, increased die-off of vegetation, increased soil temperature, increased extent of hot ground or increased snowmelt. Geothermal power production may however also result in a decrease of natural surface activity as shown by the oldest geothermal system in production in the world (Larderello field in Italy). Here most of the geothermal surface manifestations have ceased to exist as a result of pressure decrease in the reservoir mostly due to power generation from the geothermal system.

Situation in Europe

In Europe, Italy and Iceland are the two main areas where geothermal systems have been investigated with regard to natural and "man-made" carbon dioxide emissions.

- Iceland

In Iceland the geothermal power plants are situated within high temperature geothermal systems located in the three active volcanic zones. These active volcanic belts are linked to the Iceland plume, a hotspot on the Mid Oceanic Ridge which runs through the middle of the island. As Iceland lies on the divergent plate boundaries between the Eurasian and North American plates it is characterized by an extensional regime with rift structures, faults and fractures, that compartmentalize crustal blocks at any scale (Khodayar et al., 2018). The heat source for the geothermal systems is magmatic, i.e. shallow level crustal magma chambers, dyke swarms (Arnorsson, 1995) and magma injections into extensional fractures. The geothermal power plants are producing from basalt reservoirs with geothermal fluids from different origins (seawater, seawater and meteoric water, meteoric water). Based on carbon-13 isotopes the carbon dioxide present within the geothermal fluids has a magmatic origin, except in the Oxarfjordur area where it is derived from organic sediments (Armannsson, 2017). Six geothermal (combined heat and) power plants are producing electrical energy in Iceland today (Bjarnarflag, Svartsengi, Krafla, Nesjavellir, Reykjanes and Hellisheidi). The emission of carbon dioxide from these power plants has been recorded since the late 1970's. The overall trend observed is that there has been a decrease in carbon dioxide discharge per kWh produced, especially in recent years. But, although they all have a similar regional geological setting, emissions from individual power plants differ quite a lot and emissions for each power plant vary significantly over time. These differences can be attributed to natural as well as human induced processes; the Krafla fires (shallow magmatic intrusions), increased boiling and formation of a steam cap due to production, increased production from the steam cap, decreasing gas content in the steam cap, reinjection of a gas depleted waste brine (Fridriksson, 2016). Armannsson et al. (2005) doubt that carbon dioxide emissions from electricity plants are negligible. For most of the power plants, however, there are no data available concerning the initial state of natural degassing from the geothermal system. Thus, although carbon dioxide emissions from these geothermal power plants seem to decrease over time, it cannot be concluded that energy production has led to a decline of gas concentration within the geothermal fluid and to a decline in natural degassing of the geothermal reservoir. Only for the Reykjanes geothermal power plant pre-development data on natural degassing are available. Data on natural degassing during production and data on carbon dioxide emission from the power plant are available as well. Energy production at Reykjanes has resulted in a pressure drawdown with an increase in boiling and the formation of a steam cap in the upper part of the reservoir with preferential partitioning of gas into the steam cap. Lateral and upwards flow of steam (along fractures) increased, resulting in increased surface activity (hot soil, increased snowmelt, new mud pits) (Olladottir et al., 2015). Heat flow and carbon dioxide emissions at the surface have been monitored at the Reykjanes power plant. Although carbon dioxide emissions from the plant have been rather stable, with a mean flux of 25,000 tons/year, the heat flow and the carbon dioxide flux at the surface in the Reykjanes geothermal area show a clear increase. This increase was not gradual nor continuous, but in the end the natural heat flow has tripled and the natural carbon dioxide flux has quadrupled since the Reykjanes geothermal power plant has been in production. Therefore, in Iceland emissions from geothermal power plants are considered to be anthropogenic (Fridriksson, 2017). However, despite the increasing trend of emissions, it should be yet observed that for the same case a certain threshold of diffuse emission through the soil should be taken into account, both to "discount" the emission by the natural amount before the plant's operation.

Moreover, Iceland treats emissions from geothermal power plants as net direct emissions and reports them in full in the countries' annual reporting under the Kyoto protocol, based on the fact that for the case of Iceland, research has not concluded that emissions from power plants have replaced, fully or partly, naturally occurring emissions from geothermal sites. As mentioned, some research even suggests an increase of natural emissions alongside resource utilisation in geothermal power plants throughout the lifetime of the plants.

- Italy

In Italy the geothermal power plants are situated within high enthalpy geothermal fields located in the peri-Tyrrhenian area of central Italy (Larderello-Travale, Monte Amiata, Latera and Cesano; Chiodini et al., 2007). This area is characterized by a thin crust (20-25 km; Boccaletti et al., 1986) and a high heat flow. The crustal thinning is related to Neogene extension and was followed by intense magmatic activity with the emplacement of igneous rocks ranging in age from Upper Miocene to Recent (Chiodini et al., 1999). Although many authors indicate the heat source to be related to these shallow igneous intrusions, recent studies point to the upper mantle as the main active source for the thermal anomaly in the Tuscan-Tyrrhenian extensional area (Magro et al., 2009). The geothermal power plants are producing from Mesozoic evaporitic and carbonate reservoirs, that are usually structural highs and that are capped by low permeability ophiolites and pelagic sediments or Quaternary volcanics. The geothermal fluids have different origins; meteoric (Craig, 1963; Ferrara et al., 1965; Barelli et al., 2010) and deep fluids at supercritical conditions (Bozza, 1961; Sestini, 1970; Minissale, 1991), mostly with a recharge of meteoric water through the outcrop zone of the Mesozoic carbonates (Cataldi et al., 1963). Based on carbon-13 isotopes the carbon dioxide present within the geothermal fluids seems to have different origins; 41% a mantle or magma origin, 36% decarbonation of carbonate reservoir rocks and 23% an organic origin through inflow of meteoric water (Chiodini et al., 2000; 2004). The fractured carbonate structures which host the geothermal systems can act as carbon dioxide traps and become a source of carbon dioxide anomalies in groundwater and at the surface. Gas leakage from geothermal reservoirs produce an anomalous carbon dioxide flux which appears on the surface in the form of numerous gas emissions, soda springs, acid-sulfate waters, travertine deposits and altered clay ground. Locally the gas arrives at the surface after only minor interaction with groundwater, forming large emissions of dry gas, with a composition very similar to the gas present at depth. These carbon dioxide seeps reflect established fluid migration pathways from the carbonate reservoirs. The distribution of the carbon dioxide flux suggests that the extensional faults, that bound Pliocene and Pleistocene grabens and horsts, provide the easiest routes for the ascent of the gas (Chiodini et al., 1995; 2007). In the last two decades natural carbon dioxide fluxes have been measured and mapped for most of the peri-Tyrrhenian area of central Italy. However most of the geothermal power plants pre-date these observations, making it difficult to determine whether geothermal power development has led to an increase or decrease in carbon dioxide emissions over time. Still it is thought that geothermal energy production has led to a decrease of natural surface activity (fumaroles, mud pots, geysers, hot springs, …). Reduction of natural manifestations and carbon dioxide degassing have been reported by Bertani et al. (2002) in the Larderello region and by Frondini et al. (2009) in the Monte Amiata region subsequent to geothermal development. Travellers passing through the Larderello region in past centuries (Targioni-Tozzetti, 1769) were impressed by the large amounts of steam erupting violently from the ground. Today, after over a century of industrial exploitation, only a few areas naturally produce weak vents of steam. Some of these vents have died a natural death, others have been drained artificially to prevent the formation of dangerous pools. Shallow wells have also been drilled in the "lagoni" areas and have probably trapped most of the steam that would have reached the surface in a natural way through fractures. Today this no longer occurs (Minissale, 1991). Exploitation has undoubtedly depressurized the system, but the presence of the shallow low-enthalpy wells suggests that steam might still reach the surface under the natural conditions. Sammarco and Sammarco (2002) showed that natural carbon dioxide emissions in the Monte Amiata region have declined during the last century due to the geothermal power development. Some degassing areas and thermal springs of the Monte Amiata area have disappeared, some have a strongly reduced gas flux and water flow rate and some have changed their position. The cause of these changes is still debated (Frondini et al., 2009). However they argue that it is likely that natural carbon dioxide emissions in the Monte Amiata area due to volcanic degassing are much lower than those due to the exploitation of geothermal fluids at a considerable depth (Bravi et al., 2014) and that geothermal development might have reduced natural carbon dioxide discharge. According to Barelli et al. (2010) exploitation of the Monte Amiata geothermal system has caused the gas cap pressure to decrease and the gas / liquid interface to rise. Bertani et al. (2002) state that, when considering carbon dioxide emissions from geothermal plants, a very strong case can be made for subtracting the natural background emission rate pre-development from the rate being released by geothermal energy production. This is particularly relevant to the Larderello field in Italy where there has been a noticeable and measurable decrease in the natural release of carbon dioxide from the ground as a result of the geothermal power development. In areas with a high natural carbon dioxide flux from the geothermal system at the surface prior to development any measurable decrease in this natural emission resulting from the geothermal power production should be subtracted from the measured plant emission rate (Bertani et al., 2002). Furthermore, (at least for the Monte Amiata area) a recent study from Lattanzi et al., (2019), based on measurements demonstrated that contributions of Hg to the environment from present day geothermal power plants are comparatively minor in respect to contributions from abandoned mining areas. This is an important finding, as it can be stated that the geothermal plants do not have impact on natural emissions of Hg in this area of Italy.

As an area characterised by strong and also dangerous gas emissions, Italy was the object of study of the Italian project funded by the Department of Civil Defense, with the aim to develop the first catalogue of the Italian gas emissions[16].

Most of the literature on geothermal systems of the peri-Tyrrhenian area of central Italy agrees with the hypothesis that geothermal development has led to a decrease of natural degassing at the surface. Indeed, Italy is characterised by elevated emission of natural CO_2, with fluxes higher than in the other countries. Also, the peculiar geological and structural settings play a pivotal role in the geographical distribution of main degassing areas characterised by CO_2 surface anomalies (W sector) or dissolved CO_2 in regional aquifer (E sector). Although some data are available, the estimation performed represent an underestimation of the natural degassing phenomena and more data and studies would be necessary. As a result in Italy emissions from geothermal power plants are not considered to be anthropogenic as they are offset by a reduction in natural carbon dioxide emissions (Fridriksson, 2016).

Furthermore, (at least for the Monte Amiata area) a recent study from Lattanzi et al., (2019), based on measurements demonstrated that contributions of Hg to the environment from present day geothermal power plants are comparatively minor in respect to contributions from abandoned mining areas. This is an important finding, as it can be stated that the geothermal plants do not have impact on natural emissions of Hg in this area of Italy.

Finally, it is expected that in the near future results from monitoring activities about the presence of natural CO_2 emissions will be published and will provide support towards a more robust understanding about this matter.

Discussion and Conclusions

There is still active debate and no clear consensus so far in Europe about the relationship between natural gas emissions and those from operational geothermal power plants. In Italy, the topic is still a fairly sensitive one as can be seen from the various cited sources hereafter.

Goldstein et al., (2011) in Manzella et al., (2018) stated that "… varying quantities of greenhouse gases, which are usually small… originate from naturally sourced CO_2 fluxes, that would eventually be released into the atmosphere through natural surface venting. The exploitation of geothermal energy does not ultimately create any additional CO_2 from the subsurface, since there is no combustion process, though the rate of natural emissions can be altered by geothermal production depending on the plant configuration".

Bertani and Thain (2002) concluded that CO_2 emissions from geothermal plants are balanced by a reduction in natural release of CO_2 from geothermal fields. Following this line of thought, the European community does not include Greenhouse gas emissions produced from geothermal power plants in the burden shares allocated to countries.

[16] http://googas.ov.ingv.it/

Consequently, in Italy and the rest of Europe, greenhouse gas inventories do not take into account CO_2 emissions from geothermal plants (Bravi et al., 2014).

Yet in the same paper: Analysis shows that electricity from the geothermal plants in Monte Amiata area cannot be considered “carbon free” as claimed so far on the basis of literature mentioned in the introduction. Although Human Toxicity Potential did not provide worrisome values, greenhouse gas emissions are in some cases generally higher than those from natural gas plants and in some sampling not very far from the values of coal plants (Bravi et al., 2014).

It is clearly not possible to generalize the magnitude of the impact of geothermal plants on CO_2 emissions. First, there is only a limited number of studies comparing the measurements of natural emissions before and after the operation of geothermal plants. Second, it is to a large extend a parameter that is highly site specific and that can even be influenced by the nature of the dominant phase present in the reservoir.

For all these reasons we concluded that in the absence of additional scientifically based data the effect of geothermal plant operation on CO_2 emissions through natural pathways should not be taken into account in the present study. Note that this option was also the one recommended by Fridriksson et al. (2016), where it is recognized that it is not possible to make general statements about the magnitude of this effect, which is likely to vary greatly from one site to another and that available data are too limited to justify general predictions of their impact in future geothermal projects.

Scenarios Definition and Analysis

In light of the literature analysis presented, scenarios including different percentages of natural CO_2 emissions substitution are developed.

Considering the rapid evolution and progress of research with respect to the topic, such scenarios are structured for all the clusters referred to the Italian and Icelandic context, as the two main areas where geothermal systems have been investigated, with the aim of showing the potential effects of natural emissions on the LCA impacts allocated to geothermal plants.

Clearly, the actual representativeness of these scenarios is still to be robustly proven or denied scientifically, also to take into account if the findings that are now being produced can be associated with predictable trends in time.

For sake of consistency and comparability of boundariy conditions, scenarios are defined in accordance with relevant plant operators.

In both cases, scenarios are based on CO_2 substitution rates. Each rate represents the share of emissions which can be attributed to the local features of the plant site and thus, shall not be accounted for geothermal applications’ impacts estimation. In this sense, a 0% substitution scenario corresponds to the core analysis perfomed, in which no discount deriving from a natural share of the emissions is considered. Conversely, a 100% substitution scenario corresponds to a case where the entire amount of non-condensable gases emissions, including carbon dioxide and methane emissions deriving from the geothermal installation are considered as natural, and would be present even if the installation was not present.

Figure 65 illustrates for the set of clusters in which the exercise is relevant, the results of the sensitivity analysis on the global warming impact category, being the only one affected by variations in CO_2 releases. It is highlighted that the 0% substitution rate scenario corresponds to the results previously calculated, and thus, it is used as reference case for the estimation of the benefits deriving from natural emissions accounting.

Precisely, the graphs are built considering the variations on the results for life cycle GWP per kWh_e, including allocation factors for the case of CHP clusters.

In general terms, the extent of the reduction of life cycle impacts in terms of GWP caused by natural emissions depends on the contribution to each phase to overall impacts and to the presence and amount of other emissions during operation contributing to GWP (i.e.: methane). As for the last consideration, it should be highlighted that – for equal amounts – methane accounts 36.8 times more than CO_2 for GWP calculation; thus, in clusters with significant presence of methane, the effects of considering natural emissions is less evident as they may not be the major contributor to this impact category.

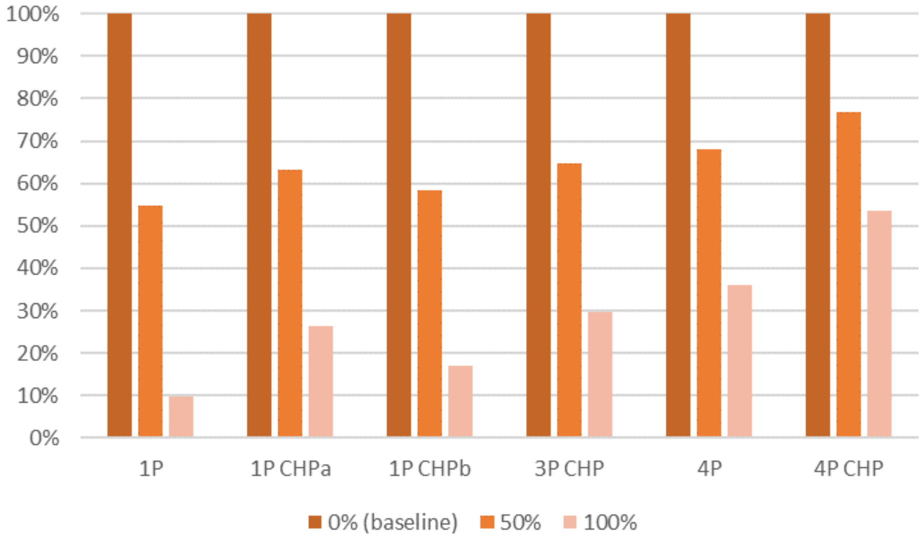


Figure 65: Sensitivity analysis – Effect of natural emissions on GWP

13.2.5 Effects and Limits of the Selection of LCIA method

H₂S impact on Acidification

According to the EF3.0 LCIA methodology, among the considered air emission flows, the ones affecting acidification are sulphur dioxide and ammonia.

However, it is not uncommon in LCA studies specific for the geothermal sector to account also the impacts of hydrogen sulphide emissions to air with respect to acidification potential (Frick et al. 2010; Marchand et al. 2015). In order to do so, an accepted methodology to compensate the absence of characterisation factor for this is to convert the mass of H_2S in an equivalent mass of SO_2, precisely using a multypling factor of 1.88. This mathematical approach reflects the oxidation of the entire amount of H_2S into SO_2, when realeased in atmosphere.

For the purpose of this study, in order to ensure immediate replicability and transparency of results and to guarantee consistency with the depth of the analyses proposed, the characterisation factor to represent the above-mentioned aspect is not introduced.

Nevertheless, in accordance with the provisions of the ILCD Handbook (Joint Research Centre, 2010) and of the Guidelines for Interpretation of LCA results (Zampori et al., 2016), proper discussions to guide to a solid understanding and interpretation of the findings is presented to address this issue.

The absence of the characterisation factor affects quantitatively the results of the clusters presenting H_2S emissions and the acidification potential results as an underestimation. In order to provide an idea of the extent of the underestimation, it should be considered that from the methodology based on SO_2 equivalence, a characterisation factor of 2.46 mole of H+ equivalents/kg of emitted H_2S, would have to be applied. Such factor is approximately twice the correspondent factor of sulphur dioxide and almost equal to the factor for ammonia.

In addition, the absence of the emission factor may lead to misinterpretation of the effects that can be obtained by the installation of abatement systems for H_2S. For example, the comparison of the same plant configuration with or without abatement system cannot be performed is the effect of H_2S to acidification is not accounted for: the two systems would result in equivalent impacts dispite aving different H_2S mass flow.

To conclude, it must be also highlighted that if the abatement system is responsible for the generation of another acidizing substance, as for the case of working principle of the AMIS technology based on a catalytic oxidation reaction producing SO_2, the mere comparison of a configuration with or without abatement system would even lead to a worse performance of the system with abatement technology, as - while the impacts of H_2S are not accounted, and would result as reduced - those associated the generated amount of SO_2 are.

Underlying that this study is not aimed at proving the efficiency of any abatement system, it is yet crucial to provide a key for correctly reading and accounting the results, avoiding wrong (or absurd) interpretation.

The beneficial effects of the existing abatement systems is given as a consolidated topic and it is numerically demonstrated by the abatement efficiency, in this case of H_2S, used to calculate raw inventory data. In this context, raw data represent the most reliable numeric source to draw any quantitative conclusion about the presence and potential effects of H_2S. In addition, even if not accounted for by the acidification potential indicators, the emissions of H_2S impact on the ecotoxicity indicator; thus their reduction contributes to lower this impact category.

For studies with different purposes, an adjument of this specific emission factor shall not be excluded.

13.3 Potential Impacts on Environment and Human Health at Local Scale

13.3.1 Rationale and general methodology

Existing main concerns about the exploitation of geothermal energy for energy generation are associated with the potential impacts arising mainly from the direct emissions and operation of the plants at local scale. For this reason, the geothermal development may be hampered by a low acceptance of communities (Manzella et al., 2018).

From this perspective, the aim of this section is to present an in-depth analysis of the results of the LCA study related to this theme with the aim of supporting and identifying potential criticalities to be address for an improved development of the geothermal sector in Europe, limiting harm on the environment and human health. Correlated with information available from non-LCA studies (e.g.: epidemiological, dispersion analyses, air quality monitoring, etc.), such indications can provide robust direction for policy making and identification of best practices. Indeed, according to the “Guide for interpreting life cycle assessment result”, published by JRC (Zampori et al., 2016), the interpretation phase of an LCA study is a key step to provide decision makers with comprehensive and understandable information, converting the numerical results of the LCIA into recommendations to ensure a wise development for the product under study.

Clearly, the extent and validity of the conclusions drawn are determined by the intrinsic features of the LCA analysis and of the LCIA method selected, in terms of applicability and quality. Hence, along the section, specific definitions and potential limitation will be highlighted to guarantee consistency with the overall approach and goal of the study.

The methodology proposed for a systemathic and structured interpretation derives from well-established techniques for impact assessment and management of environmental impacts, or other potential impacts in general. This approach does not lead to any additional quantititative results to those already reported in the LCIA phase, but it guides through a precise and systemathic identification of aspects where improvement should be pursued in the future development of the geothermal sector, as well as a preliminary identification of the receptors of the identified potential impacts.

In general terms, an impact assessment can be divided into the following steps:

- identifications of impacts aimed to determine what could potentially happen as a result of the project interaction with the physical, biological and human environment;

- definition of the impact types: any project can generate a wide range of potential impacts, which can be direct, indirect and cumulative;

- impacts evaluation once identified, potential impacts need to be assessed in order to determine their significance and mitigation/enhancement and management measures.

In particular, the impact evaluation is the results of the combination of the magnitude of the potential impacts and the sensitivity of the receptors/sources.

Generally the assessment of impacts potentially generated by the project is site-specific and project component specific. In line with the provision given by Directive 2011/92/EU (and amendments), the criteria for the evaluation of project impacts include:

- duration (the time period over which the impact is expected to last prior to resource/receptor recovery);

- extent (the spatial scale of the impact, the full area over which the impact occurs);

- scale (the scale of the impact is the degree of change in the qualitative and quantitative conditions of resource/receptor from its ante-operam baseline status).

On the other hand, the resource/receptor sensitivity is function of the baseline context where the project is located, of its quality status and, where applicable, of its ecological importance and protection status, based on the existing pressures, prior to the activity construction and operation. The criteria on which the sensitivity evaluation is based are:

- the importance/value of a resource/receptor is generally evaluated based on the legal protection (defined on national and/or international requirements), the government policy, ecological value, historical or cultural value, stakeholder views and economic value;

- vulnerability/resilience of the resource/receptor that is the ability of the resource/receptor to adapt to changes brought by the project and/or to recovery its ante-operam status.

As mentioned above, the resource/impacts sensitivity is a combination of importance/value and vulnerability/resilience.

The final significance of the impacts results from a comabination of the assessment with respect to impact assessment and resource/receptor sensitivity assessment.

Similarly to the general provisions previously introduced, the Commission Decision (EU) 2017/2285, a user's guide setting out the steps needed to participate in Community eco-management and audit scheme (EMAS), suggests the following issues to consider when assessing significance of impacts carrying out an environmental review are:

- potential to cause environmental harm;
- fragility of the local, regional or global environment;
- size, number, frequency and reversibility of the aspect or impact;
- existence and requirements of relevant environmental legislation;
- importance to stakeholders and employees of the organisation.

The above-presented scheme typical of environmental impact assessment and the EMAS framework is adapted to the scopes of this study and applied according to the procedure described below, with the aim of assessing the environmental effects associated to different configurations, in order to support in the decision-making process on a LCA methodology basis. The procedure is intended for the analysis of environmental impacts and impacts on human health.

13.3.2 Boundaries of the analysis

As a propedeutical topic, it is important to clarify the meaning associated to each impact category deriving from the LCIA phase and to map the relevant impact categories for the purpose of this analysis. This activity is crucial to set the boundaries for the expected results and findings of the analysis and the extent in which they are valid.

Table 50 shows a brief review about the main features of each impact category, highlitghting the receptor of the impact (i.e.: environment, health) and the scale of the impact (i.e.: local/regional, global). Moreover, the level of recommendation of each impact category is detailed (Fazio et al. 2018), in order to guide a proper interpretation of the results. The levels are defined within ILCD provisions as follows:

- “Level I”: recommended and satisfactory;
- "Level II”: recommended, but in need of some improvements;
- "Level III”: recommended, but to be applied with caution.

Thus, considering the scope of this analysis, the following impact categories are considered for the analysis of potential impacts on the environment:

- acidification;
- ecotoxicity freshwater;
- eutrophication (freshwater, marine, terrestrial).

As far as the potential impacts on human health, the following impact categories are considered:

- cancer human health effects;

- non-cancer human health effects;
- photochemical ozone formation;
- respiratory inorganics.

Table 50: Review of impact categories

Impact category	Details	Unit of Measure	Level of Rec.	Receptor		Scale of Impact	
				Environment	Health	Local, Regional	Global
Acidification terrestrial and freshwater	Emissions of acids (and compounds that can be converted to acids) to the atmosphere and deposited in water and soil, the addition of hydrogen ions may result in a decrease in the pH of the water body. This results in a decline of coniferous forests and increased fish mortality	Reference unit [mol H^+]	II	X		X	
Cancer human health effects	Chemicals emitted as a consequence of human activities can contribute to human toxicity via exposure to the environment. The most important routes of exposure are via the air breathed in or via other materials ingested orally, e.g. food.	Comparative Toxic Unit for humans [CTU_h], expressing the increase in morbidity in the total human population per unit mass of a given chemical emitted (cases per kilogramme)	III		X	X	
Non-cancer human health effects					X	X	
Climate Change	Changes induced to the global climate as a consequence of the emissions to the atmosphere of greenhouse gases	Reference unit [CO_2]	I	X			X
Ecotoxicity freshwater	Influence on the function and structure of the ecosystem by exerting toxic effects (acute or chronic) on the organisms which live in it	Comparative Toxic Unit for ecosystems [CTU_e], expressing the potentially affected fraction of species integrated over time and volume per unit mass of a given chemical emitted	III	X		X	

Impact category	Details	Unit of Measure	Level of Rec.	Receptor		Scale of Impact	
				Environment	Health	Local, Regional	Global
Eutrophication freshwater	Eutrophication is an impact on the ecosystems from substances containing nitrogen or phosphorus. As a rule, the availability of one of these nutrients will be a limiting factor for growth in the ecosystem, and if this nutrient is added, the growth of algae or plants will be increased	Reference unit [freshwater: kg P; marine: kg N; mol N]	II	X		X	
Eutrophication marine				X		X	
Eutrophication terrestrial				X		X	
Ozone depletion	Decrease of stratospheric ozone layer as a consequence of man-made emissions of halocarbons (as CFCs and HCFCs), halons and other long-lived gases containing chloride and bromine	Reference unit [CFC-11]	I	X			X
Photochemical ozone formation - human health	Solvents and other volatile organic compounds are released to the atmosphere (e.g. by emissions from combustion processes), they are often degraded within a few days. The reaction involved is an oxidation, which occurs under the influence of light from the sun. In the presence of oxides of nitrogen ozone can be formed. NOx are not consumed during ozone formation, but have a catalyst-like function	Reference unit [kg NMVOC]	II		X	X	
Respiratory inorganics	Ambient concentrations of particulate matter are elevated by emissions of primary and secondary particulates.	Disease incidence due to kg of PM2.5 emitted	I		X	X	

The assessment of the potential impacts on environment and human health at local scale is performed at reference plant level.

As for the case of environment, impact categories selected present a medium-confidence level of recommendation, except for the ecotoxity freshwater impact category, which reports a low-confidence level of recommendation. With this premise, the assessment covers the entire methodology presented above, leading to the identification of receptors, associated sensitivity, and significance of environmental impacts. Each plant is located in a non-specific site and classes of typical receptors are considered. By definition, the assessment is thus baseline-independent.

As far as the assessment of local impacts on human health, it is observed that human health effects (cancer/non cancer) are associated with a low-confidence level of recommendation, photochemical ozone formation with a medium-confidence level of recommendations and respiratory inorganics, addressing the effects of particulate matters, with a high-confidence level. Thus, in this case, the assessment is limited to the analysis of the quantitative relevance of the potential impacts, while a detailed analysis of the potential receptors is not carried out. Also in this case, by definition, the assessment of the quantitative significance of the impacts is baseline independent.

It is worth mentioning that following some difficulties encountered during the implementation of the PEF pilot phase, ecotoxicity freshwater, and human cancer and non-cancer toxicity excluded from the list of mandatory impact categories. Then, the European Commission required an improvement of the quality and number of characterisation factors (Saouter E., 2018), which is now currently implemented in the PEF transition phase (i.e.: EF3.0), even though with a low-confidence level.

The provisions given by the authors in the manual for the USETox model for the evaluation of characterisation factors for human toxicity and freshwater ecotoxicity, adopted by the EF3.0 framework in its most updated versions, suggest to consider the factors a useful for a first assessment, but in case any substance should present high relevance it is recommended to verify the reliability of the chemical-specific input data for such substance and to improve the data quality (Fantke, 2015).

In terms of life cycle phases, the assessment is carried out only for the potential impacts of the operation phase is concerned, with specific reference to direct emissions released during the plant's operations.

The other phases responsible for direct emissions are exploration, stimulation, testing, and drilling, casing and cementing.

The exploration and stimulation phases, responsible for emissions associated with diesel combustion, are excluded from the analysis because, according to the LCA results, the contribution of these phases for all representative plants in each impact category is negligible.

During testing phase, direct emissions accounted derive from diesel combustion for electricity generation and from releases in atmosphere of CO_2 and other gases, depending on the chemical composition of the geothermal fluid and on the solubility of the gasses. However, considering that the availability of input data for modelling the testing phase is limited only at some clusters, that testing activities are typically characterized by a short period activity (in the order of days) and that the impact at plant level on lifecycle basis is minor, the testing phase is not considered in the environmental impact assessment analysis.

Direct emissions generated during drilling phase considered in this study are related to the use of diesel engines used during the drilling activities and do not account for any release of gas from the ground. The modelling of emissions during drilling derives from a single proxy, applied transversally to all the clusters, based on the number of wells, the well depth and less significantly on the well design.

Absolute LCA results at plant scale show that the drilling phase has negligible impact compared to the other phases in most of the impacts categories for the clusters characterized also by emissions to air during the operation phase. In addition, such activitity is characterized by a short duration in compared with the operation f the plants and, also, its effects are not peculiar of the geothermal development, but are well consolidated from the oil&gas sector. Thus, it is excluded from the LCA environmental impact analysis.

Finally, the construction of equipment, the maintenance and the replacement of the equipment phases have only indirect emissions associated with materials manufacturing and energy production, whose environmental effects are not connected to the local impacts, consequently they are excluded.

13.3.3 Potential Impacts on Environment

Based on the premise discussed in Section 13.3.1 and in Section 13.3.2, the following paragraphs detail the methodological approach used to develop the qualitative evaluation of potential environmental impacts of the different phases of the representative plants analyzed in the LCA.

As previously mentioned, the proposed methodology for the analysis of potential impacts on environment aims at estimating the significance of effects of the geothermal plants emissions on the receptors potentially occurring in the areas where geothermal applications are installed. The assessment is performed trough an analysis based on:

- definition and evaluation of receptors sensitivity;
- evaluation of the quantitative relevance of impacts derived from the LCA results, obtained for the case studies considered for each cluster;
- evaluation of the significance of each impact in the different scenarios.

The methodological approach is detailed in the following paragraphs.

Receptors Sensitivity Evaluation

In the previous section 6, the clusters definition has been carried out mapping the typical geological play encountered in Europe and selecting the most relevant and typical geothermal technologies. A representative plant has been defined for each cluster to validate the LCA results and to represent the full range of production categories present in Europe, allowing the results comparison of the geothermal plants emissions, connected to different operational and reservoir conditions.

In this paragraph, the receptors potentially impacted by the geothermal power plants activities are identified, considering the environment surrounding the representative plants identified for each cluster.

For this purpose, the representative plants are associated with real existing power plants in the respective cluster and the surroundings are studied based on satellite images. However, considering that this analysis is not aimed to analyze the potential impacts of a specific existing geothermal plants, the results of the analysis of the sourrandings are illustrated only for the sake of transparency, but do not affect the following steps of the interpretation.

The analysis shows that most of them are in rural or natural environment next to populated areas (usually towns or villages) and just few geothermal power plants are near parks or natural protected areas.

Through the above described process, the following typical potential receptors have been identified:

- urban and residential areas (anthropic receptors);
- industrial areas (anthropic receptors);
- parks and protected natural areas (natural receptors).

As discussed, the receptors are to be considered as typical and are not referred to the real applications of each cluster.

The potential receptors sensitivity has been assigned considering:

- importance/value of a resource/receptor which is generally evaluated based on the legal protection (defined on national and/or international requirements), the government policy, ecological value, historical or cultural value, stakeholder views and economic value;
- vulnerability of the receptor which is the ability to adapt to changes brought by the project and/or to recovery its ante-operam status. With regards to environmental receptors, the vulnerability can be identified based on:
    - a comparison with quality standards and baseline conditions assessed,
    - the role it plays/the services/uses it provides in the ecosystem and in the community,
    - its availability and/or the presence of an alternative resource/receptor of comparable quality/use (e.g.: a suitable technically or economically feasible alternative for water supply for the community, a suitable alternative for a specific habitat that supports the development of specific flora/fauna species, etc.),
    - the possibility to easily adapt to a new condition, move or replace it.
    - With regards to social and human receptors, their vulnerability and thus their ability to adapt to changes is function of the level of livelihoods assets (such as

health or education) or of the type and level of access to services, infrastructures structures and process to protect or improve their livelihoods.

The following Table 51 shows how, through a combination of vulnerability and importance/value, it is possible to assign the sensitivity.

Table 51: Assessment of sensitivity of receptors

Receptors Sensitivity				
		Importance / Value		
		Low	Medium	High
Vulnerability	Low	Low	Low	Medium
	Medium	Low	Medium	High
	High	Medium	High	High

According to the definitions previous described, a qualitative assessment of vulnerability and importance has been carried out in order to assign the sensitivity to the typical receptors, previously identified.

The importance has been evaluated considering the presence of regulations and government policy to protect human and natural receptors, according to their ecological and cultural value. To evaluate the vulnerability, the generic ante-operam conditions have been considered, along with how the power plants can potentially influence the previous environmental conditions.

In particular, the "urban and residential areas" receptors have a high importance, evaluated considering the European and national regulations to assess the air quality, but a low vulnerability considering that these areas are already deeply influenced by the antrophic emissions. The sensitivity of the urban and residential receptors is consequently medium.

The "industrial areas" receptor have a low importance and low vulnerability, because the environmental ante-operam conditions are affected by the anthropic activities, connected to industrial processes that may generate pollutant emissions, and there are not ecological or cultural values in these areas. Consequently, the receptor sensitivity is low.

The sensitivity of the receptors "protected natural areas" is high, due to the high vulnerability (the potential impact will be introduced in an uncontaminated environment) and to the high importance, because there are strict regulations to preserve the natural protected areas.

Table 52 summarizes the results for the sensitivity assessment for the typical receptors.

Table 52: Sensitivity of typical receptors

	Importance	Vulnerability	Sensitivity
Industrial Areas	Low	Low	**Low**
Urban Areas	High	Low	**Medium**
Parks and Protected Areas	High	High	**High**

Evaluation of Quantitative Relevance of Impacts

As previously mentioned, the quantification of the project pressures associated to the different clusters has been evaluated considering the LCA results, in order to assess the quantitative relevance of each impact.

To this end, the impact of an amount of electricity from the grid (EU electricity mix, medium voltage) equal to the amount of electricity produced by the reference plant is considered as benchmark for P-clusters and for P CHP-clusters in which electricity production exceeds thermal production.

Specifically, the impacts calculated for 1 kWh of electricity – calculated with the same LCIA method than the one applied across the study – are reported in Table 53 below:

Table 53: EU28: Electricity, medium voltage, 1 kWh

Impact category	
Acidification terrestrial and freshwater [Mole of H+ eq.]	1.22E-03
Ecotoxicity Freshwater [CTUe]	3.08E+00
Eutrophication freshwater [kg P eq.]	2.37E-04
Eutrophication marine [kg N eq.]	2.50E-03
Eutrophication terrestrial [Mole of N eq.]	1.22E-03

For the case of P CHP-clusters in which thermal production exceeds electricity production and for DHC clusters, the benchmark is identified as thermal energy produced from natural gas that is currently the most used energy source for residential space heating in Europe.

Specifically, the impacts calculated for 1 kWh of thermal energy – calculated with the same LCIA method as the one applied across the study – are reported in Table 53 below:

Table-54: EU28, Thermal energy from natural gas, 1 kWh

Impact category	
Acidification terrestrial and freshwater [Mole of H+ eq.]	1.89E-04
Ecotoxicity Freshwater [CTUe]	4.75E-02
Eutrophication freshwater [kg P eq.]	6.30E-09
Eutrophication marine [kg N eq.]	7.09E-05
Eutrophication terrestrial [Mole of N eq.]	7.81E-04

Then, the quantitative relevance of each impact category for each reference plant is derived by comparing the impacts associated with the electricity generation from geothermal energy and the impacts associated with electricity from grid supply. If the ratio between the impact of geothermal electricity and the correspondent impact for grid electricity is higher than 1, the quantitative relevance indicates that the environmental aspects related with the correspondent impact category should be carefully controlled and possibly reduced, as they may generate significant environmental impacts, depending on the specific receptor , if the ratio between the impact of geothermal electricity and the correspondent impact for grid electricity is lower than 0.5, the quantitative relevance indicates that the environmental aspects related with the correspondent impact category are quantitatively negligible, minimizing the arising of any impact; in all the other cases, the quantitative relevance indicates that the environmental aspects related with the correspondent impact category should be monitored, as certain environmental impacts may arise, depending on the specific receptor. Lastly, if the impacts for all the considered impact categories are zero for a cluster, the cluster is excluded from the assessment and it is considered not to lead to any local environmental concern within the boundaries considered for this analysis. The same approach is implemented for the assessment of quantitative relevance of impacts related to thermal energy production, with respect to conventional supply.The results of this assessment will be presented in section 0 below.

The quantitative relevance of the impacts, resulting directly from the amount of direct emissions to air during the operation phase, is thus influenced by:

- the local geology (e.g.: volcanic setting vs. sedimentary basin);
- the type of geothermal play (i.e.: volcanic vs. hydrothermal);
- the characteristics of the geothermal resource (e.g.: fluid composition, gas, content and composition, temperature, pressure);
- the type of production technology and operation plants parameters (e.g.: reinjection, presence or not of abatement systems).

Estimation of the Environmental Impacts' Significance

The match of the quantitative relevance of the environmental impact aims at deriving the significance of the impacts, as a crossing between the potential receptor sensitivity and the quantitative relevance connected to geothermal power plants' impacts. The matching criteria for the estimation of the significance of each impact based on the quantitative relevance of the impact and sensitivity of the receptor are shown in the Table 55.

Table 55: Significance of impact – Matching criteria

Significance of Impact				
		Sensitivity of the Environmental Compounds		
		Low	Medium	High
Quantitative Relevance of pressures (LCA results, geothermal/convetional energy)	<0.5	Negligible impact	Impact to be monitored	Impact to be monitored
	Between 0.5 and 1	Impact to be monitored	Impact to be monitored	Impact to be carefully analyzed and mitigated
	>1	Impact to be monitored	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated

Below, the methodology above-presented is applied to each cluster with the aim of outlining the potential criticalities and priority in each case. As previously discussed, only the representative plants presenting non-zero values for the impact categories covered by the analysis are reported.

Table 56 shows the significance of impacts for cluster 1P. Despite the presence of various direct emissions during operation, the only local environmental impact with quantitative relevance higher than 1 is represented by ecotoxicity freshwater, whereas the other impacts have a quantitative relevance below 0.5. This status is due to the presence of methane (in very low portion) and, mainly, hydrogen sulphide in the geothermal fluid, causing a certain amount of direct emissions during operation.

Depending on the sensitivity of the receptor, the significance of impacts indicates mostly that these are either negligible or to be minitored. Only, for the case of ecotoxicity freshwater, with receptor of medium and high sensitivity (i.e.: urban areas and protected natural areas), the impact can result as highly significant and should be be carefully analyzed and mitigated.

Table 56: Significance of impacts – 1P

Significance of Impacts – 1P	Quantitative Relevance	Sensitivity of Receptor		
		High	Medium	Low
Acidification terrestrial and freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Ecotoxicity freshwater	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored
Eutrophication freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication marine	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication terrestrial	<0.5	Impact to be monitored	Impact to be monitored	negligible

The results presented above are valid also for the case of cluster 1P CHPa and 1P CHPb.

Table 57 shows the significance of impacts for cluster 2P. Resulting from the properties of the geothermal fluid and the absence of abatement systems, the quantitative relevance is higher than 1 for acidification, ecotoxicity freshwater and eutrophication (terrestrial), medium for eutrophication (marine) and low only for eutrophication (freshwater). This results derive directly from the presence of ammonia, hydrogen sulphide (for the impact on ecotoxicity freshwater only) and methane (in very low share).

Depending on the sensitivity of the receptor, the significance of indicates that these should be either monitored or carefully analyzed and mitigated. Only, for the case of eutrophication freshwater, with receptor of low sensitivity (i.e.: industrial), the impact has low significance and is negligible.

Table 57: Significance of impacts – 2P

Significance of Impacts – 2P	Quantitative Relevance	Sensitivity of Receptor		
		High	Medium	Low
Acidification terrestrial and freshwater	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored
Ecotoxicity freshwater	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored
Eutrophication freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication marine	Between 0.5 and 1	Impact to be carefully analyzed and mitigated	Impact to be monitored	Impact to be monitored
Eutrophication terrestrial	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored

Table 59 shows the significance of impacts for cluster 3P CHP. It is observed that the quantitative relevance is lower than 0.5 for eutrophication (marine and freshwater), between 0.5 and 1 for acidification and terrestrial eutrophication due to the presence of ammonia emissions to air and higher than 1 for ecotoxicity freshwater, for a combination of hydrogen sulphide with mercury, arsenic and ammonia.

This leads to a delicate significance of impacts, which should be mostly monitored or carefully analyzed and mitigated. However, for the case of industrial areas as receptors, the significance of the impacts is either negligible or associated with monitoring actions.

It is highlighted that the quantitative relevance is evaluated with respect to the grid.

Table 58: Significance of impacts – 3P CHP

Significance of Impacts – 3P CHP	Quantitative Relevance	Sensitivity of Receptor		
		High	Medium	Low
Acidification terrestrial and freshwater	Between 0.5 and 1	Impact to be carefully analyzed and mitigated	Impact to be monitored	Impact to be monitored
Ecotoxicity freshwater	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored
Eutrophication freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication marine	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication terrestrial	Between 0.5 and 1	Impact to be carefully analyzed and mitigated	Impact to be monitored	Impact to be monitored

Table 59 shows the significance of impacts for cluster 4P. The quantitative relevance is dependent on the specific impact category: it is lower than 0.5 for the eutrophication (freshwater and marine), between 0.5 and 1e for acidification and terrestrial eutrophication and above 1 for ecotoxicity freshwater. The same considerations presented for the cluster above apply, as this picture results from a combination of effects the multiple emissions flows associated with this cluster.

Table 59: Significance of impacts – 4P

Significance of Impacts – 4P	Quantitative Relevance	Sensitivity of Receptor		
		High	Medium	Low
Acidification terrestrial and freshwater	Between 0.5 and 1	Impact to be carefully analyzed and mitigated	Impact to be monitored	Impact to be monitored
Ecotoxicity freshwater	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored
Eutrophication freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication marine	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication terrestrial	Between 0.5 and 1	Impact to be carefully analyzed and mitigated	Impact to be monitored	Impact to be monitored

Table 60: shows the significance of impacts for cluster 4P CHP. Quantitative relevance is lower than 0.5 for marine and freshwater eutrophication, between 0.5 and 1 for ecotoxicity freshwater and higher than 1 for acidification and terrestrial eutrophication. This results are very close to the situation already commented for cluster 4P above, and the same conclusions apply.

It is highlighted that the quantitative relevance is evaluated with respect to the grid.

Table 60: Significance of impacts–4P CHP

Significance of Impacts – 4P CHP	Quantitative Relevance	Sensitivity of Receptor		
		High	Medium	Low
Acidification terrestrial and freshwater	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored
Ecotoxicity freshwater	Between 0.5 and 1	Impact to be carefully analyzed and mitigated	Impact to be monitored	Impact to be monitored
Eutrophication freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication marine	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication terrestrial	>1	Impact to be carefully analyzed and mitigated	Impact to be carefully analyzed and mitigated	Impact to be monitored

Table 60: shows the significance of impacts for cluster 7P CHP. For all the impacts, the quantitative relevance is lower than 0.5, resulting in negligible impacts or impacts to manage by monitoring actions, depending on the receptor.

It is highlighted that the quantitiative relevance is evaluated with respect to the heat production.

Table 61: Significance of impacts – 7P CHP

Significance of Impacts – 7P CHP	Quantitative Relevance	Sensitivity of Receptor		
		High	Medium	Low
Acidification terrestrial and freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Ecotoxicity freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication marine	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication terrestrial	<0.5	Impact to be monitored	Impact to be monitored	negligible

Finally, for the case of DHC-clusters, Table 62 shows the significance of impacts for cluster 3DHC. As for the previous case presented, for all the impacts, the quantitative relevance is lower than 0.5, resulting in negligible impacts or impacts to manage by monitoring actions, depending on the receptor .

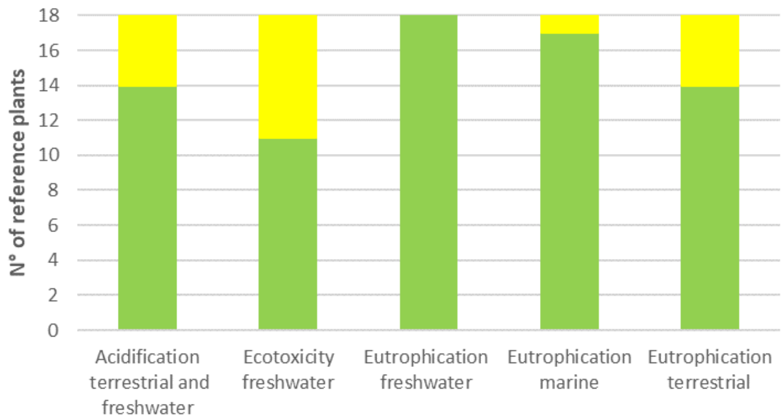
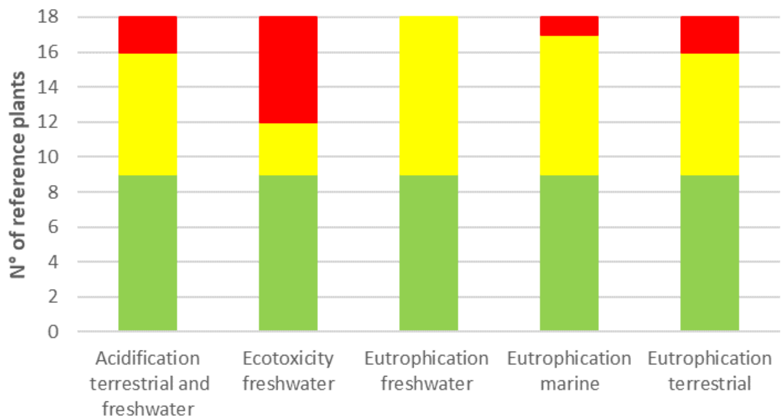
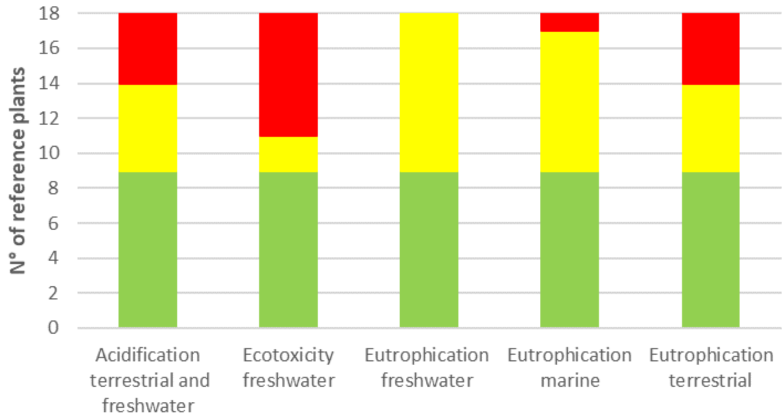
Table 62: Significance of impacts – 3DHC

Significance of Impacts – 3DHC	Quantitative Relevance	Sensitivity of Receptor		
		High	Medium	Low
Acidification terrestrial and freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Ecotoxicity freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication freshwater	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication marine	<0.5	Impact to be monitored	Impact to be monitored	negligible
Eutrophication terrestrial	<0.5	Impact to be monitored	Impact to be monitored	negligible

In order to summarize the information provided, and to provide an overall mapping about the significance of impacts on each environmental receptor - industrial areas, urban areas, natural protected areas Table 63 is presented.

Each graph shows, by impact, the number of clusters reporting a certain level of impact significance, for the respective receptor. For this assessment, the significance of impacts for the clusters that are not associated with direct emissions during operation is labeled as negligible.

Table 63: Significance of local environmental impacts

<table>
<tr><th>Sensitivity of Receptor</th><th>Significance of Impact</th></tr>
<tr><td>Low</td><td>
</td></tr>
<tr><td>Medium</td><td>
</td></tr>
<tr><td>High</td><td>
</td></tr>
<tr><td>Legend</td><td>Negligible Impact to be monitored Impact to be carefully analyzed and mitigated</td></tr>
</table>

It is clear that in most of the geo-technological configurations analysed impacts show low or medium significance, providing a positive basis for the development of geothermal energy. Specifically, in case of a local context with low sensitivity to environmental impacts, most of the clusters show low impacts significance, and only few of them medium values.

However, it shall be taken into consideration that if the sensitiveness of receptors increases in a few cases the significance of impacts reaches high values. Such situations are related with applications for power generation, typically characterized by high amounts of non-condensable gases in the geothermal fluid, combined with the presence ammonia emissions to air. Moreover, the additional presence of hydrogen sulhpide and heavy metals air emissions is relevant for some specific impact categories, ecotoxicity freshwater in particular. As a result, in case the emissions are simultaneous caution should be put to ensure sustainable energy exploitation.

The most likely environmental impact is represented by ecotoxicity freshwater, which has a high significance for medium and high receptor sensitivity in a number of reference plants. Acidification and marine and terrestrial eutrophication became relevant especially in the proximity of natural protected area, while they remain confined to one high significance case for urban areas. As for marine eutrophication, only one reference plant leads to high significance in areas with medium and high sensitivity. Finally, it is observed that the eutrophication freshwater impact category, dominated by indirect emissions, does not generate any concerns deriving from air emissions at local level.

13.3.4 Potential Impacts on Human Health

In coherence with the methodology proposed for the evaluation of the significance of local impact on the environment, this section aims at providing a qualitative simplified approach to propose an interpretation of the LCA results on potential impacts on human health at local scale.

In particular, the next sections describe:

- the potential impact on human health connected to the emissions to atmosphere, focusing on the compounds emitted from the geothermal power plants considered in the LCA inventory, through the analysis of several literature texts;
- a qualitative comparison of the LCA results with the range values obtained for the same power plants typology considered for the environmental impacts analysis to assess the magnitude of impacts of each cluster.

Preliminary Assessment of the Potential Impact on Human Health

Although geothermal energy is generally considered a clean and sustainable energy source, geothermal industrial development may produce impacts both on the environment and human health (Manzella et al., 2018).

Among other effects, effusions from geothermal plants may occur if the produced geothermal fluids contain polluting elements and in case they are not completely contained and treated in order to avoid the contact with air, water and soil. In general, the potential emissions into the air include carbon dioxide, hydrogen sulfide, hydrogen, ammonia and methane, radon, volatile metals, silicates, carbonates, metal sulfides and sulfates and traces of mercury, arsenic, antimony, selenium and chromium (Shortall et al., 2015). CO_2

and CH_4 emissions are generally lower compared to the emissions from carbon and fossil fuel-based plants, but they can impact the environment and contribute to climate change (Somma et al., 2017). Indeed, in fluids containing non condensable gases, CO_2 is the most abundant and its emission from some geothermal electricity plants is not negligible (Ármannsson et al., 2005).

The representative geothermal power plants, considered for each cluster in the LCA analysis, are characterized (if applicable) by the following main pollutant elements emissions:

- carbon dioxide;
- methane;
- hydrogen sulfide;
- nitrogen;
- ammonia;
- mercury;
- arsenic;
- sulphur dioxide.

Among them, methane, ammonia, mercury, arsenic and sulphur dioxide emissions are associated with potential impacts on human health in the LCA models developed for this study.

Ammonia is a colourless toxic gas with a characteristic pungent odour, soluble in water and is essential in the chemical turnover cycle of the soil because it provides nitrogen, one of the three main nutritional elements of plants and animals. Negative effects on human health derive by direct contact with this element, and can cause skin burns, lung damage[17].

Methane, at normal environmental concentrations, has no impacts on human health but at extremely high (artificial) concentrations in an enclosed space the reduction in oxygen levels could lead to suffocation.

Mercury occurs naturally in the earth's crust. It is released into the environment from volcanic activity, weathering of rocks and as a result of human activity.It is found in mineral form or in very small metal droplets. Since it is volatile, mercury vapour can be transported into the atmosphere and transformed into the very toxic methylmercury in animal organisms, also reaching the human food chain (Manzella et al. 2018).

Arsenic is an extremely toxic and carcinogenic substance, found in many organic and inorganic compounds, and in different oxidation states due to its high reactivity. Arsenic

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[17] web site ARS Toscana, https://www.ars.toscana.it/home-geotermia-e-salute.html

emission into the atmosphere is frequent during volcanic eruptions, but rare in geothermal manifestation. Wherever present in geothermal fluids, arsenic remains in the aqueous phase and can be easily reinjected. The effects of a long term exposure to arsenic can cause damage and possible tumor to skin, liver, bladder, prostate, kidney, lung. The main way of exposure is connected with ingestion of food and water contaminated with arsenic (web site ARS Toscana).

In addition to the general considerations above-presented, the issue of the potential effects of geothermal applications on human health deserves a few punctual specifications.

Firstly, it should be highlighted that there is ongoing debate with specific reference to the available characterisation methods anda factors for substances with impacts on toxicity, highliting difference limitations also in the most updated and well accepted characterisation models with specific reference to metal flows (Zampori L. et al., 2016; Saouter E. et al., 2018; Gerbinet at al., 2019; Parisi et al., 2019; Ferrara et al., 2019). In the adopted LCIA method, the characterisation factors for metals are indeed corrected using uncertainty factors, the impact assessment should be interpreted with caution (Saouter E. et al., 2018; Fazio, S. et al., 2018).

As a second major issue proposed, as already discussed to fairly address the effects of the AMIS abatement system used in some power applications, it must be observed that the flow of H_2S is not associated to any characterisation factor, expect for ecotoxicity freshwater, resulting thus as an uncharacterized flow with respect to human health impact categories.

The toxicity and foul smell of hydrogen sulfide creates one of the main environmental problems associated with geothermal utilisation (Gunnarsson et al., 2011) and it is the only emission probably causing the greatest human health concern in moderate concentrations (Kristmannsdóttir and Ármannsson, 2003).

However, it is well-known that effects of H_2S on human health can be very severe. The H_2S is a toxic gas, formed in anaerobic environments and unstable in oxidizing environments, it occurs in volcanic emissions, hydrothermal manifestations and geothermal fluids, and wherever anaerobic decomposition of organic substances occurs. H_2S produces severe health effects including eye irritation, loss of smell, pulmonary edema, and loss of respiration (WHO, 2000). In general terms, low level, prolonged exposure can cause inflammation and irritation of the eyes whereas high levels of exposure for brief periods of time can cause dizziness, headache, nausea and even death (Gunnarsson et al., 2011).

Reported effects from short-term inhalation exposure to high concentrations of hydrogen sulfide include death and respiratory, ocular, neurological, cardiovascular, metabolic, and reproductive effects. Respiratory, neurological, and ocular effects are identified as the most sensitive end-points in humans following inhalation exposure (Selene J. Chou, 2003).

Table 64 summarizes the observed effects of exposure to H_2S and correspondent level of concentration.

Table 64: Human health effect resulting from exposure to H_2S (Karapekmez et Dincer, 2017)

Exposure (mg/m^3)	Effect/Observation
0.011	Odor threshold
2.8	Bronchial constriction in asthmatic individuals
5.0	Increased eye complaints
7.0–14.0	Increased blood lactate concentration, decreased oxygen uptake
5.0–29.0	Eye irritation
>140	Oldfactory paralysis
>560	Respiratory distress
≥700	Death

The World Health Organisation (WHO) guidelines for the protection of human health recommend the following tolerable values:

- 150 µg/m³ average concentration over a period of 24h;
- 100 µg/m³ over a period of 14 days;
- 20 µg/m³ over a period of 90 days (WHO, 2000).

As for the current development status of geothermal projects in Europe, as well as quite solid awareness about health and safety requirements, the matter of short-term exposure to H_2S is not of high concern and priority for the normal operation of the geothermal applications. Monitoring activities, where present, confirm that the concentration limits set by the WHO are normally not exceeded, at least where measurements stations are available (Minichilli et al, 2012; ARPAT Toscana[18]; Finnbjornsdottir et al. 2015; Carlsen at al., 2012).

On the other hand, information about long-term exposures to hydrogen sulfide is scanty and retrivable findings are not always statistically significant.

Generally, chronic exposure to low level concentrations of hydrogen sulfide is associated with neurological symptoms that include fatigue, loss of appetite, irritability, impaired memory, altered moods, headaches, and dizziness (McGavran, 2001) or inflammation and irritation of the eyes (Gunnarsson et al., 2011), but the need for epidemiological studies on possible effects of longterm, low-level hydrogen sulfide exposure is highlighted in various research studies (WHO, 2000; Skrtic, 2006; Legator et al.2010) and also the fragmentation and non-coherence of available information is encountered (Lewis et Copley, 2014; Nuvolone et al., 2018; Bustaffa et al., 2019). Indeed, there are are no adequate data on carcinogenicity and no toxicity data exist on medium- or long-term exposures of humans to low levels of hydrogen sulfide. This kind of data is of priority for evaluating health risks of exposure to hydrogen sulfide for populations living in the vicinity of

[18] http://www.arpat.toscana.it/temi-ambientali/sistemi-produttivi/impianti-di-produzione-di-energia/geotermia/monitoraggio-qualita-dellaria/ar_areegeotermiche.html

hazardous waste sites and other potential sources of Hydrogen sulfide, such as hot springs and wastewater treatment plants (Selene J. Chou, 2003).

The general lack of knowledge about the effects of long-term exposure to low concentrations of H_2S affects also the possibility of assessing the effects of H_2S emissions encountered in some geological fields. As a matter of fact, the toxic effect of H_2S in geothermal field is not well modelled and documented yet in the literature, although the reduction of H_2S emission represents an important issue for the resident population (Parisi et al., 2019).

In the latest years, sensitivity to the issue seems to be increasing. Even though, currently, air quality regulations at European level[19] do not include this substance within the paramenters to be reported, some Countries and Regions presenting potential criticalities related to hydrogen sulphide concentrations in atmosphere have already developed specific legislations (Iceland, Tuscany region) to keep H_2S emissions deriving from geothermal applications at controlled and acceptable levels. Local resulations have thus resulted as strong drivers for the development and installations of hydrogen sulphide abatement systems such as the Sulfix pilot (Juliusson et al., 2015).

In parallel, environmental and epidemiological studies are trying to spread light on the chronic effects of H_2S exposure and to address potential criticalities highlighted in past research works. Mentioning a few examples, some associations between increased H_2S exposure and human health have been found, as well as evidence of exposure-related trends for respiratory disease (Nuvolone et al. 2018).

Still, methodological limitations exist and no evidence for wide generalisation of spare results obtained seems to be applicable. The pursue of robust findings remains as a priority and should benefit from the support of prosecution and the systematisation of health surveillance and human biomonitoring activities associated with permanent control of atmospheric emissions from both industrial and natural plants (Bustaffa et al. 2017; Bustaffa et al., 2020).

Having in mind the uncertainty and the fragmentation fo the panorama above-presented, it is clear that it is not reasonable to derive robust conclusions about the effects of the H_2S emissions mapped for this study, even though raw inventory data (and not LCIA results) were considered.

For future developments, it is auspicable that health effects of H_2S emissions typical of geothermal applications are further investigated and robustly understood. On this basis, a more tailored legislative framework may be enforced and extended coherently at European level. As for current knowledge, the approach of the limits set by existing regulations seems to be a reasonable precaution derived from the WHO limits rather than a scientifically motivated threshold. Nevertheless, an enforcement and monitoring of air quality with respect to H_2S concentration is surely an enabler of development of mitigation measures.

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[19] https://ec.europa.eu/environment/air/quality/existing_leg.htm

Finally, when solid information will be gained, the existing LCA methodologies should be updated to take into account the potential impacts related to this substance, to the extent of the typical application of the LCA analyses.

Evaluation of Quantitative Relevance of Impacts

As previously implemented for the environmental impacts, the evaluation of quantitative relevance of potential impacts on human health is carried out with reference to the impacts calculated for electricity grid supply and for thermal energy from natural gas, considering the amount of energy produced during each plant's lifecycle. The methodology to assess the relevance is the same reported for the environmental impact categories.

Considering what previously discussed, it is highlighted that H_2S emissions do not influence the assessment below, as they are not accounted. Punctual considerations about these emissions would possibly lead to some different findings. For the sake of completeness, the occurring presence of H_2S in clusters is specified.

Specifically, the impacts calculated for 1 kWh of electricity – calculated with the same LCIA method than the one applied across the study – are reported in Table 63 below:

Table 65: EU28: Electricity, medium voltage, 1 kWh

Impact categories	
Cancer human health effects [CTUh]	1.44E-10
Non-cancer human health effects [CTUh]	2.64E-09
Photochemical ozone formation - human health [kg NMVOC eq.]	6.57E-04
Respiratory inorganics [Disease incidences]	1.01E-08

The impacts calculated for 1 kWh of thermal energy – calculated with the same LCIA method than the one applied across the study – are reported in Table 64 below:

Table 66: EU28, Thermal energy from Natural Gas, 1 kWh

Impact categories	
Cancer human health effects [CTUh]	2.58E-10
Non-cancer human health effects [CTUh]	1.60E-10
Photochemical ozone formation - human health [kg NMVOC eq.]	2.16E-04
Respiratory inorganics [Disease incidences]	1.78E-09

The following tables show results of the qualitative comparison above described for each cluster and impact category. The analysis is reported only for the clusters associated with direct emissions, whereas when direct emissions are zero, the analysis is not performed.

Table 67 shows the results of the analysis for cluster 1P. The relevance of the impact is lower than 0.5 for all the considered impact categories, despite the presence of some air emissions during the operation of the plant.

It is highlighted that this cluster is associated also with H_2S emissions during operation.

Table 67: Quantitative relevance of impacts–1P

Impact	Quantitative Relevance
Cancer human health effects	<0.5
Non-cancer human health effects	<0.5
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	<0.5

The results presented above are valid also for the case of cluster 1P CHPa.

Table 68 shows the results of the analysis for cluster 1P CHPb. The relevance of the impact is lower than 0.5 for all the considered impact categories, except for human toxicity – non cancer effects that shows a quantitative relevance between 0.5 and 1. This results is due to the presence of methane emissions during operation.

It is highlighted that this cluster is associated also with H_2S emissions during operation.

Table 68: Quantitative relevance of impacts-1P CHPb

Impact	Quantitative Relevance
Cancer human health effects	Between 0.5 and 1
Non-cancer human health effects	>1
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	<0.5

Table 69 shows the results of the analysis for cluster 2P. The relevance of the impact is lower than 0.5 for all the considered impact categories, except for respiratory inorganics that shows a quantitative relevance highe than 1. This result is due entirely to ammonia emissions associated with the operation phase.

It is highlighted that this cluster is associated also with H_2S emissions during operation.

Table 69: Quantitative relevance of impacts – 2P

Impact	Quantitative Relevance
Cancer human health effects	<0.5
Non-cancer human health effects	<0.5
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	>1

Table 70 shows the results of the analysis for cluster 3P CHP. The quantitative relevance is lower than 0.5 for all the impact categories, except for non-cancer human toxicity due to the presence of mercury and arsenic emissions during operation.

It is highlighted that this cluster is associated also with H_2S emissions during operation and that the quantitative relevance is evaluated with respect to the grid.

Table 70: Quantitative relevance of impacts – 3P CHP

Impact	Quantitative Relevance
Cancer human health effects	<0.5
Non-cancer human health effects	>1
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	<0.5

Table 71 shows the results of the analysis for cluster 4P. The quantitative relevance is lower than 0.5 for photochemical ozone formation and respiratory inorganics, between 0.5 and 1 for human toxicity (cancer effects) and higher than 1 for human toxicity (non cancer effects). As in previous case, these increases in relevance are mainly caused by heavy metals emissions to air.

It is highlighted that this cluster is associated also with H_2S emissions during operation.

Table 71: Quantitative relevance of impacts – 4P

Impact	Quantitative Relevance
Cancer human health effects	Between 0.5 and 1
Non-cancer human health effects	>1
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	<0.5

Table 72 shows the results of the analysis for cluster 4P CHP. The quantitative relevance is lower than 0.5 for photochemical ozone formation, between 0.5 and 1 for human toxicity (cancer effects) and respiratory inorganics, higher than 1 for human toxicity (non cancer effects). As in previous case, effects on human toxicity are mainly caused by heavy metals emissions to air, whereas the medium relevance of respiratory inorganics is caused by ammonia.

It is highlighted that this cluster is associated also with H_2S emissions during operation and that the quantitative relevance is evaluated with respect to the grid.

Table 72: Quantitative relevance of impacts – 4P CHP

Impact	Quantitative Relevance
Cancer human health effects	Between 0.5 and 1
Non-cancer human health effects	>1
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	Between 0.5 and 1

Table 73 shows the results of the analysis for cluster 7P CHP. The relevance of the impact is lower than 0.5 for all the considered impact categories, despite the presence of some air emissions during the operation of the plant.

It is highlighted that the quantitative relevance is evaluated with respect to heat production.

Table 73: Quantitative relevance of impacts – 7P CHP

Impact	Quantitative Relevance
Cancer human health effects	<0.5
Non-cancer human health effects	<0.5
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	<0.5

Table 74 shows the results of the analysis for cluster 3DHC. The relevance of the impact is lower than 0.5 for all the considered impact categories, expect for human toxicity – non cancer effects, because of the presence of methane air emissions during operation.

Table 74: Quantitative relevance of impacts – 3DHC

Impact	Quantitative Relevance
Cancer human health effects	<0.5
Non-cancer human health effects	>1
Photochemical ozone formation - human health	<0.5
Respiratory inorganics	<0.5

In order to summarize the information provided, and to provide an overall mapping about the quantitative relevance of impacts related to human health, Figure 66 is presented. Specifically, it shows, the number of clusters reporting a certain value of quantitative relevance, by impact category. For this assessment, the quantitative relevance of impacts for the clusters that are not associated with direct emissions during operation is labeled as negligible.

It is worth noticing that among the clusters proposed, seven are associated with H_2S emissions.

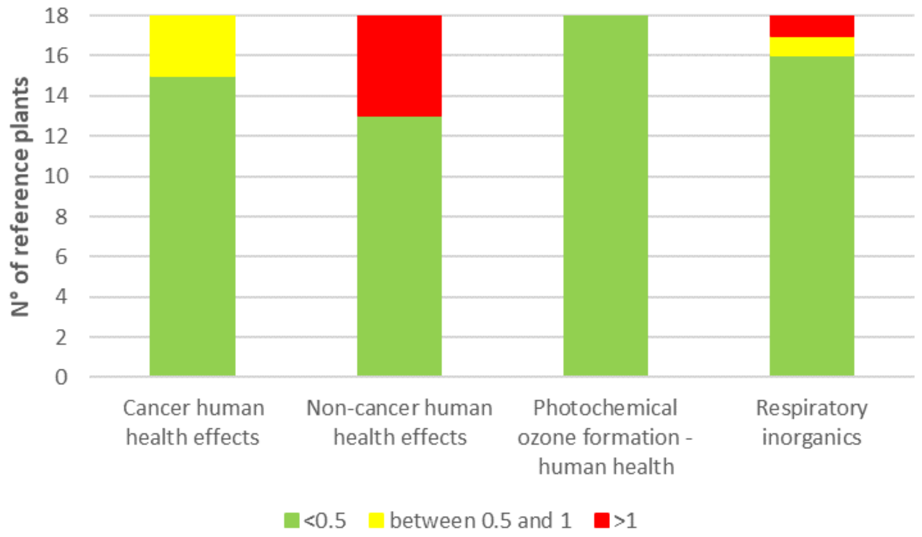

Figure 66: Quantitative relevance of impacts on human heath

It appears that in most conditions, the quantitative relevance of potential impacts on human health is low. In rare cases, high relevance is reached in a limited number of reference plants, with respect to human toxicity (non-cancer effects) and respiratory inorganics impact categories. Such result is associated with plants for power generation where air emissions of ammonia, as the major contributor to the respiratory inorganics impact category, and heavy metals (and ammonia and methane in more limited share), as major contributor to the human toxicity (non-cancer effects) impact category are present.

MAIN OUTCOMES AND RECOMMENDATIONS

This chapter summarizes the main outcomes derived from the calculation performed in this studies and lists the recommendations proposed for the for the enhancement of the deep geothermal sector In Europe.

14 MAIN OUTCOMES

The present study falls within the outstanding need of a clear and comprehensive assessment of the emissions from deep geothermal plants and applications, and the potential impact of their emissions, based on a life cycle approach methodology applied at sector level.

With the aim of representing the characteristics of each unique geothermal reservoir and the numerous technological options to produce and utilize geothermal energy, power plants and district heating applications existing in Europe have been clusterized depending on a selection of geological/geographical parameters and technological parameters.

In parallel, a dedicated focus on Sector Category Rules, setting guidelines and requirements for the development of LCA analyses at cluster level in the geothermal sector has been developed to provide methodological basis for the LCA analyses to be carried out.

As a subsequent step, a set of proxies have been modeled in order to estimate homogeneous and consistent inventory input and output flows at plant level, having identified for each cluster a representative plant size and typology. The inventory data have been compared against primary data whenever available from literature or from direct contact with plant operators.

From a robust self-assessment of data quality for the implementation of the LCA, the overall rate ranges from medium to high, depending on the specific cluster, except for cluster 1DHC, cluster 2P and for some aspects of cluster 6P.

Finally, LCA results have been generated. For comparability purposes, it is highlighted that such results are based on the following high level assumptions:

- functional unit: 1 kWh of net energy produced;
- lifetime of the plant: 30 years;
- life cycle phases included: testing, exploration, stimulation, drlling, casing and cementing, manufacturing of building and equipment material, operation, ordinary maintenance during operation activities, replacement of construction material;
- direct emissions during plants' operation included in the inventories (whenever applicable): carbon dioxide, methane, hydrogen sulphide, nitrogen, ammonia, mercury, arsenic, sulphur dioxide;
- characterisation method: Environmental Footprint 3.0.

Overall, quantitative results show a great variability. Such variety is due to the intrinsic nature of the clusters, which determines the type and amount of emissions associated with energy production for each representative plant, as well as the technologies that are in place to reduce or avoid the amount of emissions (such plant as configuration itself, reinjection and abatement system). In addition, it results directly from the uncertainty of the data available and calculated.

For the case of **P-clusters**, the analysis of the results leads to the identification of a set of highlights across the representative plants for each cluster. In order to provide a clear representation of the findings and for the sake of coherence with intrinsic features of the cluster and respective representative plants, the behavior is discussed separately for the case of clusters associated with low NCG content (5P, 5P CHP, 7P CHP, 8P, 8P CHP), with moderate NCG content, including H_2S emissions to air and potentially limited heavy merals emissions (1P CHPa, 1P CHPb), with high NCG content (6P), with high NCG content, including H_2S, NH_3 and potentially limited heavy merals emissions (1P, 2P) and – finally - with high NCG content, including H_2S, NH_3 and heavy metals emissions to air (3P CHP, 4P, 4P CHP).

Specifically, the following information can be drawn:

- **direct emissions** during operation phase represent the most influencing factor on the environmental performance of geothermal applications. Depending on the nature of the emissions generated, which is in turn dependent on the composition of geothermal fluid and the characteristics of the reservoir, different impact categories are affected.

  For the case of clusters associated with low NCG content, in which binary technology is used in combination with the application of pressure higher than the bubble point, there are not direct emissions. Usually, such situation is encountered in extensional fault-controlled, intracratonic and orogenic geological plays.

  In all the other cases, the presence of at least carbon dioxide emissions – deriving from the intric nature of geothermal areas and geothermal energy exploitation, rather than from combustion processes as the case of other forms of energy generation - is registered, possibly complemented by other substances. Thus, the global warming potential increases significantly as the amount of NCG gases is increased. It is highlighted that also minor presence of methane can lead to visible increase of this indicator.

  For the other impact categories, the behavior is regulated by the occurring types of emissions.

  The presence of H_2S – significant especially for clusters with moderate NCG contents among those considered – affects the impacts on ecotoxicity freshwater. The presence of NH_3 has predominant effects on acidification, eutrophication (marine/terrestrial), as well as respiratory inorganics effects. Finally, the presence of heavy metals emissions, determines the results for human toxicity (cancer and non cancer effects); however, if direct air emissions during operation are low, their effect may not be predominant for these categories. It is clear, that a combined presence of multiple substances leads to a decrease of environmental performance not only in terms of impacts' magnitude, but also in terms of types of impacts generated.

- effects of **drilling operations** during plant construction are negligigle for those impact categories influenced by direct emissions during operation of the plant.

  For the case of clusters associated with low NCG content, resulting in the absence of direct emissions during operation, drilling is the most significant phase for all the impact categories except for cancer and non-cancer effects.

  Conversely, for clusters reporting not only GHG gases emissions, but also other substances such as mainly ammonia, hydrogen sulphide and heavy metals, its effect is always negligible or low in the impacts categories affected by direct emissions (see first point).

- the **use of chemicals** for prevention and treatment of scaling and corrosion and for fluid treatment, leads to an increase especially visible for cancer effects, ecotoxicity, freshwater eutrophication, marine eutrophication, ozone depletion and photochemical ozone formation;

- the **manufacturing of construction materials** is significant for cancer and non-cancer effects, being the only relevant parameter for these categories when there are not additional effects from direct emissions during operation. This is especially related to the presence of some types of metals and plastics;

- **exploration, testing and stimulation** can be considered as negligigle for this life-cycle based assessment.

It is worth mentioning that cluster 6P has a stand alone behavior when quantitatively analyzing the results, even though the general behavior can be classified together with the other plants. It is characterized by direct emissions affecting the global warming impact category, but it is highlighted that data quality for this cluster is less robust than in the other cases and, thus, major conclusions should be drawn only after a further round of proper data and results validation.

For the case of heat production in **CHP-clusters**, the nature of the impacts reflects what is already discussed above for electricity production of the same clusters, due to the allocation procedure. Overall impacts are generally lower than those calculated for heat production in DHC-clusters, except for the case where direct emissions are registered.

For the case of **DHC-clusters**, applications report in general lower potential impacts than power clusters, mainly because direct emissions of non-condensable gases during operation are encountered only in cluster 3DHC, associated with partial degassing to the atmosphere. For the sake of transparency it shall be highlighted that in this cluster, some plants have flaring and combustion abatement systems, but they are not accounted for in the study due to lack of specific data.

Specifically, the following information can be drawn:

- **direct emissions** characterize the results of global warming potential and photochemical ozone formation for cluster 3DHC, due to the presence of methane in the geothermal fluid;

- **drilling operations** are predominant in the case of ecotoxicity, freshwater eutrophication, terrestrial eutrophication, ozone depletion and respiratory inorganics, due to diesel combustion and drilling waste treatment, depending on the specific category;

- **electricity consumption for fluid pumping** plays a non-negligible role on the overall performance of the clusters where pumping is needed to lift the fluid, but is pumped. It contributes to abiotic potential, cancer effects (in minor proportion), global warming potential, ecotoxicity, freshwater eutrophication, marine eutrophication, terrestrial eutrophication and photochemical ozone formation;

- as for the case of P-clusters, the performance of cancer and non-cancer effects is related to the **manufacturing of construction materials** and the use of **chemicals** for scaling and corrosion control or for generic fluid treatment can lead to significant effects in ecotoxicity, freshwater eutrophication and ozone depletion;

- **exploration, testing and stimulation** can be considered as negligigle for this life-cycle based assessment.

After having elaborated and analyzed the final quantitative results, their interpretation allows to derive robust conclusions and recommendations to support policy makers, providing them with comprehensive and understandable information to guide the indentification of priorities to ensure a sustanaible development of the geothermal sector in Europe. Correlated also with information available from non-LCA studies (e.g.: epidemiological, dispersion analyses, air quality monitoring, etc.), such indications will provide a robust direction for policy making and identification of best practices.

The extent and validity of the conclusions that can be drawn from this study are determined by the intrinsic features of the LCA analysis and of the LCIA method selected, in terms of applicability, validity and robustness, as well as the boundaries and the level of detail set within the study itself to meet the time-schedule and scale foreseen for the activity.

Considering that existing main concerns about the exploitation of geothermal energy are associated with potential impacts arising from direct emissions and operation of the plants, the focus of the interpretation is on the local scale, covering potential impacts on environment and human health. The methodology proposed to present a systematic and structured interpretation is derived from well-established techniques for impact assessment and management of environmental impacts.

Specifically, the significance of environmental impacts – providing indication about the priority of the associated concern – is assessed based on a combination of two factors: quantitative relevance with respect to conventional energy supply (i.e.: electricity from grid and thermal energy from natural gas) and sensitivity of receptor, considered high for natural protected areas, medium for urban areas and low for industrial areas. In the most severe scenario (i.e.: plants in the proximity of natural protected areas), the majority of the plants is associated with low or medium significance of impacts, but limited concerns arise for impacts on ecotoxicity freshwater, followed by acidification and terrestrial eutrophication, in which a few plants are associated with high significance of impacts. Conversely, in the scenario of plants in the proximity of industrial areas, none of the reference plants shows high values of impacts significance. Thus, it is clear that in most of the geo-technological configurations analysed impacts show low or medium significance, providing a positive basis for the development of geothermal energy.

As for the case of human health, the assessment is focused on the quantitative relevance of potential impacts, with reference to conventional alternative energy supply as in the previous case. In most conditions, the quantitative relevance of potential impacts on human health is low. In rare cases, high relevance is reached in a limited number of reference plants, with respect to human toxicity (non-cancer effects) and respiratory inorganics impact categories. However, it shall be highlighted that health effects of hydrogen sulphide emissions, present in a limited number of cases, are not captured (or properly captured) by the current LCIA methods. Even though urgent concerns about the well-known short-term effects of these emissions on human health can be reasonably excluded in the European context, as monitored hydrogen sulphide concentrations in areas of geothermal applications are well below the limits given by the World Health Organisation, a clear understanding of effects of long-term exposure to low concentration of this substance is missing at scientific level. Overcoming this knowledge gap in the near future would provide solid information to address existing concerns also in the geothermal sector.

Finally, it is worth mentioning that the extent and validity of the main outcomes drawn from this study are determined by the intrinsic features of the LCA analysis and of the LCIA method selected, in terms of applicability, validity and robustness, as well as the boundaries and the level of detail set within the study itself to meet the time-schedule and scale foreseen for the activity, against the ambitious target of the study of providing an overview and analysis of the emissions deriving from main existing geothermal applications for electricity and heat production.

15 RECOMMENDATIONS

The present study has provided a comprehensive overview of geothermal plants' and applications' emissions[20], allowing to draw preliminary conclusions about the potential impacts of deep geothermal energy exploitation in Europe.

Based on the main outcomes of the study, a set of recommendations for the enhancement of the deep geothermal sector in Europe has been identified. Such recommendations are not limited to the technical and technological sphere, but also include non-technical aspects that are crucial to pave the way towards a solid and widely accepted development of a low-impact geothermal sector, focusing also on application of Life Cycle Assessment for the geothermal sector.

[20] direct emissions during plants' operation included in the inventories (whenever applicable): carbon dioxide, methane, hydrogen sulphide, nitrogen, ammonia, mercury, arsenic, sulphur dioxide

Acknowledge the role of geothermal as a renewable energy source to fight climate change and understand the variability of environmental performance within the geothermal sector

The results calculated for this study show that almost half of power generation capacity installed in Europe and over 75% of the installed capacity for district heating covered by this study[21] (representing in turn 85% of the total capacity for district heating in Europe) presents greenhouse gas emissions lower than 100 gCO_{2e}/kWh (electrical/ thermal).

In addition, it should be mentioned that heat production from geothermal energy often constitutes and alternative to heat produced by fossil fuels sources (which represent 80% of the heat consumption today in Europe), thus contributing to the increase of the share of renewables in heating and cooling systems.

This study has analysed a large and representative sample of geothermal installations in Europe relying on a homogeneous and coherent approach.The results show a large variability that derives not only by an intrinsic uncertainty of the data and the models used for this study, but is primarily dependent on the geological features of each cluster/site and, in second place, on the technologies implemented.

Thus, in order to guarantee a fair development of the sector, inclusive of all the solutions already established nowadays, the diversity and peculiarity of each situation should be taken into account. In this sense, policy making, funding initiatives, financial instruments, technological developments, market maturity and conditions shall be fairly addressed to cover the highlighted variability.

For the same reason, relying on general considerations at sector level should be done only if sustained by carefully framed and solid objective results.

Improve data availability and data sharing

Data availability and accessibility have constituted a challenging aspect of this study. Although several databases about geothermal applications exist, the retrivable information is extremely fragmented. Data are often published only in national languages, making hard to find them and to use them properly. Additionally, data are reported with various degree of uncertainty, different units and different ways of measuring. It is obvious that in some cases this leads to misinterpretation of reported quantities. In the current study, as much as possible information was collected for each cluster but for some clusters it was simply not possible to find more than mean values or one single published data. Also, it cannot be excluded – considering the macro-geological features of some European areas – that considering the lack and fragmentation of regulations for geothermal plants' emissions, some types of emissions are not tracked at all, resulting as completely unknown data at current status.

A harmonisation of available information and a standardisation of data to be collected at international scale should be promoted to facilitate robust and homogeneous scientific

[21] excluding cluster 1DHC for which calculations are not performed

outcomes for the environmental assessment of the geothermal sector and to improve and validate the quality of subsequent mapping activities.

Harmonize and promote best practice

For numerous industrial sectors the European Union promotes the developement of Best Available Techniques Reference Documents (BREF), to be used by competent authorities in EU countries when issuing operating permits for industrial installations that represent a significant pollution potential, but also by interested stakeholders to retrieve practical information about best available techniques for pollution control and prevention, as well as emerging techniques.

The geothermal sector encloses some peculiar situations to be addressed in future development. Thus, it is advisable to collect and harmonize the large amount of scientific knowledge in a reference document. Indeed, this study has highlighted the lack of homogeneous information to assess the performance of single geothermal installation, starting from technical parameters. In addition, this fact is worsen by the absence of homogeneous implementations for a specific legislative framework at European level.

Use complementary assessment methods and tailor LCA methodology for geothermal applications

The complexity of the geothermal sector and its multiple implications on different receptors make of paramount importance the selection of analysis tools that are suitable and effective towards the desired purpose. As an example, Life Cycle Assessment is undoubtedly among the most widely appreciated methodologies for assessment of the environmental performance of a product or a process (in this case, energy generation). However, while being effective in highlithing the critical hotspots of processes and addressing sustainable design in future projects, it cannot be robustly relied upon for analyses aimed at the characterisation of local effects of geothermal plants on both environment and human health, as it may fail to catch impacting mechanisms related to specific substances. This issue is related on the usual application of the tool, very often focused on only a limited numbers of well-known impact categories and on the scientific gap existing for a full characterisation of all the potential impacts of each substance.

Within the extent of its applicability, in order to ensure consistent and systemathic application of the LCA methodology to the geothermal sector, sectoral guidelines with minimum standards shall be adopted at European level, to ensure comparability and consistency across the studies performed.

In parallel, the ongoing progress in the definition of standard characterisation methods should continue progress towards improvement of robustness for toxicity impact categories, which are very relevant for the geothermal sector. Also, characterisation of the impact of metals and hydrogen sulphide should robustly take into account potential scientific progress with respect to the understanding of potential harmful mechanisms, especially on human health.

Moreover, for a coherent resolution of environmental concerns arising form certain geothermal applications, multiple and complementary analyses should be performed. Indeed, the spectrum of tools for environmental performance evaluation and impacts assessments existing in the scientific panorama is huge, providing the opportunity to evaluate several aspects of interest for the geothermal sector with the necessary detail and consistency. Forcing the results obtained into conclusions outside the boundaries and scope of each tool used to assess them can be misleading and should be clearly avoided.

Characterize baseline scenario of existing and future geothermal installations

A crucial aspect is the differentiation between anthropogenically and naturally emitted gases from geothermal systems. There is only a limited number of studies comparing the measurements of natural emissions before and after the operation of geothermal plants. Moreover, the ratio of natural over anthropogenic emissions is highly site specific. It can even be influenced by the nature of the dominant phase present in the reservoir. For all these reasons we concluded that in the absence of additional scientificdata the effect of geothermal plant operation on CO_2 emissions (or other gases) through natural pathways cannot be accounted for in a general way and thus, this aspect have not been taken into account in the present study.

Nevertheless, it is recognized that such information is vital to substantially improve the quality of potential impact assessments, especially at plant-scale anlaysis (rather than cluster scale).

Monitoring of natural emissions before the development of geothermal applications on new sites would be the obvious solution to tackle this issue. The natural state before operation of geothermal energy plants could then be used as a reference to compare with the one after the start of the exploitation of the resource. The monitoring should take place on the development site and at suitable distance from it to make sure that the subsurface area that can be impacted by the geothermal energy production would be included in the monitoring perimeter.

Address the development for the most significant life-cycle phases of geothermal energy generation

The analysis of LCA results performed in this study has shown how the largest contribution to the overall environmental impacts of geothermal plants is given, both for power plants and DHC plants, by the direct emissions occurring during plant operation (if any, depending on the technology implemented and on the characteristics of the geothermal resource) and by the drilling phase (due to the intensive use of energy, usually in form of diesel, and to the disposal/treatment of muds and drilling fluids); for DHC applications, a relevant share of the impacts is also attributed to the electricity consumption for geothermal fluid pumping.

When focusing on the life cycle phases studied, in most cases it is also beneficial to adopt electricity-based drilling rigs instead of diesel-based ones; clearly, this depends on the production mix of the specific country of operation, but in a very wide range of locations this constitutes a good practice.

As concerns plant operation, significant benefits can be achieved by increasing the efficiency of the plant through the reduction of losses of its main components, which lead to lower energy self-consumptions or higher energy production. This target may be achieved through conventional energy efficiency interventions on mechanical and electrical components, e.g. pumps, compressors, turbines, valves, pipes, heat exchangers. This applies not only to components for geothermal power plants but even more to those for DHC geothermal systems.

Similarly, other improvements related to plant operation can be achieved by extending the lifetime of the whole plant as well as of its components and equipment, which can be done by acting on materials and also through the optimisation of O&M aimed at the reduction of scaling and corrosion or fluid treatment. This leads on one side to a reduction of the replacement rate of the single components, which reduces the indirect impacts due to materials production and end-of-life, and on the other decreases downtimes due to maintenance and extends project lifetime, thus increasing production and therefore minimizing the impacts per unit of produced energy. In addition, considering that environmental effects of use of chemicals may be significant, the use and development of products with an improved environmental performance shall be pursued.

Generally speaking, the realisation of CHP-type geothermal plants, aimed at combined production of electricity and heat, leads to benefits under an environmental perspective, since two useful energy vectors are produced with the exploitation of a given geothermal resource and therefore with the production of the associated environmental impacts. Further benefits can be achieved by increasing flexibility of CHP plants to operate with variable cogeneration ratios and to integrate heat from other renewables, especially solar and/or biomass, or waste heat recovery from industries or other sources.

Limit the flow of direct emissions with mitigation measures

As previously highlighted, direct emissions occurring in some applications during the plants' operation are the most crucial factor for the environmental performance of geothermal applications.

The emissions generated are often of multiple types and associated with a wide range of potential impacts, on health and environment and at local or global scale.The amount and flow of emissions encountered in a geothermal installation are characterized by the physical properties of the reservoir. In general terms, while CO_2 is the most common and aboundant gas in all the reservoirs, the other substances may occur only in some situations and vary in amount.

As a result, it may happen that GHG emissions of geothermal installations reach considerable values. In case of geothermal fluids with high amounts of NCGs, they shall be limited as much as possible, especially as far as methane emissions are concerned. As an example, burning or electricity generation from methane should be introduced as best practices.

Among the other substances, ammonia is responsible for potential harmful impacts on multiple receptors, as well as repiratory effects on human health, even if present in low amounts. Hydrogen sulphide has a significant effect on toxic contamination of freshwater ecosystems. As far as human helth is concerned, given as mandatory that in the areas where plants are located WHO concentration limits are never exceeded, the effects of long-term low concentration exposure to hydrogen sulphide emissions – typical of some geothermal areas – are not well-known. Thus, reduction at minimum levels may be pursued as a precautionary measure, while scientific knowledge on the subject should be enhanced, also providing solid information to address existing concerns also in the geothermal sector. Finally, heavy metals emissions (mercury and arsenic in this context), cause concern with for potential toxic effects on freshwater ecosystems and human health; as such, they shall be kept under controlled limits.

It is highlighted that – whenever technically feasible - total reinjection of the geothermal fluid is a suitable technique that allows an improved control of non-condensable gases, in turn reducing environmental impacts correlated to the operation of the geothermal plant. Since a high concentration of NCGs generally constitutes an obstacle to total reinjection, the main identified need is to identify materials, devices and processes to maximize the applicability of this option and to reach the levels of productivity that can be gained with different technologies. Overall, several technological solutions have already proven their efficiency. The solutions to be used is obviously site (or cluster) specific and highly depends on the resource itself, and mainly on the NCG gas content and on its composition. On the one hand for flash and dry plants, the AMIS technology has shown its efficiency to reduce the emissions of H_2S and Hg in Italy whereas the pilots for the fixation of H_2S and CO_2 show some potential in Iceland. On the other hand, the application of pressure higher than the bubble point in most binary plants is also very efficient to keep the gas into solution and to enable its reinjection after the heat exchange has taken place.

The total reinjection is especially feasible for binary plants; regarding this kind of plants, also the use of organic working fluids with low ODP and GWP, flammability and explosivity, presents a potential for the reduction of the environmental impacts, provided that it is evaluated together with thermal properties and other characteristics that may influence the efficieny of the ORC cycle.

CLOSURE

The European Commission has committed a study on "Geothermal plants' and applications' emissions: overview and analysis" to Ernst & Young, RINA and VITO to provide a consistent, harmonized and exhaustive assessment about the possible release of greenhouse gases and other pollutant emissions in geothermal sector.

The overall assessment has encompassed four interconnected tasks, over a time span of 14 months; the activities carried out by the Project Team across the whole assignment are summarized in the breakdown list below:

- *definition of a shared methodology for the collection of data on geothermal emissions (Task 1):*
  - *mapping and classification of reservoirs,*
  - *inventory of technologies,*
  - *definition of geothermal energy technology clusters,*
  - *definition of key parameters,*
  - *definition of dataset requirements and data handling approach,*
  - *organisation of validation workshop;*
- *collection of data and development of a comprehensive overview of emissions from geothermal plants and DHC applications (Task 2 & Task 3):*
  - *description of LCA methodology,*
  - *foreground data gathering,*
  - *background database selection and use,*
  - *life Cycle Inventory development,*
  - *GHG Emissions inventory development;*
- *analysis of the impact of geothermal emissions on human health and environment (Task 4):*
  - *definition of set of impact categories and related indicators,*
  - *calculation and comparison of LCIA results,*
  - *interpretation of LCIA results: environmental impacts,*
  - *interpretation of LCIA results: impacts on human health,*
  - *organisation of a final workshop.*

In particular, the analyses of the present report have focused on:

- *the development of LCIs for power generation and DHC applications;*
- *the development of GHG emissions inventories;*
- *the interpretation of the results of the Life Cycle Inventories, with assessment of environmental impacts and impacts on human health;*
- *the provision of recommendations based on the main outcomes.*

ANNEX I: INVENTORY OF TECHNOLOGIES

DRILLING TECHNOLOGIES

Drilling techniques efficiency

Baujard et al (2017) analyzed and compared the rate of penetration (ROP) data from 18 wells in hard rocks versus depth. The authors concluded that the general trend is a decrease of the ROP with increasing depth. For the investigated sites, the ROP ranges from 3 to 6 m/h in the shallower section and between 2 and 5 m/h in the deepest one. Additionally, by analyzing the impact of lithology on the ROP they observed that massive granite and fractured granite have similar ROP values ranging between 3.5 and 4.5 m/h. This ROP can be taken as current ROP values for conventional drilling technologies in hard rocks.

Note that recently, PDC (Polycrystalline Diamond Compact) bits have used in the drilling of the Illkirch well in the Rhine Rift. It enabled to improve significantly the ROP, reaching values up to 20 m/h with PDC, while in same geological conditions the maximum ROP was only 5 m/h (ES Geothermie, pers. Com.).

Innovative Drilling techniques

Any innovative drilling technologies that can increase both the life time of the equipment and the rate of penetration will have a positive impact on direct and indirect emissions. Hence reducing the use of materials and of fuel used during the drilling process.

Richter et al. (2017) mentioned more than 20 innovative drilling technologies such as enhanced rotary, laser, spallation, plasma, electron beam, electric spark and discharge, electric arc, water jet erosion, ultrasonic, chemical, induction, nuclear, forced flam explosive, turbine, high frequency, microwave, hammer and several others. The most promising technologies are summarized in Table A 1. All these techniques present the advantage of increasing the rate of penetration and of decreasing the use of materials and as such will result in decreasing the direct and indirect emissions from the geothermal sector. However, these technologies are not yet widely adopted in Europe and as such are not detailed in this report.

Table A 1: Promising innovative drilling technologies and main expected impact on emissions

Drilling technology	Application fields	Concept	Main benefits and Impact on Drilling Time/Material/Energy Use
Thermal shock or thermal stress failure of rock induced by rapid cooling	Supercritical geothermal developments	Thermal shock failure induced by decompression, boiling and cooling of drilling fluid bottom hole	

Drilling technology	Application fields	Concept	Main benefits and Impact on Drilling Time/Material/Energy Use
Lightning (Electro Impulse Technology (EIT))	Hard Rocks	High electric voltage impulses impinge on and pulverize rock. Driven by a mud motor	The system being developed would have a lifetime of 350h (increase of up to 7 times when compared to conventional systems). Reduction in the number of tool change.
Laser Jet drilling	Hard Rocks	Use of high power industrial laser source of up to 30kW, providing additional thermal load to mechanical load leading to rock pulverisation. In tandem with a mechanical drill bit that can more easily crush and remove the rock and remaining particles.	Increase both: ✓ Rate of penetration (ROP) increase in hard rocks up to 10m/h. ✓ Service time of drilling tools The technique should improve the overall footprint of geothermal energy utilisation (energy-efficient rock pulverisation)
Percussion drilling: Hydraulic down-the-hole Hammer (DTH)	EGS (hard rocks)	Percussion hammer powered by drill air, water or mud. The percussion mechanism converts hydraulic energy to a percussive movement.	Water hammers tested in shallow wells (up to 200m) in sandstone and claystone layers, very high ROP (~45 m/h). In granite and leptite ROP ~20m/h.
Combination of conventional drilling with water jetting	EGS (hard rocks)		Aim is to achieve a minimum of 50% ROP improvement in crystalline and hard clastic rock.
Existing Percussion drilling		use either air DTH hammers of hydraulic driven top hammers. So far only water powered percussion drills have been available for geothermal	

PRODUCTION TECHNOLOGIES

Self-Flowing

Self-flowing wells occur in artesian flow reservoirs. They do not require electrical power to produce geothermal fluids, as such they do not require auxiliary energy consumption. However, especially in high temperature settings if the temperature is above the boiling point or if there is a high gas concentration degassing can happen leading to direct emissions of geothermal gas. The composition of the geothermal fluid as well as the characteristics of the reservoir are key factors to assess these potential emissions. Febrianto et al (2019) mention that resources with reservoir temperatures <210°C typically cannot be developed using self-flowing wells as the obtainable flow rates are too low – exceptions are systems with elevated gas contexts (e.g., systems in the Menderes Graben, Turkey) and systems with shallow or artesian piezometric surfaces.

Downhole Pumps

Downhole pumps are placed in the tubing of the production wells. For pumped wells, line shaft pumps and electrical submersible pumps are the two most common technologies that are widely used (Lobianco and Wardani, 2010; Qi et al., 2012). The motor of the pumps consumes electricity during the whole well operation. In the context of an LCA analysis, electricity consumption should be considered.

Electrical Submersible Pumps (ESP)

Electrical submersible pumps (ESP) have all mechanical components downhole, leaving only the controller above ground. The technology can be applied in deviated and horizontal wells. The ESP system consists of a multistage down hole centrifugal pump, a down hole motor, a protector section between the pump and motor to the surface power supply. The large flow rates associated with geothermal systems require high electrical power which can exceed 735 kW per well (NREL, 2014). Current ESPs have a typical operational life of only two to three years, life expectancy is further reduced with increasing temperature (Vandevier 2010).

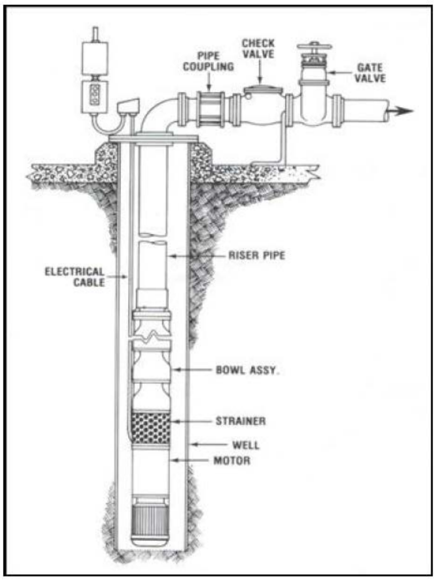

Figure A 1: Electrical Submersible Pump (ESP) - Kaya and Mertoglu (2005)

It is worth noting that ESP can be equipped with gas separation systems that are active before the intake of the pump. These gas separators systems enable steam to bypass the pump are common in oil and gas wells.

Line-Shaft Pump

Line shaft pumps operate in the well under the water level whereas the motor of the long shaft that drives the multistage centrifugal pump is at the surface. The shaft can be as long as 80-100 m which can put some limitations to their application. Depth aside, LSPs are incapable of operating in horizontal wells or other highly deviated wells.

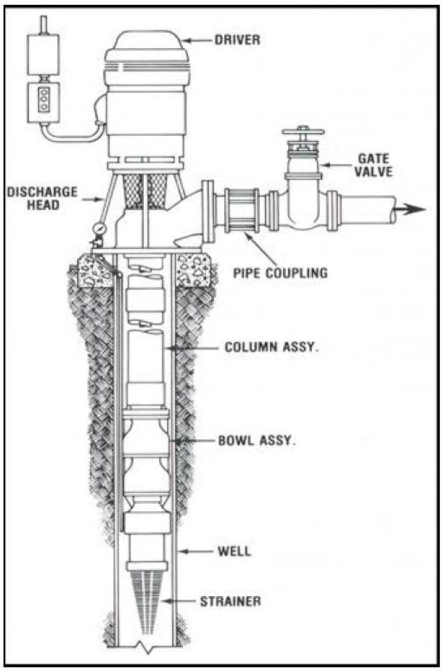

Figure A 2: Line-Shaft Pump - Kaya and Mertoglu (2005)

POWER CONVERSION TECHNOLOGIES

Dry Steam Plants for Power Generation

Dry steam power plants use steam directly from a geothermal reservoir to rotate generator turbines. Whereas the steam also contains gases such as carbon dioxide, hydrogen sulfide, methane, and others in trace amounts, there is little or no liquid present.

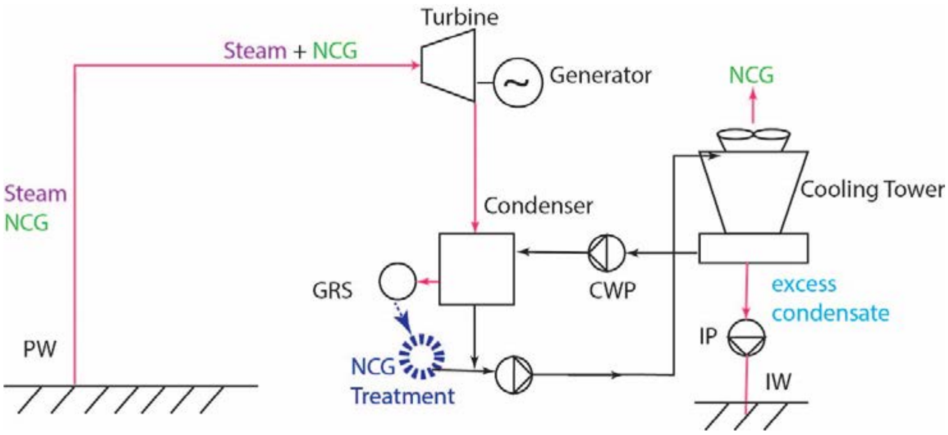

Figure A 3: Schematic Drawing of a Dry Steam Condensing Plant

Since almost all geothermal resources in the form of dry steam has dissolved 2 to 10% non-condensable gases, the geothermal plants are equipped with built-in system for their removal. In a geothermal dry steam condensing power plants, vapor at the exit of the turbine is not discharged directly into the atmosphere, but passed in a condenser where constant temperature is maintained, usually 35 to 45 o C. In Figure A-3 the scheme of a dry steam condensing plant is shown, where: IP = Injection Pump; PW = Production well; IW = Injection Well; GRS =Gas Removal System. Here, several paths for NCGs are presented: NCG treatment after gas removal system or exhaust into atmosphere.

In such plants the non-condensable gases in the steam are isolated in the condenser and removed by means of vacuum pumps or steam-jet ejectors, and they can be treated. NCGs are ejected from the top of the cooling towers whereas the excess condensate from the cooling tower is reinjected as is any liquid trapped from the steam transmission pipelines (DiPippo, 2012). Dry steam plants are not used in Europe for combined heat and power (CHP) applications. In 2017, there were 30 dry-steam condensing units in operation in the EU (ETIP vision document 2018) all located in Italy.

Flash Steam Power Plants for Power Generation

Flash steam power plants are the most common type of geothermal power plants, making up about two thirds of geothermal installed capacity. The single-flash steam plant is often the first power plant installed at a newly-developed liquid-dominated geothermal field (hydrothermal resources with a temperature above 180 °C).

The term flash refers to the pressurized liquid that is flashed into a steam and liquid mixture by reducing the pressure of the liquid below the saturation pressure of water for a given temperature. Flashing can occur in the reservoir, in the production well, in the gathering pipes leading to a steam separator or at the separator inlet.

The two-phase flow (steam + liquid) from production wells flows through a separator. The flow path for the steam after the separator is usually the same for flash plants as with dry steam power-plants. The steam is directed to the inlet of the turbine while the water phase is either used for heat input to a binary system in a direct-use application or injected directly back into the reservoir. In flash plants, at the exhaust of the turbine a specialized cooling system including a condenser is added.

In Figure A 4 the scheme of a single flash condensing plant is shown, where: IP = Injection Pump; PW = Production well; IW = Injection Well; GRS =Gas Removal System. Here again, several paths for NCGs are presented: NCG treatment after gas removal system or exhaust into atmosphere.

As of 2017, there were 9 flash steam units in the EU (Italy and Iceland) mainly of single flash type (EGEC report 2017). They provide 1GW geothermal power capacity in Europe.

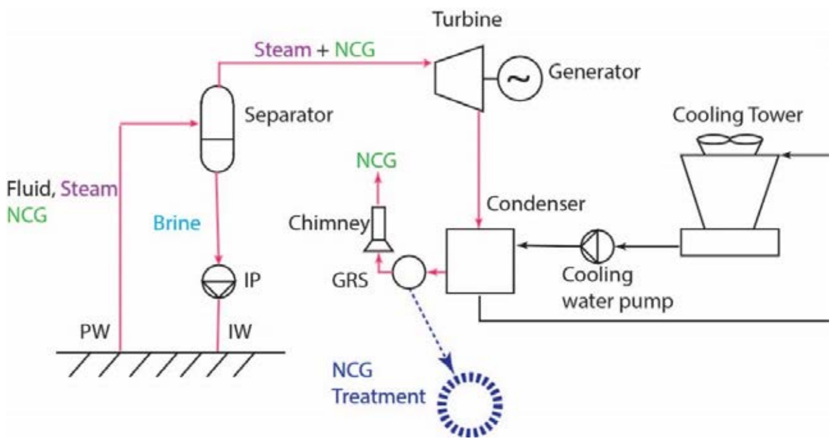

Figure A 5: Schematic Drawing of a Single Flash Steam Condensing Plant

Different types of cooling condensers systems are available either direct or indirect (see section 4.4.5). In any case, the gas is removed from the condenser to prevent build-up of NCGs and, then, in some case can be treated before being exhausted through a cooling tower or a chimney. When direct contact condensers are used a higher fraction of NCGs (mainly the water-soluble gases CO_2 and H_2S) are partly captured into the condensate (Sigfusson and Uihlein, 2015).

In case of double-flash steam power plant, the separated water is flashed in a flasher where additional steam is generated at lower pressure than the first flash and diverted into the turbine at a lower pressure stage. The two stage separation of geothermal fluid results in two steam admission pressures at the turbine.

Binary Plants for Power Generation

In binary systems the heat is transferred from geothermal fluids to a secondary fluid through a heat exchanger. The heat causes the second liquid to turn to vapor, which is used to drive a generator turbine. Binary plants are of two types, single phase and two-phase binary.

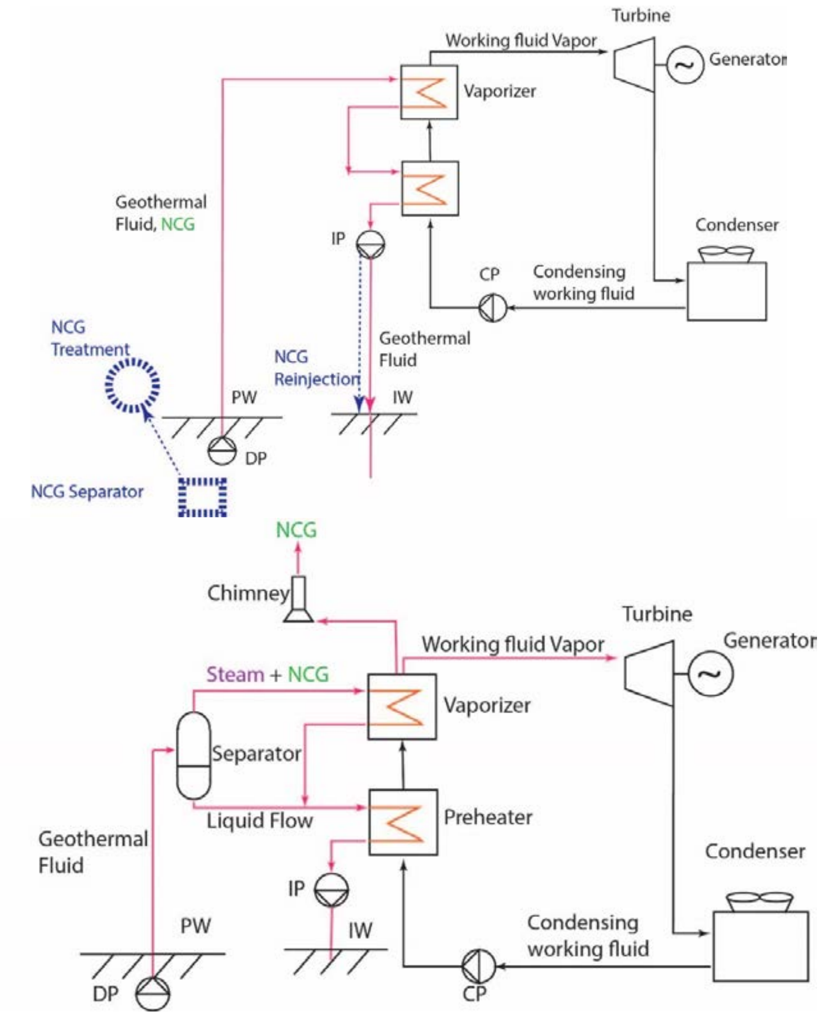

Figure A 6: Schematic Drawing of a Single Phase (Top) and Double Phase (Bottom) Binary Plants

When the temperature of the geothermal fluid is too low binary systems must be used. They present the highest conversion efficiency for low to medium-temperature geothermal resources. These systems are extensively used in Europe. A schematic drawing of a binary system is shown in Figure A 7, for single phase and double phase, respectively, where: DP = Downhole Pump; IP = Injection Pump; PW = Production well; IW = Injection Well; CP = Cycle Pump. Several options for NCGs treatment are presented: NCG separation before the intake of the downhole production pump or reinjection with the brine after the injection pump. Another option which is not drawn in the top schema is to have automatic gas vent pipes at several locations of the system or to separate the NCG before the heat exchanger and to send the gas back to an injection column to reinject it in the reservoir with the fluid.

Binary systems are based on two different technologies, Organic Rankine cycle (ORC) systems with various organic working fluids and Kalina cycle systems with ammonia and water as working fluid. DiPippo (2012) gives a good overview of binary cycle power plants and the functional principles of ORC and Kalina cycle systems.

Geothermal binary plants normally emit no gases at all as the geothermal fluid is circulated in a closed circuit and is reinjected into the geothermal reservoir after being cooled down. When the brine is produced in the liquid phase with the NCG still in solution, the NCG remain in solution throughout the heat transfer processes and return to the reservoir with the waste brine during reinjection.

In single-phase binary plants, to prevent the formation of a gas phase throughout the process from extraction of the fluid to reinjection, the fluid pressure must be kept high enough. However, at high flow rates and with high gas content in the fluid, this process remains a challenge due to kinetics issues. Indeed, the gas separates from the fluid at locations where pressure drops occur throughout the process and may not have time to re-dissolve completely before the reinjection (due to kinetics, temperature and pressure,…). Additionally, the technical challenge increases with the gas content. Indeed, the higher the gas content in the fluid, the higher the pressure that needs to be maintained throughout the system to prevent phase separation.

In general, in case of pumped binary, if the pressure is higher than the gas break out pressure, emissions are limited to potential binary cycle leaks and small venting pots. However, in case of self-flowing plants which normally have gas separator before the heat exchanger, some emissions can occur.

The reinjection of waste brines from geothermal plants avoids contamination of surface and groundwater aquifers (DiPippo, 2012). Gas emissions of binary plants are limited to working fluid leakage, which is typically very small. Indirect emissions are related to the energy that is used for the surface plant operation, such as pumping the working fluid or the cooling.

COOLING TECHNOLOGIES

Direct Contact Condenser

The fluid leaving the steam turbine can enter a direct contact condenser (DCC) where the steam is condensed by the cold geothermal water flowing from the cooling tower basin or from external water supply.

The steam and NCGs are cooled directly with a downward spray of cold water. Steam is mostly condensed and sinks to the bottom of the condenser as liquid. The fraction of NCG which do not dissolve in water and remain as a mixture of low pressure gas and water vapor is extracted from the condenser by a multi-stage centrifugal compressor which brings the NCG up to the atmospheric pressure. The gas removal system prevents pressure build up in the condenser. The two most common types of gas removal devices are ejectors and liquid ring vacuum pumps. The gas is extracted from the condenser and can be treated before either being vented into the atmosphere via the chimney or the cooling tower fan stacks. It is worth noting that direct contact condenser requires large amounts of water, indeed the evaporative cooling used in water cooled systems requires a continuous supply of cooling water and they generate vapor plumes.

Wet Cooling Towers and Dry Coolers

Geothermal plants produce waste heat as a by-product. As opposed to direct cooling condenser, surface (indirect) condenser are also available. Surface condensers are tubular exchangers. The main heat transfer mechanisms in a surface condenser are the condensing of saturated steam on the outside of the tubes and the heating of the circulating water inside the tubes.

Surface cooling is achieved by two different types of cooling systems either wet or dry cooling systems. The role of cooling towers is to dissipate the waste heat, in order to allow the plants to operate efficiently.

Wet cooling towers evaporate water into the air flowing through the tower whereas dry coolers transfer heat from the power plant into the air.

Wet cooling towers, on the one hand, consume less electricity, and improve the thermal energy conversion efficiency (Kutscher, 2002). Wet cooling towers generally require less land than dry coolers, and in overall are considered to be effective and efficient cooling systems. Geothermal flash plants usually produce sufficient water from the condensed steam to allow wet cooling. Indeed, for such plants, Di Pippo (2016) states that around 75% of the condensed steam is evaporated in the cooling tower, whereas 25% is still available for makeup water and blowdown from the cooling tower.

Dry or air cooled systems, on the other hand, do not need water to be evaporated for the cooling process. They are beneficial in areas where extremely low emissions are desired or no water is available. Dry cooling towers conduct heat transfer through air-cooled heat exchanger that separates the working fluid from the cooling air (Guan et al., 2016). In such systems, air can be introduced by either mechanical draft fans to move the air across the air-cooled heat exchangers. Moreover, the main advantage of dry cooling systems is that they avoid site restrictions due to water availability. They are particularly well suited to be applied in arid regions where water resources are limited or simply in regions where water abstraction is strictly regulated. In running hydrothermal plants in South Germany, air cooling is often used. According to Mishra et al. (2011) this type of cooling accounts for 78% of geothermal capacity. Regarding auxiliary power consumption, dry cooling towers usually consume twice as much electricity than wet cooling towers. Moreover wet cooling towers can cool to lower temperatures as the wet-bulb temperature is the limit (which is lower than the dry-bulb temperature).

When it comes to NCG in dry steam or flash plants, air cooled systems would result in lower emissions than wet cooling systems since no fluid needs to be evaporated for the cooling process. Using wet cooling towers implies that complete reinjection of the geo-fluid cannot be obtained, as part of the condensate leaves the tower as a wet plume with droplet drift (Bruscoli et al., 2015); this latter can be responsible for marginal transfer to the atmosphere of H2S and Hg, which escape the gas treatment section (effective only on the gas phase). On the other hand, air-cooled condensers allow complete recovery of the liquid condensate and can eliminate the problem of droplet drift of H2S and Hg. However, Di

Pippo (2016) mentions that for a geothermal flash power plant there are several challenges in using air coolers and that this results in performance and cost impact which are considerable burden for geothermal projects. As a consequence, so far, there is only one example of a flash plant equipped with air coolers instead of wet cooling systems, the Mutnovsky plant in Russia.

Hybrid and Combined Cooling Systems

Some hybrid combined cooling systems are possible. Bertani (2017) mentions that hybrid condensers such as wet and dry condensers in parallel or dry and direct spray condensers can be considered to combine the advantages of the dry and wet cooling.

In flash plants, where there is plenty of steam condensate to use as make up water, the standard technology adopted almost exclusively is cost effective direct contact condensers coupled with wet cooling towers (Mendrinos et al., 2006).

Additionally, systems combining air cooling and wet cooling systems have been proposed for steam geothermal plants. McIntush et al. (2017) concluded that air-cooled exchangers can be used for example to cool part of the water used in direct-contact condensers so that more condensate is available for use than with commonly cooling tower designs (due to loss through evaporation). By doing so, they assume that the overall injection rate from geothermal plant could reach about 85% compared to the 15%-20% for typical geothermal steam plants using steam condensate in wet cooling towers.

In binary plants, where the more expensive shelland-tube or plate heat exchangers are used as surface condensers, the selection of the cooling system type is governed by water availability, local water use regulations and economics.

HEAT/COLD GENERATION TECHNOLOGIES

Absorption Chillers/Heat Pumps

The cycle on which the heat pumps are based is reversible meaning that they can be used for both heating and cooling purposes.

The heat pump’s theoretical cycle proceeds from the Carnot cycle. Heat pumps transfer heat by absorbing heat from a cold space and releasing it to a warmer one, and vice-versa. The heat is transferred by a working fluid media and requires additional energy input.

Absorption chillers are driven on a heat source with a broad temperature range of 85°C–150°C.

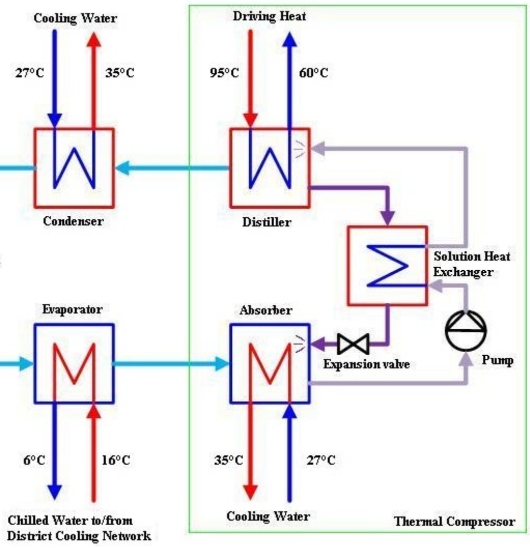

Figure A 8: Absorption Chiller - Typical Working Process

The absorption cooling cycle can be described in three phases (Johannesson and Chatenay, 2014):

- Evaporation: the liquid refrigerant evaporates in a low partial pressure environment, thus extracting heat from its surroundings;
- Absorption: the gaseous refrigerant is absorbed – dissolved into another liquid - reducing its partial pressure in the evaporator and allowing more liquid to evaporate;
- Regeneration: The refrigerant-laden liquid is heated, causing the refrigerant to desorb. It is then condensed through a heat exchanger to replenish the supply of liquid refrigerant in the evaporator after expanding to the lower pressure.

Lithium bromide is commonly used as the carrier fluid and water as refrigerant. The working fluid used in absorption chillers is environmentally friendly and non-toxic. Lithium bromide can be easily transported, as white odorless salt, and stored. Other pairs are water – ammonia where water is the carrier fluid and ammonia the refrigerant. Those systems allow to cool below 0°C.

Adsorption Chillers / Heat pumps

Adsorption heat pumps/chillers operates by cycling adsorbate between adsorber, condenser, and evaporator (Ülku, 1986; Meunier, 2002). Geothermal heat is used as the driving energy source (Holbein et al., 2016).

A basic adsorption heat pump/chiller cycle consists of four main parts:

- an adsorber (container filled with an adsorbent such as zeolite, active carbon, silica gel, etc.);
- a condenser;

- an evaporator;
- an expansion valve.

This basic system is comprised of two linked containers, the generator which contains the solid adsorbent and the receiver combining the evaporator and the condenser in which the refrigerant is evaporated and condensed. Initially the system is at a low temperature and pressure and the adsorbent contains a high concentration of refrigerant, whilst the receiver contains only refrigerant gas.

The generator is then heated which causes refrigerant to be desorbed, raising the system pressure. Refrigerant condenses in the receiver, rejecting heat and producing a useful heat output if the system is to be used as a heat pump.

Cooling the generator back down to its initial temperature completes the cycle and causes the adsorbent to re-adsorb the refrigerant. The system pressure is reduced and the liquid refrigerant in the receiver evaporates, absorbing heat. This produces the useful cooling effect if the system is to be used as a refrigerator.

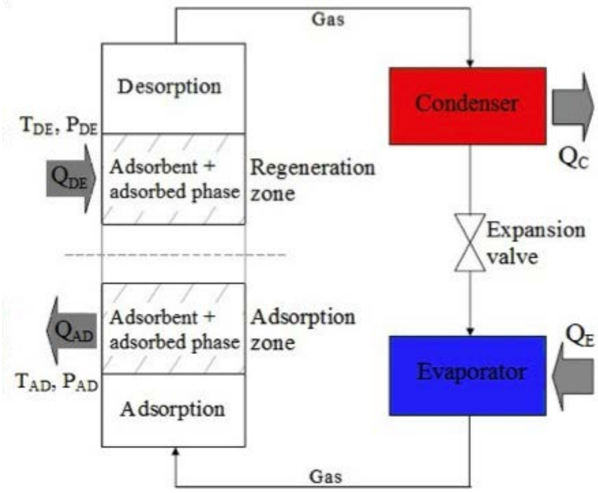

Figure A 9: Example of Adsorption Cycle

In the adsorption heat pump cycle, adsorption phenomena play the same role of mechanical power, so that the working fluid can be circulated in the cycle without any mechanical power.

The temperature level necessary to drive the process (high temperature level) depends on the type of refrigerants and sorption materials used. Typical materials are silica gel, zeolite or active carbon that work with the refrigerants water, methanol or ammonia and allow a driving temperature of below 100°C.

Demir et al., (2008) provide a detailed review on adsorption heat pumps.

An example of adsorption cycle is shown in Figure A 10. Here, during the cooling step, heat (Q_E) is transferred to the evaporator, the evaporated working fluid is adsorbed by an adsorbent material, releasing the heat (Q_{AD}). During the regeneration step, when an input of heat (Q_{DE}) occurs, the gas is desorbed and condensed releasing heat (Q_C), which closes the thermodynamic cycle.

GAS CONTROL SYSTEMS

The following sub-sections discuss the technologies and methods currently available to separate the NCGs from geothermal process fluids and to treat them. The efficiencies of the separation processes vary greatly with the composition of the geothermal resource.

NCG Removal Systems

To remove the NCGs from the condenser downstream of the turbine several options exists. To remove and compress NCGs the most commonly used gas removal system is steam jet ejector (SJE). Jet ejectors are typically suitable for low NCG flows (<3%). An ejector is a type of vacuum pump driven by steam. Alternatively, to increase the gas removal system efficiency Liquid Ring Vaccum Pumps (LRVPs) are used in series after the first stage of compression by the steam jet ejector. Integration of a steam jet ejector with a LRVP is commonly referred as a hybrid system (Yildirim and Gokcen, 2015). Finally, when dealing with large quantities of NCGs (>3%) the preferred option can be centrifugal compressors systems (CS), which are said to be 30% more efficient than LRVPs and 250% more efficient than steam jet ejectors (Barber-Nichols, 2010).

Additionally, reboilers system (RBs) is one the technologies available to remove NCGs upstream of the turbine. With this system most of the NCGs will be exhausted in the vent stream before entering the turbine.

Finally, separation of the NCGs can be performed in the well, to keep free gas from entering the ESP pump. The system can use mechanical gas separator (static or dynamic). Static gas separators offer an overall limited separation efficiency (Schlumberger website). Dynamic gas separators, on the other hand, impart energy to the fluid to separate the vapor from the fluid. Vortex gas separator removes the free gas from the produced fluid and vent this gas to the annulus. This type of separator prevents cycling, gas lock, and cavitation, resulting in a stable motor load and increased run life.

After the separation stage, the NCGs can either be discharged to the atmosphere or removed by abatement systems. Increased interest in methods for emissions reductions from geothermal plants through abatement systems have led to the development of various treatment systems, such as for abatement or for potential use of the gases in order to generate value for use in industrial or energy processes.

The most common systems to treat NCGs are the following:

- Flaring of combustible gasses;
- Gas turbine to valorize combustible gasses;
- H_2S abatement systems (and Hg);
- NCG reinjection.

Flaring of Combustible Gases

Flares are used for the combustion and disposal of combustible gases. In such case, gases are transported to a usually remote and elevated location (elevated vertical chimney) where there are burned in an open flame in the open air. Combustible gases are flared mostly in emergency relief situations such as overpressure, start-ups, shutdowns, etc.

Flaring is a high-temperature oxidation process used to burn combustible components, mostly hydrocarbons. In combustion, gaseous hydrocarbons react with atmospheric oxygen to form carbon dioxide (CO_2) and water. In some waste gases, carbon monoxide (CO) is the major combustible component. During a combustion reaction, several intermediate products are formed, and eventually, most of them are converted to CO_2 and water. However, some quantities of stable intermediate products such as carbon monoxide, hydrogen, and hydrocarbons may escape as emissions (Gervet, 2007). Flaring methane containing gasses allows to reduce methane quantities released into the atmosphere.

Gas Turbine to valorize Combustible Gasses

In many aquifers in Europe, natural gas, primarily methane, is found dissolved in geothermal brines. The geothermal-geopressurised methane can be stripped from the hot produced geothermal brine and send to gas turbine to be valorized. The cogeneration gas engines produce electricity for well operation, or increase the temperature of the geothermal fluid. The gas at the exhaust of the gas engine can be either vented to the atmosphere or reinjected into the geothermal reservoir.

As an example, a recent geothermal project proposed by CLEAG includes the use of hybrid geothermal system that uses two sources for its energy production: hot water as well as the combustible gases dissolved in it. In this hybrid system the gases are separated from the geothermal brine and burned in a gas engine. The CO_2 from combustion, as well as any brought up with the hot water, is captured at a rate of 98% and safely re-injected into the aquifer, where it stays.

NCGs Abatement Systems

H2S Abatement Systems

There are two main approaches for removing H_2S: upstream and downstream of the turbine, as described by Stephens, et al. (1980). Rodriguez et al. (2015) discussed some of the H_2S abatement methods available to the industry as well as tools for screening suitable abatement methods for geothermal fields. All of the methods they present are capable of achieving over 90% removal of H_2S carried with the geothermal fluid.

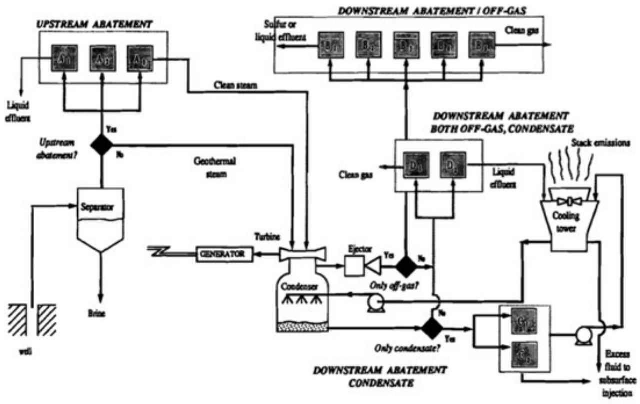

Figure A 11: Classification of Options for H2S Abatement (Sanopoulos & Karabelas, 1997)

Upstream Abatement

While the removal of the H_2S upstream protects the turbine components from corrosion and scaling and improves power production, there is an inherent loss of steam and its associated enthalpy from these treatments (Sanopoulos and Karabelas, 1997). In that case, the method to achieve H_2S abatement uses scrubbing system with an alkali.

Downstream Abatement, Off-Gas and Both Off-Gas, condensate

Following Sanopoulos and Karabelas, (1997) and Rodriguez et al. (2015), downstreams abatement systems can be divided into three types:

- downstream off-gas: concerned with the stream of gas exiting the condenser through the NCG removal system;
- downstream condensate: remove H_2S that is partitioned into the water in the condenser before the water makes it to the cooling tower;
- hybrid downstream: treatment on both the condensate stream and the gas stream resulting from the condenser stage of the energy production process.

Downstream methods can prevent the release of hydrogen sulfide (H_2S) and elementary mercury by chemically treating the NCG or scrubbing. Abatement systems require either a surface or a direct surface condenser (Rodriguez et al. (2015).

Scrubbing with alkali treats the gas by neutralisation with alkali, generally with solutions of NaOH. The process is carried out in a scrubbing tower and can be used upstream or downstream of the turbine (Bogarin Chaves, 1996).

Liquid redox process removes H_2S with reduction-oxidation chemical reactions; There are several liquid redox processes, the "most common reaction uses vanadium or iron as oxidation agents. The most widely used liquid redox system is the **LO-CAT II process**. This process employs a ferric catalyst to oxidize the H_2S, producing elemental sulfur and water. Additionally various other process exist. The **Stretford process** converts H_2S to sulfur by catalytic air oxidation. The **Unisulf process** uses a solution for absorbing H_2S from gas streams, and oxidizes it to elemental sulfur. The **SulFerox process** involves the usage of chelating iron compounds in a concentrated solution to oxidize the H_2S to elemental sulfur. The **LO-CAT process** uses an extremely dilute solution of iron chelates. The gas containing the H_2S reacts with the iron solution in an absorber to form elemental sulfur, which is removed through centrifugation. The reactions involved in this process are the same as in the SulFerox process (Abdel-Aal, 2003). Nagl (2009) mentioned high efficiencies (above 99.99%) reached by the LO-CAT systems in the Coso geothermal plant. The **Hiperion process** uses a chelated iron catalyst combined with naphtaquinone to remove H_2S from hydrocarbons. The operating experience of this process is limited.

Peabody-Xertic process uses a solution of citric acid to perform an oxidation reaction in the liquid phase with solid sulfur as a final product (Vancini, 1986). The process is used downstream off-gas.

The **Claus process** transforms the H_2S to sulfur in two steps. First a partial oxidation with air at high temperatures (1000-1400°C) produces elemental sulfur, H_2S and SO_2. Then a catalytic reaction between H_2S and SO_2 produces sulfur and water; the temperature in this second step is lower (200-350°C). The catalytic step is normally carried out in two or three stages. The sulfur recovery rate is close to 99.8%.

Catalytic oxidation process uses the Claus reaction in gas phase. Part of H_2S is oxidized to SO_2 with Fe_2O_3 as a catalyst, but the rest of the H_2S reacts with the SO_2 to produce elemental S. Alternatively, the **Selectox process** combines the Selectox catalyst with a Claus reaction to produce solid amorphous sulfur. This process is applied downstream off-gas.

Another downstream process that can be applied both in the off-gas stream and in the condensate tream is the **burner-scrubber process**. In the off-gas stream H2S is burned to S02 then it is scrubbed with the condensate for the oxidation of H_2S to soluble thiosulphates.

So-called "secondary abatement" methods are applied to remove H_2S from the condensate stream. They include caustic scrubbing with H_2O_2 and Steam stripping process (Rodriguez et al., 2015). **H_2O_2 process** treats the water with hydrogen peroxide to oxidize the H_2S into elemental sulfur or sulfates. **Steam stripping process** is analogous to a water scrubbing process, whereby the scrubbing is done by clean steam. Here the H_2S contained in the condensed water is stripped using waste steam from the steam ejectors. Rodriguez et al. (2015) mention that steam stripping appears to have a comparatively low H_2S removal efficiency.

The **BIOX process** is a downstream process, in which the off-gases are compressed and mixed with the condensate before entering the cooling tower. H_2S is converted to H_2SO, with the addition of the BIOX reactant (an oxidizing biocide used for biological growth control in the cooling tower), in combination with oxygen (Bogarin ,1996). Using this method, both primary and secondary emissions of hydrogen sulfide from the cooling towers are achieved (Gallup, 1992). The attainable removal efficiencies of this method may not be as high as other methods (Rodriguez et al., 2015).

A downstream off-gas process that is currently used in several dry steam and flash units is the **AMIS** process patented in 2001 by ENEL (Baldacci, 2001). AMIS is a primary emissions abatement method that aims at the abatement of H_2S and Hg emissions. The process is especially suited to the Italian geothermal fluids having a high content of NCG such as in Larderello region where NCG content can reach 8 to 10%. This process removes mercury and hydrogen sulfide from the gases extracted from the condenser. The abatement of hydrogen sulfide takes place in a catalytic oxidation reaction at 240 °C to produce SO_2 (Baldacci, 2004). The AMIS process operates well with a direct contact condenser and low ammonia content in the geothermal steam. Unlike the liquid redox processes, AMIS generally does not produce sulfur based by-products (Manente et al., 2019). AMIS process exhibits a very high abatement efficiency (> 99%) for both Hg and H_2S pollutants. Due to secondary emissions of H_2S through the cooling tower the abatement of H_2S emission from the overall plant is lower than the 99% efficiency achieved after the NCG are extracted from the condenser. However overall efficiency is still higher than 90%.

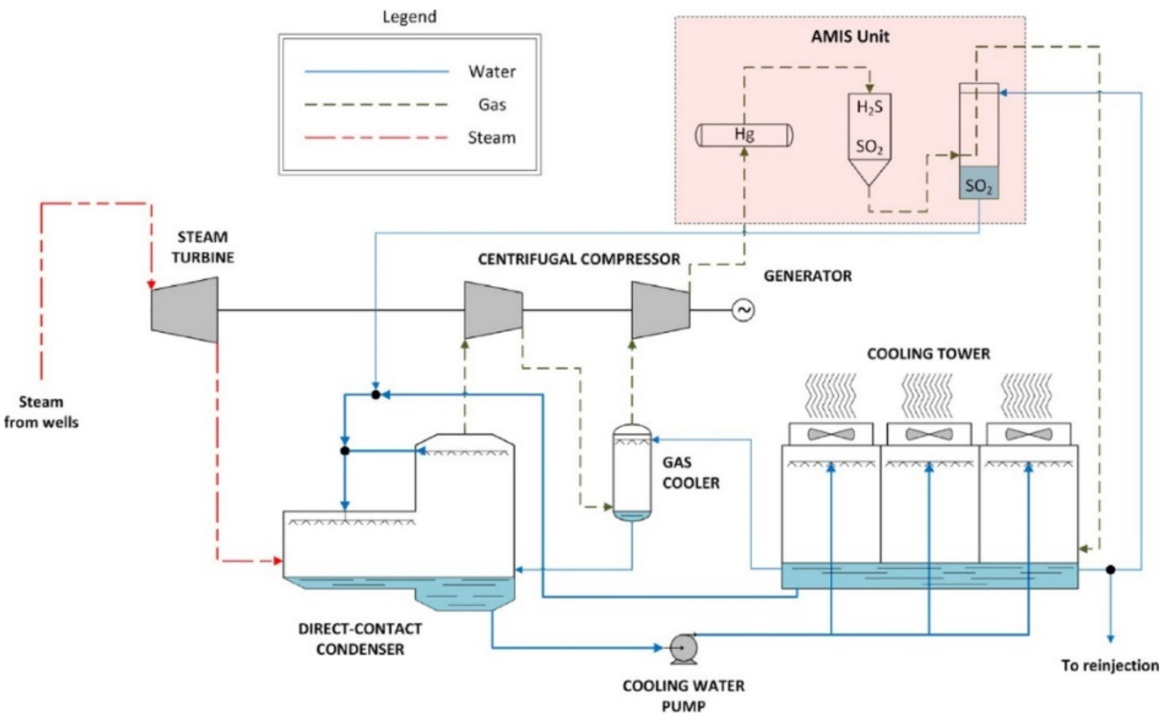

Figure A 12: Schematic Layout of the Existing Geothermal Power Plant equipped with AMIS (adapted from Baldacci et al., 2005)

Manente et al. (2019) analysed real plant data provided by ENEL and noticed that the H2S fraction which evolves in the vapor phase is higher than 80% of the total hydrogen sulfide entering the turbine with the geothermal steam. Hence, 20% of the H_2S leaves the direct condenser towards the cooling tower where part of H_2S is emitted due to the desorption of H_2S dissolved in the geothermal water. Note that the H_2S portion depends mainly on the solubility of the H_2S and hence on the pH. They provided a summary of the emissions and efficiency from the AMIS unit and the overall plant.

Table A 1: H2S Emissions and Abatement Efficiency from the AMIS Unit and the Overall Typical 20MW Geothermal Power Plant Equipped with the AMIS Unit (from Manente et al. (2019)

Emission / Efficiency	Value
H_2S emission from the AMIS unit (kg/hr)	0.7
H_2S entering the AMIS unit (kg/hr)	120
H_2S removal efficiency AMIS unit	>99%
H_2S emissions from cooling tower (kg/hr)	12.6
H_2S entering the geothermal power plant (kg/hr)	133
H_2S abatement efficiency overall plant	>90

It is worth noting that emissions from NOx were also observed in a few of the units where the combustion process that oxidizes the H_2S was used (DiPippo, 2012). However, combustion for H_2S abatement is not common practice and therefore most geothermal plants emit no NOx at all.

NH3 Abatement Systems

Abatement systems have also been developed to target NH_3 emissions. Indeed, as it appears from the report "Monitoraggio delle aree geothermiche toscane, Controllo alle emissioni delle centrali geotermiche, Anno 2017", prepared by ARPAT, in the region of Mount Amiata, the geothermal resource is characterized by a high concentration of ammonia (compared to other geothermal areas). To mitigate this emissive impact of ammonia (NH3), the Tuscany Region had prescribed the installation of a system of abatement for ammonia for a selection of power plants.. The minimum abatement efficiency requirement is 75% (with respect to the ammonia entering the plant). The principal treatment is based on the acidification of the circulating condensates with sulfuric acid, thus obtaining the salification of ammonia to ammonium sulphate, with the consequent unavailability of the same to be stripped by the aeriform emitted by the evaporative tower. This acidification of the condensates also favors the distribution of H_2S towards the gaseous phase compared to the liquid phase, thus increasing the amount sent to the AMIS treatment. In Italy, for H_2S, the abatement requirement is more than 90% (with respect to the pollutant entering the plant). Table below shows the ARPAT results.

NCG Reinjection

Additionally, the partial or total reinjection of NCG back into the reservoir is possible after they have been compressed and redissolved into the waste brine. This latter approach, however, may lead to an increase in the NCG concentration in the geofluids coming from the production wells.

Reinjection of NCG can be achieved when recompression of NCGs is included in the plant operational scheme. They are reinjected into the liquid condensate stream (in thermodynamic conditions where complete gas dissolution in the liquid can be achieved with suitable equipment) and as such emissions to the atmosphere (CO_2, H_2S and Hg) are completely avoided;

Currently, a research project is underway at the Hellisheidi field in Iceland involving distillation and reinjection of CO_2 and H_2S into the geothermal reservoir. There the "SulFix" and "CarbFix" projects aim at fixing H_2S and CO_2, respectively, in the reservoir through gas-rock interactions (Aradottir et al, 2015). The design and operation of the pilot scale gas separation station is described by Gunnarsson et al. (2015). The less soluble geothermal gases (H_2, N_2, CH_4, Ar) are separated from the more soluble sour gases CO_2 and H_2S, which are aimed at a separate reinjection. Over 95% of the CO_2 injected into the CarbFix site at Hellisheidi was mineralized to carbonate minerals in less than two years (Matter et al., 2016).

Manente et al. (2019) propose several alternatives process to achieve reinjection of NCG that could suit the conditions encountered at Italian power plants (high NCG content). In their study the AMIS unit is substituted by an absorption column where the NCG are dissolved in water before reinjection in the reservoir. They compare different systems combining the absorption column with either, dry, wet or dry-wet cooling tower.

ANNEXES II: METHODOLOGY AND EQUATIONS USED TO ESTIMATE EMISSIONS BASED ON PROXIES

EMISSIONS RELATED TO EXPLORATION

Pratiwi et al. (2018) used an average fuel consumption of 2,000 l/day (+/- 500 l/day) of seismic survey. The duration of the survey can be used as a proxy to determine how much fuel is used during the seismic exploration phase.

EMISSIONS RELATED TO SURFACE CONSTRUCTION MATERIALS

These proxies cover materials used for construction of surface components, including power and heat equipment, collection pipeline (whenever applicable) and plant structure.

Proxies for construction of equipment for energy production are summarized in Table A 2 below. Figures are in kg/MWe for the case of single flash, double flash and binary plants, while they are in kg/MWth for heat supply.

Table A 2: Proxies for Equipment Materials

Flow	Single Flash	Double Flash	Binary	Heat Supply
Steel	8,186 – 9,046	8,564 – 9,466	35,630-43,430	170 – 290
Stainless steel	2,226 – 2,460	2,008 – 2,220	2,000 – 3,000	2,000 – 3,000
Aluminum	182 – 302	191 – 319	6.3 – 7.7	6.3 – 7.7
Copper	327 – 399	339 – 415	806 – 1,206	4.8 – 7,2
Titanium	497 – 549	442 – 488	n.a.	n.a.
Mineral wool	221 – 271	238 – 290	30 – 50	30 – 50
Plastic	2,018 – 2,230	2,043 – 2,259	850 – 1,350	850 – 1,350
Transformer oil	596 – 728	615 – 751	n.a.	n.a.
Organic chemicals	n.a.	n.a.	2,600 – 4,400	n.a.

For steel for building construction, generally used for reinforcement bars, support beams and machinery supports, the following relationship is defined:

*emissions['steel'] = a * capacity * capacity + b * capacity*

with a and b defined as 0.4 +/-0.04 and 10,000+/-1,000, with the amount of steel expressed as kg and the capacity expressed as MW.

For concrete:

*emissions['concrete'] = a * capacity * capacity + b * capacity* with a and b defined as 0.5 +/-0.25 and 70,000+/-17,500 , with the amount of cement expressed as kg and the capacity expressed as MW.

Additional proxies for construction of the plant's building are summarized in Table A 3. The proxies for stainless steel, aluminum, copper, mineral wool and plastic are based on data published by Karlsdóttir et al., (2015).

Table A 3: Proxies for Construction Materials used for the building

Flow	U.M.	Building
Stainless steel	kg/MW	621 – 629
Aluminum	kg/MW	520 – 636
Copper	kg/MW	120 – 180
Mineral wool	kg/MW	561 – 599
Plastic	kg/MW	706 – 734

Figures for piping are summarized in Table A 4 and are provided in kg/m. The distance of pipeline depends on the type of plants. It is calculated assuming a pipeline length of 100 m/well for heat and binary plants. For single flash and dry steam plants, the distance is a function of the capacity of the plant and is approximated by the function (25 * capacity/ .2) with the capacity defined in MWe. This constant 25 was defined based on data from Karlsdóttir et al., (2015) and from available primary data, the division by the factor .2 is to approximate the thermal output of the field. For double flash plants, the distance is approximated by the function (capacity/ .2).

Table A 4: Proxies for Collection pipeline

Flow	U.M.	Collection Pipeline
Steel	kg/m	173 – 197
Aluminum	kg/m	4.7 – 6.2
Mineral wool	kg/m	42.9 – 47.1
Concrete	kg/m	0.9 – 2.7

EMISSIONS RELATED TO DRILLING

Energy consumption

Two different approaches are used to estimate the energy consumption for drilling:

- in case a well design is available, the energy consumption for drilling is calculated using the method given by Legarth and Saadat (2005).

- in case only the final depth of the well is known, the energy consumption is calculated using an exponential function of depth.

The method reported by Legarth and Saadat (2005) used an estimation of the energy that is needed to drill one m3 of rock at a given depth. The energy consumption per volume of rock removed is estimated using an analytical function depth:

$$E_v = y_0 + A \times e^{\frac{x-x_0}{t}}$$

With E_v the energy consumption per volume of rock removed [MWh/m3] and x the depth (m MD). A, y_0, x_0 ant t are constants that can be derived from field data.

Using E_v, the energy consumption related to drilling can be assessed. This is done by integration of E_v over the well path.

Data collected from literature and provided by plant operators summarized in table NUM have been used to derive the constants. Fitting the calculated against reported energy consumption for selected geothermal wells using a least squares method, the values derived for the constants are: d_0 = 0.000404, E_0 = 1.97, A = 0.915 and t= 1345. Note that in case a diesel-driven rig was used, the net energy use was derived from the reported fuel consumption using an efficiency of the diesel generators of 40% and an energy density for diesel of 38.6 MJ/L.

Table A 5: Proxies for Drilling – Energy Used

Well Name	Total drilled depth (m)	drilled volume (m3)	En (MWh)
GT01	3,148	447.58	1,428.896
GT01T	3,957.2	470.23	1,978.702
GT02	4,328	677.61	3,424.152
GT03	4,480	668.89	3,035.092
GT03T	5,077	690.75	3,447.294
KW1*	5,048	390	2,852
KW2*	5,100	735	7,511
GRT-1	2,580	330.16	1,275.516
GRT-2	3,942	383.88	2,656.967
Deep geothermal well (electrical rig)**	5,700		5,232
GPK-3	5,101		4,432
GPK-4	5,235		4,549

Well Name	Total drilled depth (m)	drilled volume (m3)	En (MWh)
DSL-NZM	604		97
GT-Uha1a	3,446		2,524.621
GT-Uha2a	3,864		2,792.257
well**	3,400		2,085.258
well**	3,818		2,341.622
Hellisheidi	2,200		586.6667
well**	780		595.4693

* Hydrocarbon well, data from Legarth and Saadat (2005)

**confidential data

The same dataset has been used to derive a relationship to estimate the energy consumption for drilling as a function of the final depth of the well. The energy consumption as a function of the total drilled depth is plotted in Figure A 10 below for the wells reported in table above.

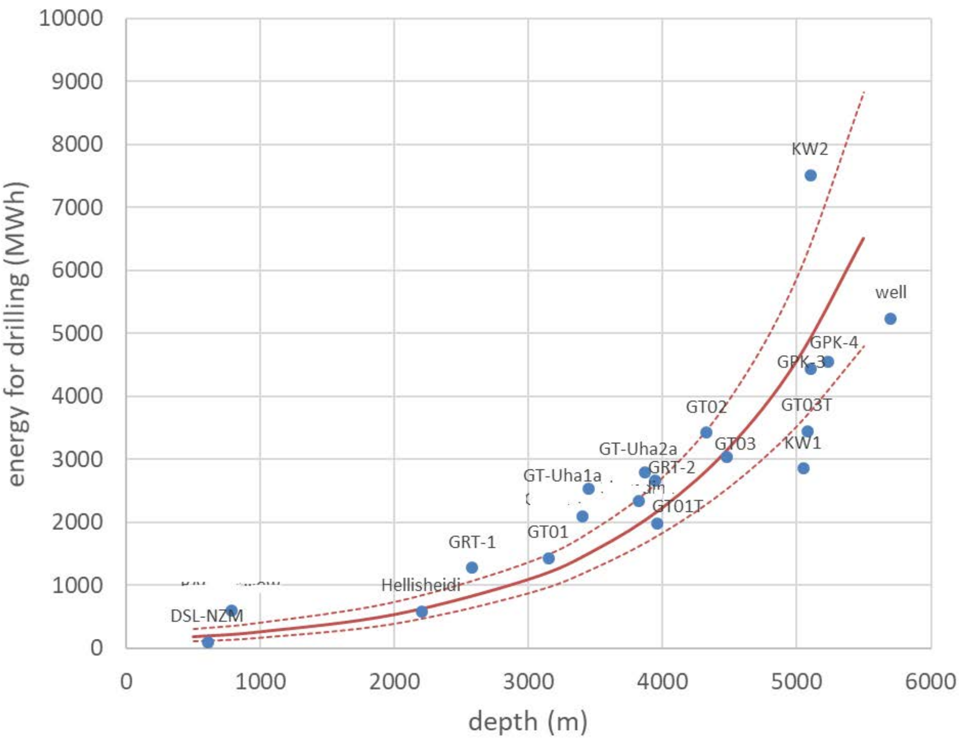

Figure A 13: Reported values for the net energy consumption of drilling as a function of the drilled depth for various geothermal wells and two hydrocarbon wells.

Based on this dataset, the energy consumption for drilling can be estimated by:

$$\log(E) = 0.000319 \times d + 2.04$$

With d the total depth (m) and E the energy consumption in MWh.

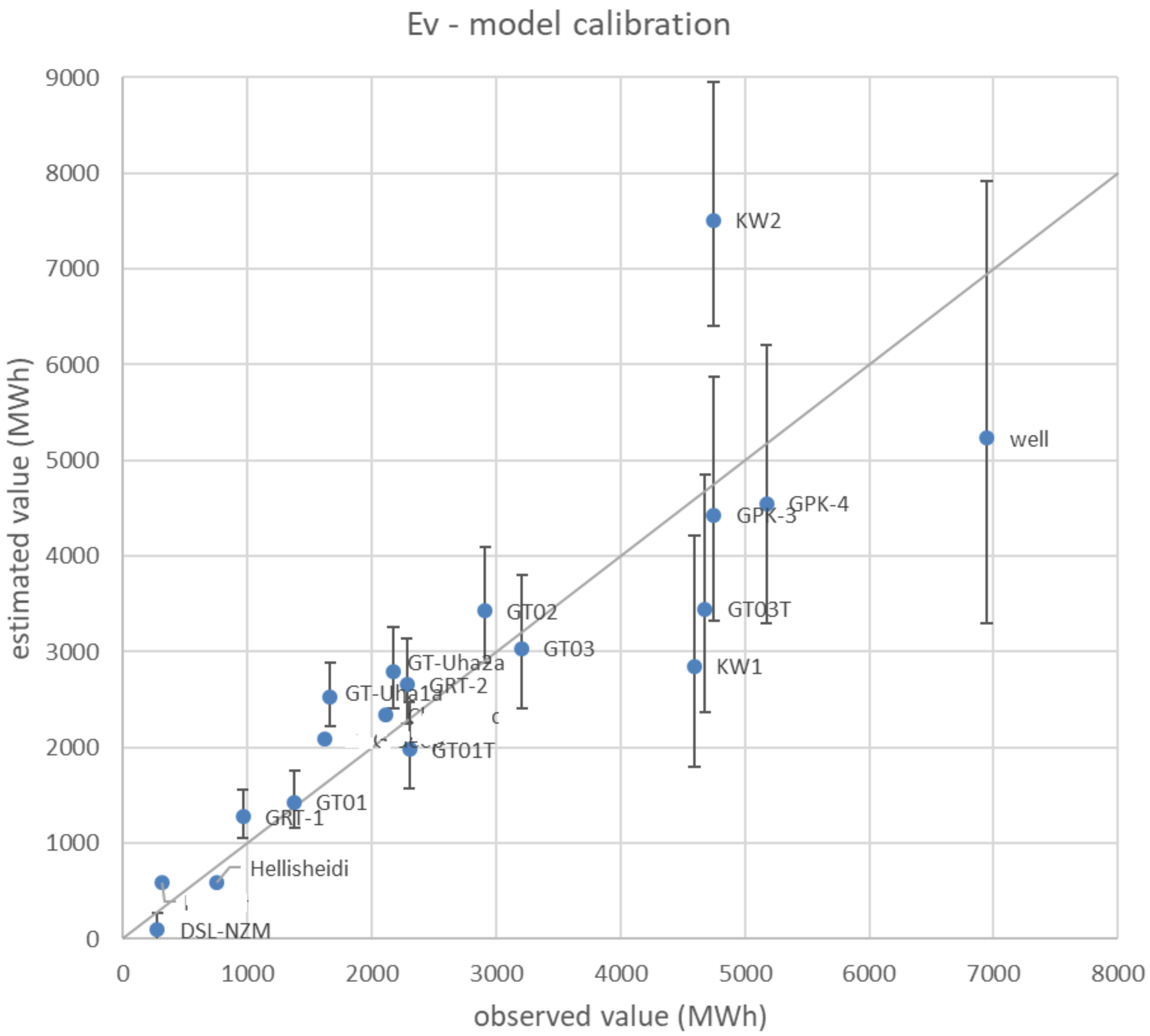

Figure A 14: Comparison of the estimated and reported values for the net energy consumption of drilling.

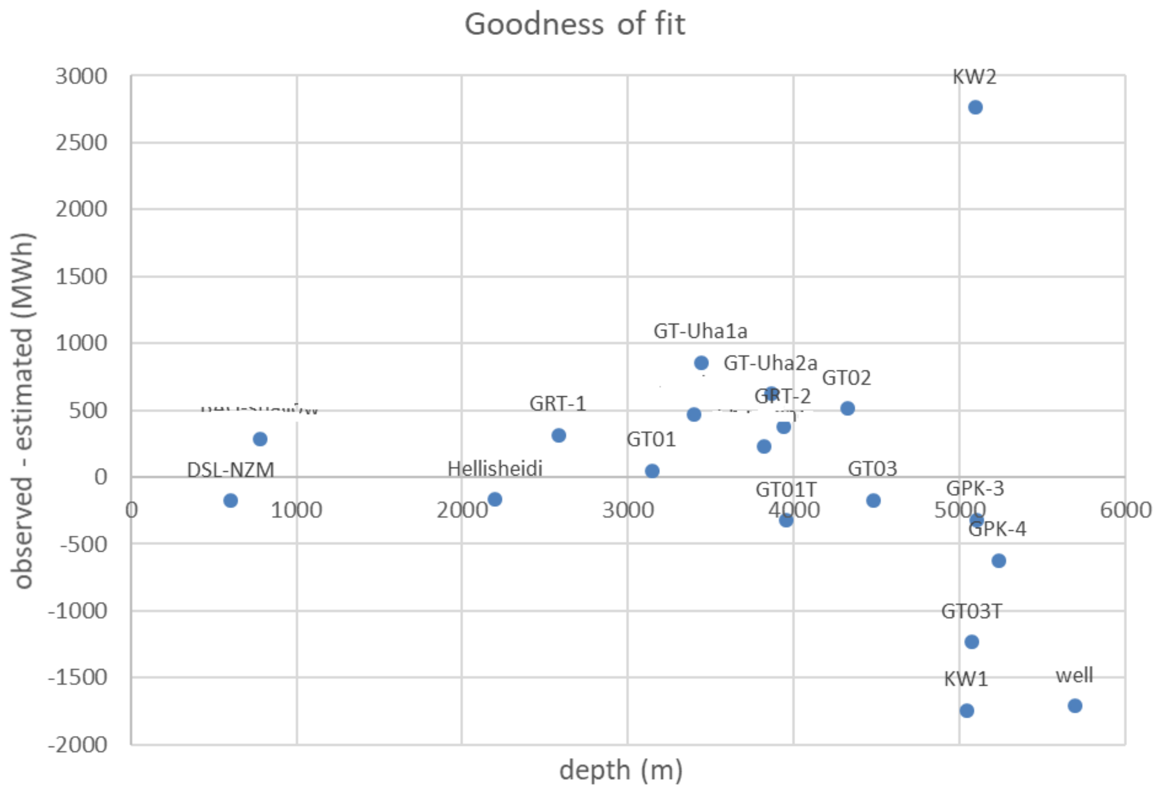

Figure A 15: Results of least squares fitting of observed energy consumption for drilling versus total depth of the well.

Steel usage

The amount of steel used to complete a geothermal well is either calculated from the well design or estimated from the depth of the well.In case a well design is available,the mount of steel is calculated from the weight of the casing from each of the borehole sections.The weight of the casing is taken from the API specifications for steel casings.

In case a well design is not available,the amount of steel used to complete a well is estimated using the following equation:

$$log(steel) = 1.22 \times log(d) - 1.78$$

with d the total depth of the well and Steel the amount of steel used in tons.

This relationship is derived from the data reported in table below. The steel quantities reported in the table are calculated based on the well design reported in the literature or by plant operators using a cost model for geothermal wells developed by VITO.

Table A 6: Proxies for Drilling – Steel Used

	depth	steel (ton)
MOL-GT-03	4,905	472.5
MOL-GT-02	4,341.2	500.6
MOL-GT-01	3,610	357.8
DSL-NZM	604	11.5
GPK-3	5,101	528.9
GPK-4	5,235	572.4
GRT-01	2,579.9	242.6
GRT-02	3,196	259.3
KW1	5,048	776.9
GT-Uha1a	3,446	490.9
GT-Uha2a	3,864	390.4
HH1	692.2	72.5
HLN3	412.8	35
HLN1	229.8	23.9
CAL-GT-04	3,037.4	236
CAL-GT-05	2,433	172
CAL-GT-02	1,694.3	120.7
GVLB2	1,690	133.1
GVLB1	1,689	133.7
Cha-trias	623	41.1
Saint-Ghislain	3,000	137.8
well*	3,500	283.1
KW2	5,100	1,284.3
well*	3,818	1,458.5
well*	740	92.5
well*	3,400	279
Hellisheidi**	2,200	220.5

*confidential data

**GEOENVI

The estimate does not include any steel needed for the construction of the cellars and the drilling floor.

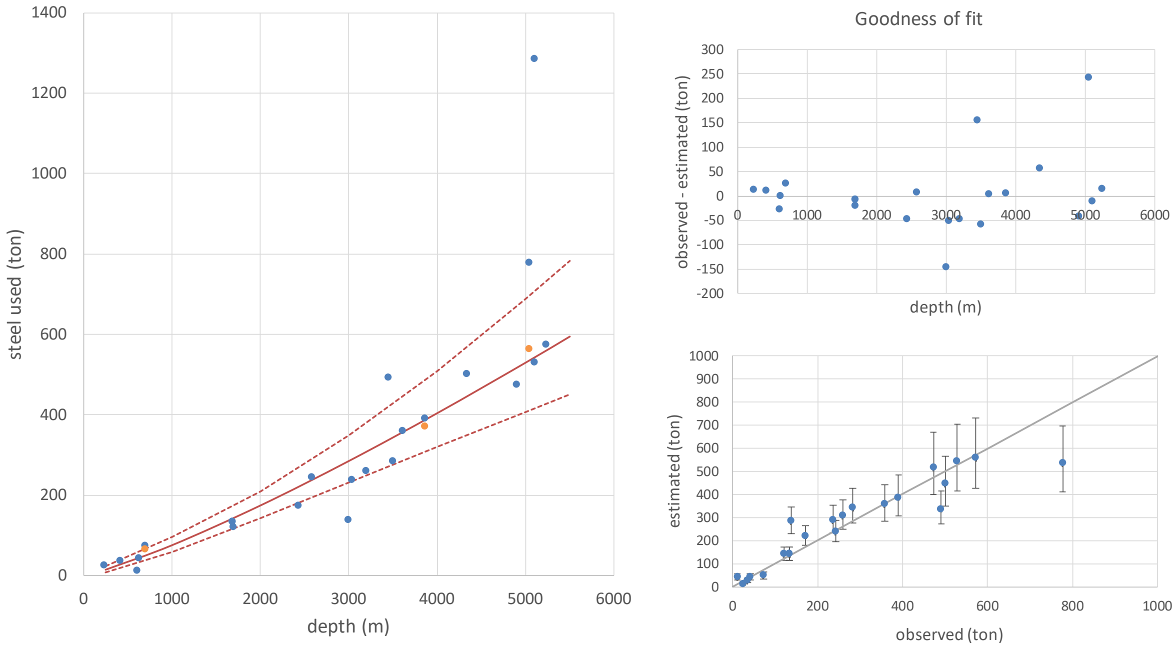

Figure A 16: Results of the least squares fit of steel used version the measured depth of selected wells. Orange dots are control data points.

Cement usage

The amount of cement used to complete a geothermal well can be either calculated from the well design or estimated from the depth of the well.

In case a well design is not available, the amount of steel used to complete a well is estimated using the following equation:

$$log(cement) = 1.23 \times log(d) - 2.15$$

With d the total depth of the well and cement the amount of cement used in m^3.

This relationship is derived from the data reported in Table A 7. The cement quantities reported in the table are calculated based on the well design reported in the literature or by plant operators using a cost model for geothermal wells developed by VITO.

Table A 8: Proxies for Drilling – Cement Used

	depth	cement (m^3)
MOL-GT-03	4,905	308.7
MOL-GT-02	4,341.2	320.2
MOL-GT-01	3,610	221
DSL-NZM	604	25.6
GPK-3	5,101	140.3
GPK-4	5,235	175.1
GRT-01	2,579.9	157.4
GRT-02	3,196	223.9
KW1	5,048	137.1
GT-Uha1a	3,446	273
GT-Uha2a	3,864	170.6
HH1	692.2	32.6
HLN3	412.8	6
HLN1	229.8	5.9
CAL-GT-04	3,037.4	120.4
CAL-GT-05	2,433	111.1
CAL-GT-02	1,694.3	76.5
GVLB2	1,690	70.9
GVLB1	1,689	71.2
Cha-trias	623	20.8
Saint-Ghislain	3,000	58
well*	3,500	168.6
KW2	5,100	578.6

* confidential data

The estimate does not include cement needed for the cellars and for the construction of the drilling floor.

Bentonite can be added to the cement formulation. This is especially the case for deeper section. The added amount typically is in the range of 0.5 - 2% of the cement mixture. Bentonite used for cement is not included in the estimation of the materials used for drilling.

Filler (silica, fiber glass, ...) can be added to the cement formulation. The added amounts vary widely. Filler for cement is not included in the estimation of the materials used for drilling.

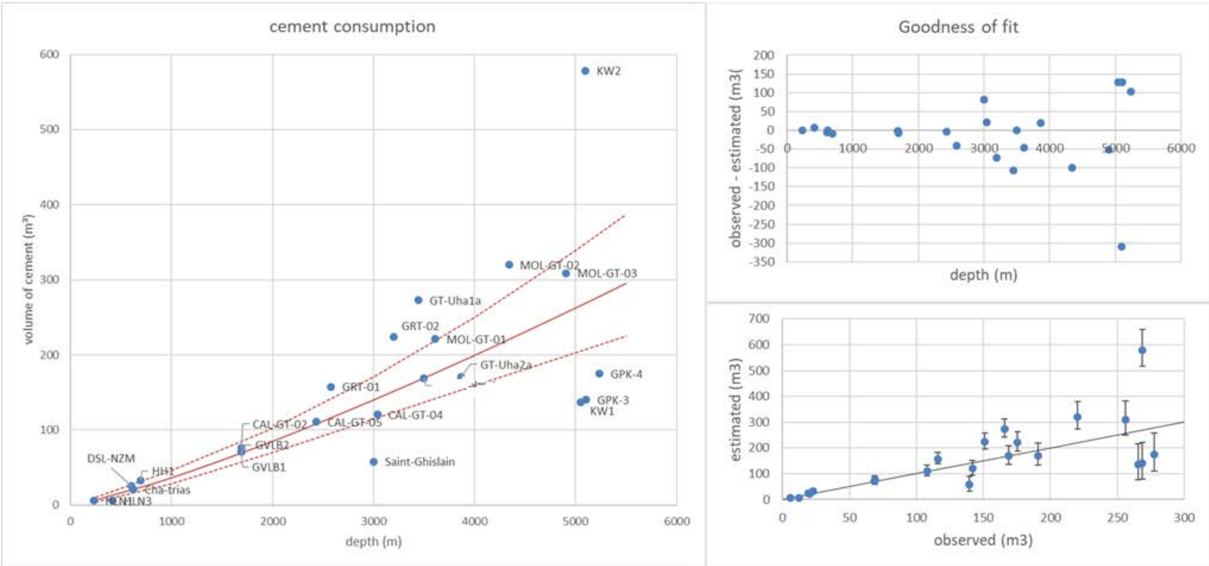

Figure A 17: Results of the least squares fit of cement used version the measured depth for selected wells.

Cuttings removed

The volume of cuttings removed from the well is calculated from the drilled volume considering an average oversize of the well of 25%. The excavated volume was calculated from the well design of selected geothermal wells covering the ranges in depth and final hole diameter encountered in geothermal wells drilled in Europe Table A 10.

Table A 9: Proxies for Drilling – Cuttings produced

	depth	cuttings (ton)
MOL-GT-03	4,905	798.8
MOL-GT-02	4,341.2	781.2
MOL-GT-01	3,610	587.8
DSL-NZM	604	44.3
GPK-3	5,101	670.7
GPK-4	5,235	714.7
GRT-01	2,579.9	411.7
GRT-02	3,196	531.4
KW1	5,048	489.6
KW2	5,100	922.3
GT-Uha1a	3,446	643.7
GT-Uha2a	3,864	586.1
HH1	692.2	84.9
HLN3	412.8	59
HLN1	229.8	41.3
CAL-GT-04	3,037.4	383.1
CAL-GT-05	2,433	346.9
CAL-GT-02	1,694.3	226.8

	depth	cuttings (ton)
GVLB2	1,690	193.4
GVLB1	1,689	193.9
Cha-trias	623	78.5
Saint-Ghislain	3,000	203.4
Well*	3,500	492.4

*confidential data

The correlation with depth length is:

$$cuttings\ [m^3] = 0.0948\ \times depth\ [m]^{1.046}$$

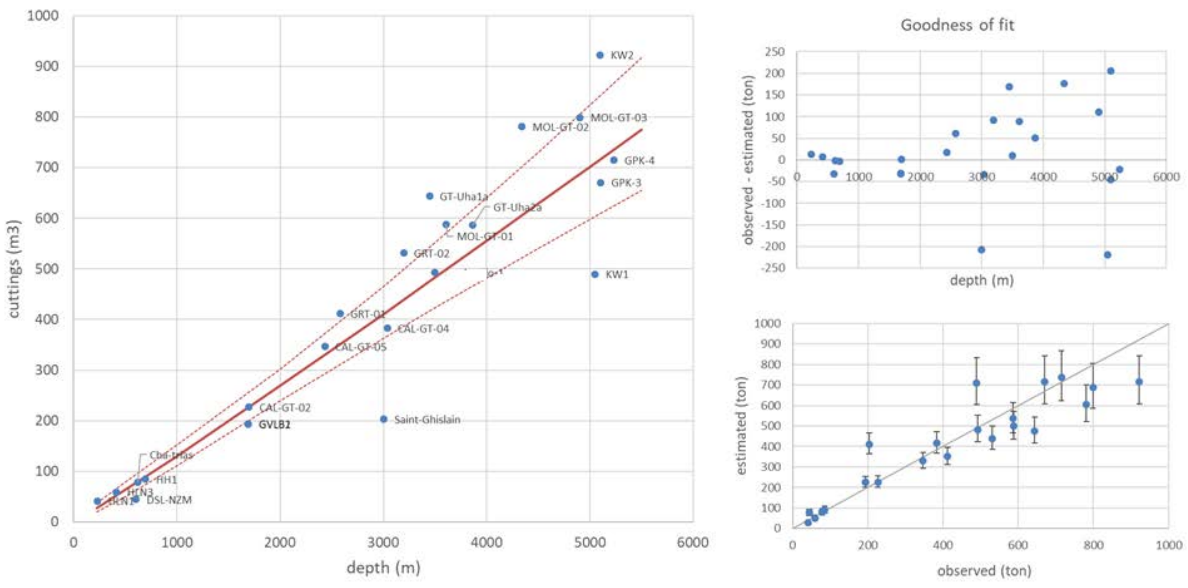

Figure A 18: Results of the least squares fit of cuttings removed against the measured depth of selected wells.

Mud used

The amount of drilling mud is estimated from a cost model for geothermal wells developed by VITO. The correlation used is:

$$drilling\ mud\ [m^3] = 0.157 \times MD\ [m]$$

The reliability of the estimate is judged to be moderate, resulting in an uncertainty of 15%.

EMISSIONS RELATED TO STIMULATION

Energy consumption

The energy consumption for stimulation is calculated from the power needed to pump the stimulation fluid and the volume of stimulation fluid used in the operation. In case more than one stimulation job was performed, the energy consumption of the different jobs is summed.

The energy usage is calculated using the flowing equation (Equation 1):

Equation 1: $$E = \frac{\Delta P \times V}{3.6 \times 10^4 \times n_p}$$

with E the energy consumption in MWh, ΔP the pressure difference delivered by the pump in bar, V the pumped volume in m3 and n_p the efficiency of the pump.

In case the pumped volume and pressure difference are not given, standard values are used. The proxies for the different types of information are based on the depth and type of the reservoir and overpressure (Table A 10).

Table A 10: Standard values used to calculate energy usage for stimulation in case no well-specific values are available. Pe stands for the overpressure in bar and d the reservoir depth in meters below the surface

Type	volume per job	jobs / well	pressure difference
Acid stimulation	250 m^3/job	2	P_e + .030 x d
Thermal stimulation	10,000	1	P_e + .015 x d
Hydraulic stimulation	EGS: 27,000 m^3/well hydrothermal: 15,000 m^3/job	1	EGS: P_e + .125 x d hydrothermal: P_e + .062 x d

Hydraulic stimulation

There is little information available in literature to calibrate the proxies. When it comes to hydraulic stimulation, Clark et al. (2012) mention that published information on the volumes of stimulation fluids used in EGS projects is limited. Based on available data from EGS projects with different geological characteristics they conclude that average volume of water used is 26,939 m3 per well. Based on the inventory given by Treyer et al. (2015) and data from Basel (Häring et al., 2008) and Landau (Schindler et al., 2010), a dataset of 26 stimulation jobs was compiled for calibration of the proxies. From this dataset, the average water consumption for hydraulic stimulation of low-transmissivity geothermal reservoirs is estimated at 15,000 +/- 5,000 m^3 per job. For EGS, the average amount of fluid injected is about 27,000 +/- 10,000 m^3 per job. In many cases three or more jobs are performed in order to achieve sufficient connectivity between the wells. By default, the number of hydraulic stimulation jobs is set at 1 per well.

Wellhead pressure applied for hydraulic stimulation tend to increase with reservoir depth. From the calibration dataset a linear correlation against reservoir depth was derived to assess the pump pressure needed to inject the stimulation fluid (Figure A 19). For EGS projects, the estimated pump pressure equals the overpressure within the reservoir, if any, plus 0.125 times the depth of the reservoir. For thigh hydrothermal reservoirs, the pump pressure is set at 0.062 times reservoir depth plus any overpressure.

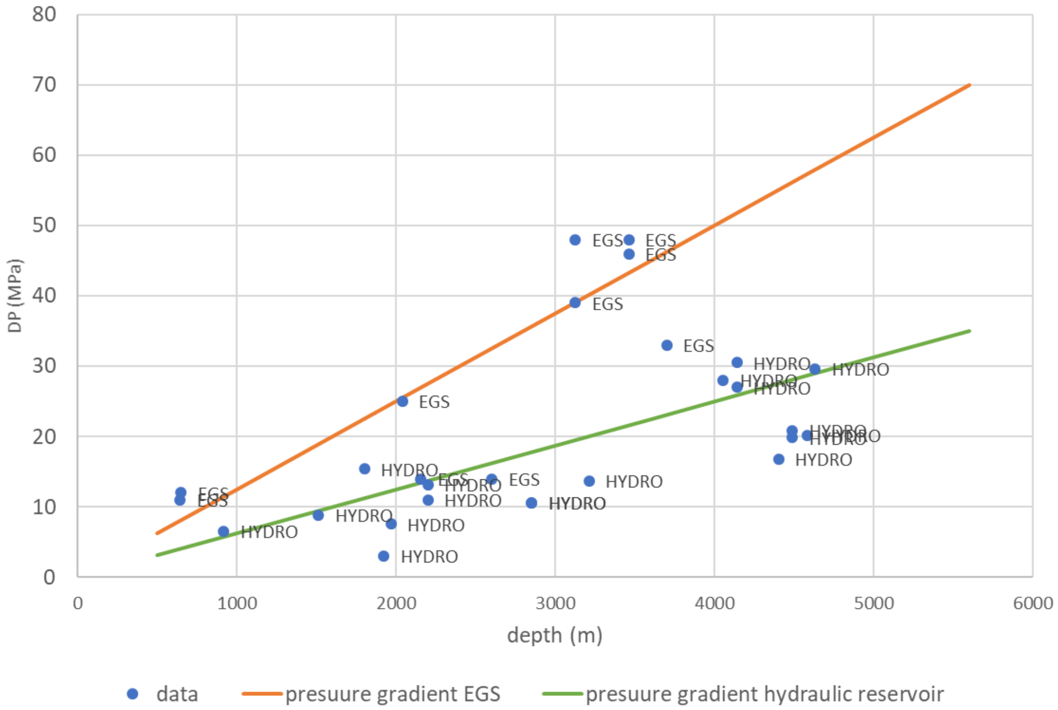

Figure A 19: Pressure applied for hydraulic stimulation in EGS projects and to stimulate low-transmissivity hydraulic reservoirs. The orange line represents the pressure-depth relationship used to calculate the pump pressure applied for fracking in EGS projects. The green line represents the pressure-depth relationship used to calculate the pump pressure applied to hydraulically stimulate low-transmissivity hydraulic reservoirs.

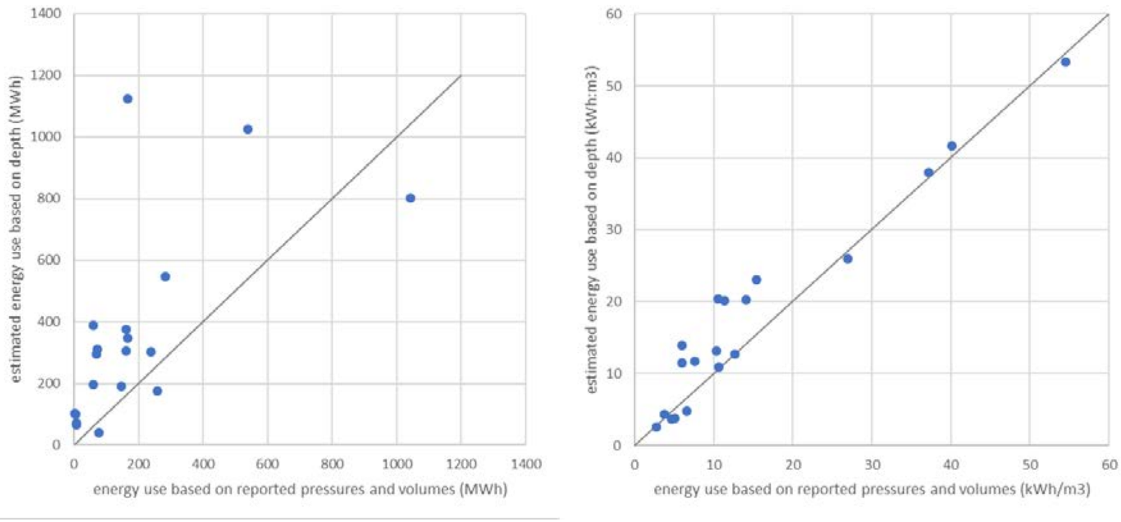

Figure A 20: Comparison of the results of the proxy based on depth with the calculated values for the calibration dataset.

Figure A 20 shows a comparison of the estimated energy consumption for hydraulic stimulation based on the proxy with the calculated energy consumption for the stimulation of 19 geothermal wells based on reported stimulation pressures and pumped volumes. For most of the wells the proxy based on reservoir depth results in overestimation of the total amount of energy needed. For about 40% of the wells, the proxy also overestimates the energy use per m^3 of water injected.

Literature data on the energy consumption for hydraulic stimulation is limited. Table A- 11 summarizes literature data on the water use and energy consumption for hydraulic stimulation of geothermal wells. The reported energy use varies between 20 and 100 kWh/m3 of injected water.

The energy use calculated for the calibration dataset using **Equation 1** and reported injection pressures and volumes ranges from 1,200 kWh to 1,404,000 kWh. The large range is mainly due to differences the injected volume: it ranges from 200 up 34,000 m^3 per job. The injection pressure applied largely differs. It ranges from 66 to 655 bar. The energy used per volume of water pumped ranges from 2.8 to 54.5 kWh/m^3. The average value is 15.1 kWh/m. The value increases with reservoir depth.

The calculated values are low compared to the figures reported in literature. Only Lacirignola and Blanc (2013) report similar figures. They derived their estimate form literature from Soultz-sous-Forêts and Landau. A comparison of the total amount of energy used for these locations reveal similar results: 388,920 kWh according to Lacirignola & Blanc (2013) versus 636,500 +/- 283,500 kWh.

Acid stimulation

Unless the injected volume are given, the volume of injected fluid (including pre- and post-flush) is set at 250 m^3 per acidizing job. The average volume is derived from data reported for Landau (Schindler et al., 2010),Soultz-sous-Forêts (Portier et al., 2009) Rittershofen (Vidal et al., 2016) and Balmatt (Van Gastel & Van Zutphen, 2016a,b). In the Molasse Malm reservoir, wells are usually treated with 100 – 600 m^3 of HCl (Wolfgramm). The reported volumes are in line with the ball-park figures reported by service companies (Barrios et al., 2012):

- For wells with high contents of silica and damage caused by mud and cuttings the amount of fluid used (pre-flush + main flush) for acid stimulation is about 0.88 m3 per meter of productive interval;

- For wells with a potential of calcite and mud damage the amount of fluid used (pre-flush + main flush) for acid stimulation is about 1.25 m^3 per meter of productive interval.

In many cases one to three acidizing jobs are performed on per well. The default value for the number of acid jobs used for assessing the emissions from the chemical stimulation is set at 2.

The injection pressure is by default set at 0.03 times the reservoir depth plus the overpressure within the reservoir, is any. De default value is overruled in case the injection pressure is reported.

Thermal stimulation

Thermal stimulation is not widely applied in the European geothermal sector. The only case is cluster 2DHC.

EMISSIONS RELATED TO TESTING

Direct emissions

Direct gas emissions during testing are based on the concentration of specific gasses in the geothermal fluid and the solubility of the gasses in the fluid.

Equation 2: $$\boldsymbol{G = max\lfloor 0, m_g + s_0 - s_i,\ \ m_g + s_0 - s_a \rfloor \times V}$$

With G the mass of gas released during testing in kg, V the volume of fluid produced during testing in m^3, m_g the measured gas content of the geothermal fluid in kg/m^3, s_0 the solubility of the gas in the geothermal fluid under measurement conditions in kg/m^3, s_i the solubility of the gas the geothermal fluid under wellhead conditions and s_a the solubility of the gas the geothermal fluid under atmospheric conditions in kg/m^3. Unless information about the analytical method is available s_0 is set at 0 kg/m^3.

The solubility of CO2 in the geothermal fluid is calculated using the model published by Duan and Sun (2006). For CH4, the model published by Bebout and Bachman (1981) is used, for H2S the model published by Suleimenov and Krupp (1994). For other gasses, full degassing is assumed.

Energy consumption

In case of a pumped well, the energy consumption during testing is calculated using Equation 1. The deltaP during testing is either supplied as an input parameter or calculated from the productivity function or production index of the well.

EMISSIONS RELATED TO PRODUCTION

Direct and indirect emissions related with production are calculated on an annual basis. In order to get the lifecycle emissions, the figure need to be multiplied by the life time of the plant.

Direct emissions

Direct gas emissions during production are estimated using a procedure that is similar to the one used to assess direct emissions during testing. They depend on the gas content and compositions of the geothermal fluid and the solubility of the gasses in the fluid.

Equation 3: $$\boldsymbol{G = max\lfloor 0, m_g + s_0 - s_i,\ m_g + s_0 - s_e \rfloor \times V}$$

where s_i stands for the solubility of the gas under the pressure and temperature conditions at the production site and s_e stands for the solubility of the gas injection or disposal of the geothermal fluid.

Energy consumption

For pumped production wells, the energy consumption during the production phase is calculated in the same way as the energy production during testing. In case of pumped wells, the energy consumption for the production and injection wells is calculated as follows:

Equation 4: $$\boldsymbol{E_p = \sum_{i=1}^{w} \frac{\Delta P_i \times V_i}{3.6 \times 10^4 \times n_{p,i}}}$$

with E_p the energy consumption in MWh, ΔP_i the pressure difference delivered by the pump in well i in bar. The pressure difference is either supplied as an input parameter or calculated from the productivity function or productivity index / injectivity index of the well. A positive value is used in case of pressure drawdown (production wells), a negative value to pressure buildup (injection wells)

V_i is the volume of geothermal fluid produced or injected in well i m^3. For production, the volume is a positive value. For injection it is negative. $n_{p,i}$ the efficiency of the pump in well i.

In case of multiple pumped production or injection wells, the produced and injected volume are equally divided over the number of wells.

PROXIES USED TO ASSESS PRODUCTION RELATED EMISSIONS

Efficiency of electricity production

Binary systems

The net efficiency of binary systems is derived from the enthalpy of geothermal fluid entering the unit:

Equation 5: $$n_e = 13.40 * ln(h_i) - 74.60$$

with hi the enthalpy of geothermal fluid entering the unit in kJ/kg.

The correlation is based on the data published by Moon and Zarrouk, 2012 (Figure A 21).

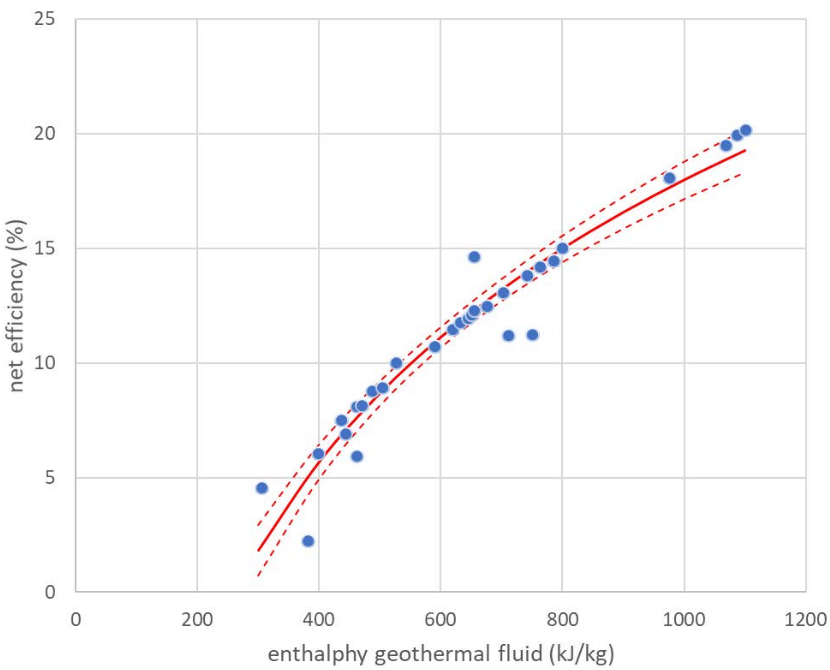

Figure A 21: Net efficiency of binary geothermal plants as a function of the enthalpy of the geothermal fluid entering the power unit

Table A 12: Plants' features

Country	Field (Plant name)	No. Unit	Start Date	Installed Capacity (MWe)	Running Capacity (MWe)	m (t/h)	Tin (℃)	Tout (℃)	h (kJ/kg)	cp (kJ/kg/°C)	h_in	h_out	Dh	m (kg/s)	P_th (MW)	net efficiency (%) based on running capacity
USA	*Alaska (Chena Hot Springs)*	2	2006	0.5	0.4	471	73	57	306	4.19	306	239	67	131	8.77	0.05
USA	*Wyoming-Casper (Rmotc-Ghcg)*	1	2008	0.25	0.171	166	91	52	381	4.19	381	218	163	46	7.53	0.02
Germany	*Neustadt-Glew*	1	2003	0.23	0.165	93	95	70	398	4.19	398	293	105	26	2.71	0.06
USA	*Nevada (Wabuska)*	3	1984	2.2	1.5	407	104	62	436	4.19	436	260	176	113	19.91	0.08
Australa	*Altheim*	1	2002	1	0.5	172	106	70	444	4.19	444	293	151	48	7.20	0.07
Australa	*Blumau*	1	2001	0.2	0.18	103	110	85	461	4.19	461	356	105	29	3.00	0.06
USA	*California-Honey Lake (Wineagle)*	2	1985	0.7	0.6	226	110	82	461	4.19	461	344	117	63	7.37	0.08
China	*Nagqu*	1	1993	1	1	300	112	77	470	4.20	470	323	147	83	12.24	0.08
Thailand	*Fang*	1	1989	0.3	0.175	28	116	55	487	4.20	487	231	256	8	1.99	0.09
Germany	*Unter-Haching (Unter-Haching)*	1	2009	3.36	3.36	424	120	44	504	4.20	504	185	319	118	37.59	0.09
USA	*California-East Mesa (Ormesa IE)*	10	1989	10	9	1054	136	58	527	3.88	527	225	302	293	88.49	0.10
USA	*Idaho (Raft River)*	1	2007	13	10	1440	140	85	589	4.21	589	358	231	400	92.56	0.11
USA	*California-East Mesa (Ormesa 1)*	26	1987	24	24	2652	147	80	619	4.21	619	337	282	737	207.84	0.12

Country	Field (Plant name)	No. Unit	Start Date	Installed Capacity (MWe)	Running Capacity (MWe)	m (t/h)	Tin (℃)	Tout (℃)	h (kJ/kg)	cp (kJ/kg/°C)	h_in	h_out	Dh	m (kg/s)	P_th (MW)	net efficiency (%) based on running capacity
Germany	*Landau (landau)*	1	2008	3	3	231	150	56	632	4.21	632	236	396	64	25.41	0.12
USA	*California-East Mesa (Ormesa IH)*	12	1989	12	10.8	935	153	71	645	4.22	645	299	346	260	89.78	0.12
USA	*California-East Mesa (Ormesa 2)*	20	1988	20	18	1555	154	73	650	4.22	650	308	342	432	147.67	0.12
France	*Soultz-Sous-Forets*	1	2008	1.5	1.5	98	155	49	654	4.22	654	207	447	27	12.18	0.12
Nicaragua	*Momotombo (Unit3)*	1	2002	7.5	6	628	155	100	654	4.22	654	422	232	174	40.48	0.15
USA	*Nevada-Washoe (Steamboat1,1A,2,3)*	13	1986	35.1	31	6120	160	126	676	4.23	676	532	144	1700	244.21	0.13
USA	*California-Heber (Heber2)*	12	1993	33	33.5	3266	166	100	702	4.23	702	423	279	907	253.21	0.13
Turkey	*Salavatli*	1	2006	7.4	6.5	545	170	80	710	4.18	710	334	376	151	56.90	0.11
USA	*California-Casa Diablo (MP-1,2/ LES-1)*	10	1984	40	40	3240	175	100	741	4.23	741	423	318	900	285.81	0.14
USA	*Utah-Roosevelt Hot Springs (Blundell2)*	1	2007	11	10	840	177	88	750	4.24	750	373	377	233	87.99	0.11
Mexico	*Los Azufres (U-11,12)*	2	1993	3	3	280	180	117	763	4.24	763	496	267	78	20.77	0.14
El Salvador	*Berlin (U4)*	1	2008	9.4	8	1018	185	140	785	4.24	785	594	191	283	54.00	0.15

Country	Field (Plant name)	No. Unit	Start Date	Installed Capacity (MWe)	Running Capacity (MWe)	m (t/h)	Tin (℃)	Tout (℃)	h (kJ/kg)	cp (kJ/kg/°C)	h_in	h_out	Dh	m (kg/s)	P_th (MW)	net efficiency (%) based on running capacity
USA	*Nevada-Fallon (Soda Lake1)*	3	1987	3.6	2.7	181	188	105	799	4.25	799	446	353	50	17.74	0.15
New Zealand	*Northland (Ngawha)*	2	1997	10	8	417	228	142	975	4.28	975	607	368	116	42.60	0.19
Japan	*Oita (hatchobaru)*	1	2006	2	2	82.1	246	146	1068	4.34	1068	634	434	23	9.90	0.20
New Zealand	*Te Huka*	1	2010	24	21.8	750	250	133	1086	4.34	1086	578	508	208	105.89	0.21
Portugal	*Ribeira Grabde*	4	1994	13	13	452	253	139	1100	4.35	1100	604	496	126	62.23	0.21

Efficiency of heat production

Efficiency of heat delivery is fixed at 0.95.

Enthalpy of the geothermal

The enthalpy of the geothermal fluid leaving the plant is calculated from the running power and/or heating capacity and the mass flow rate of the wells:

$$\text{Equation 6:} \quad \boldsymbol{h_e = h_i - \frac{P}{\dot{m}_b \times n}}$$

With P the power or heating capacity of the plant in watt, $\dot{m}_b$ the mass flow rate in kg/s and n the efficiency of the power or heat generation. In case of a combined heating and power geothermal plant, h_e is calculated as the mixing temperature of the geothermal fluid leaving the power generation unit and the heat delivery unit.

Flash and Dry systems

For flash and dry steam plants the direct emissions are estimated based on a step by step methodology. In general, the steam flow rate entering the turbine combined with the gas content and composition, as well as the efficiency of the abatement systems will be used to assess the production related emissions of flash plants.

The data used for the calculation of direct emissions are the following:

- Steam NCG gas content and composition
- Efficiency of abatement system
- Annual electricity production
- Mean mass flow rate
- Steam mass produced per year

The first steps consists in estimating the steam mass produced per year which is derived from the annual electricity production and the efficiency of the plant.

Step 1: calculate the efficiency of the system:

n = We * 1000 * 100/ ((hi - he) * m)

With m the flow rate (kg/s), We the plant running capacity (MWe), hi, the inlet enthalpy (kJ/kg), he the outlet enthalpy (kJ/kg) and n the efficieny of the system (%).

Step 2: Calculate total mass of geothermal fluid (steam) passed through the system per year (kg)

M_e = E * 3.6e+6 / (n/100 * Dh)

Where E is the energy delivered by the system (MWh) per year, n the net efficiency of the system (%), Dh the enthalpy difference between the geothermal fluid entering and leaving the system (kJ/kg) and M_e the total mass of geothermal fluid (steam) passed through the system per year (kg/yr).

Note that for flash and dry steam plants, it is assumed that all NCG are partitioned into the gas phase in the condenser.

Step 3 - Calculate annual direct emissions without abatement

The amount of NCG flowing through the turbine can be calculated based on:

Equation 7: $$\boldsymbol{m_{NCG} = f * m_s}$$

Where, f is the NCG mass fraction in the steam and m_s is the steam flow rate passing through the turbine.

To calculate the proportion of the individual NCG the steam composition is used.

Equation 8: $$\boldsymbol{m_{i,NCG} = m_{NCG} \times mass\ fraction\ of\ NCG, i}$$

Step 4 – Calculate annual direct emissions for gasses witht abatement

Finally, the overall efficiency of the abatement system that is selected for the specific NCG is applied and the amount of NCG released into the atmosphere from flash and dry plants is calculated:

Equation 9: $$\boldsymbol{m_{i,NCG-released} = m_{i,NCG} \times (1 - \eta_{i\ abatement})}$$

Table A 13: Abatement systems efficiencies assumed in the study

	Cluster 3P-CHP	Cluster 4P	Cluster 4P-CHP
Efficiency of AMIS towards H2S [%]	92.5	94.3	98.1
Efficiency of AMIS towards Hg [%]	92.5	92	86.7
Efficiency of NH3 abatement [%]	87*	98.3	94.8

For cluster 1P-CHPa, to account for the abatement of H2S and CO2 via reinjection (Sulfix, Carbfix projects) abatement efficiencies of 30% for CO2 and 75 % for H2S.

Applications of the methodology:

Step 1 and step2 have been perfomed for all clusters comprising dry steam and flash steam plants to estimate the volume of steam produced annually. Table A 14 below shows the volume estimated and the ones calculated based on actual plants datafor a few plants where field data were provided by operators.

Table A 15: Steam Production

Plant	steam produced / year based on the methodology proposed [kg/yr]			Steam produced/ year based on load in hours* flow rate [kg/yr] field data
	Mean Value	Min value	Max value	
4P CHP	3,498E+09	3,465E+09	3,53E+09	3,5E+09 (8752 h* 400t/h)
4P	3,453E+09	3,42E+09	3,48E+09	3,48E+09 (8700 h * 400 t/h)
1P CHPa	5.25E+09	4.99E+09	5.51E+09	5.41E+09 (8766h*0.95*650)
3P CHP	1,167E+09	1,11E+09	1,225E+09	1,134E+09 (8400 h*135 t/h)

The data for flash and dry steam plants were mainly collected in the lieterature. For the Italian plants, which comprise dry and single flash plants, for most plants only the installed and running capacities has been reported for 2018 (Annexes of EGEC Market report, 2018 and Manzella et al. (2019)) not the steam flow rate of the individual plants. For the flash plants in Iceland, the steam flow rate has been reported for the year 2018 (Ragnarsson et al., 2018) as well as the installed capacity.

In that case the outlet enthalpies is not available the steam flow rate is estimated using the thermodynamics considerations discussed by DiPippo, 2012. The proxies to be used are the installed or running power capacity, W_e [MW], the pressure at the inlet of the turbine [bar] (or temperature) and the condenser pressure [bar].

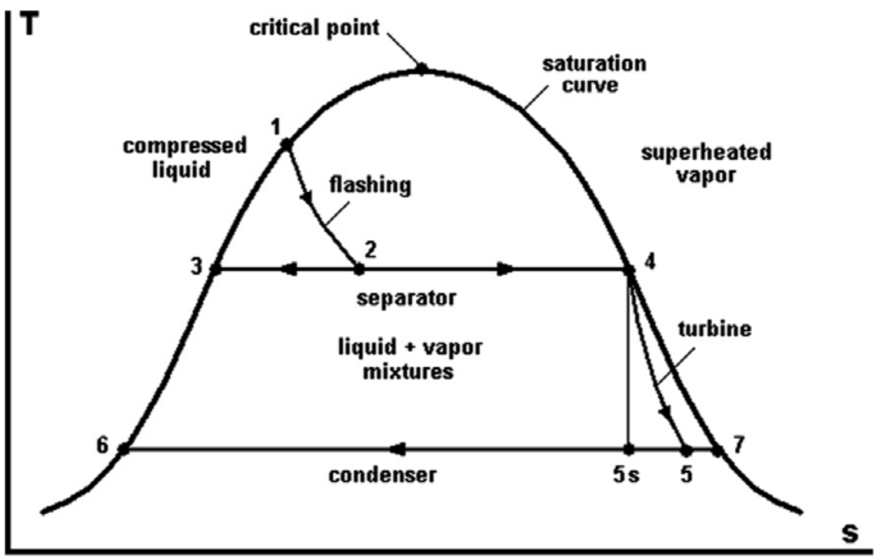

Figure A 22: Temperature-entropy state diagram for single – flash plants (DiPippo, 2012).

Figure A 22 displays in a thefrmodynamic state temperature-entropy diagram the processes undergone by the geofluid in single-flash plants. Note that similar diagram can be used for dry plants, in that case, the processes start at state 4.

For single flash plants, the sequence of processes begins with geofluid under pressure at state 1, close to the liquid saturation curve. The flashing process is modeled as one at constant enthalpy:

Equation 10: $h1=h2$

After flashing, the separation process takes place (isobaric process). The quality or dryness fraction, x, of the mixture that forms at state 2, is described by:

Equation 11: $\boldsymbol{x_2 = \frac{h_2-h_3}{h_4-h_3}}$

It represents the steam mass fraction of the mixture and is the amount of steam that goes to the turbine per unit total mass flow into the separator.

After separation, the steam flows through the turbine where it is expanded. The work produced by the turbine per unit mass of steam flowing through it is given by:

Equation 12: $\boldsymbol{w_t = h_4 - h_5}$

The power developed by the turbine is given by:

Equation 13: $\boldsymbol{\dot{W}_t = m_s \times w_t}$

The maximum possible work would be generated if the turbine operated adiabatically and reversibly, i.e., at constant entropy. The process shown in Figure A 22 from state 4 to state 5s represents the ideal process. The isentropic turbine efficiency, η_t, is defined as the ratio of the actual work to the isentropic work, namely:

Equation 14: $\boldsymbol{\eta_t = \frac{h_4-h_5}{h_4-h_{5s}}}$

$\dot{W}_t$ represents the gross mechanical power developed by the turbine from which the gross electrical power can calculated when multiplied by the generator efficiency:

Equation 15: $\boldsymbol{\dot{W}_e = \eta_t \times \dot{W}_t = \eta_t \times \dot{m}_s \times w_t}$

Finally, all auxiliary power consumption for the plant must be subtracted from the gross electrical power to obtain the net power. These so-called parasitic loads include all pumping power, cooling

tower fan power, and station lighting. Based on published data (DiPippo, (2012) and data provided by plant operators we assume the parasitic load to range between 5 and 9 %.

Equation 16: $\boldsymbol{\dot{W}_{e-net} = \eta_t \times \dot{m}_s \times w_t \times (1 - parasitic\ load)}$

Adopting the Baumann rule, the isentropic efficiency for a turbine operating with wet steam is given by:

Equation 17: $\boldsymbol{\eta_{tw}} = \boldsymbol{\eta_{td}} \times \left[\frac{x_4 - x_5}{2}\right]$

Where the dry turbine efficiency, η_{td}, may be conservatively fixed at 85%.

State 5 is determined by solving Equation 17 using the turbine efficiency and the fluid properties at state 5s, the ideal turbine outlet state (calculated from the known pressure and entropy values at state 5s). The ideal outlet enthalpy is :

Equation 18: $\boldsymbol{h_5} = \boldsymbol{h_6} + [\boldsymbol{h_7} - \boldsymbol{h_6}] \times \left[\frac{s_4 - s_6}{s_7 - s_6}\right]$

Incorporating the Baumann rule into the calculation, the following equation gives the enthalpy at the actual turbine outlet state:

Equation 19: $\boldsymbol{h_5} = \frac{h_4 - A\left[1 - \frac{h_6}{h_7 - h_6}\right]}{1 + \left[\frac{A}{h_7 - h_6}\right]}$

Where the factor A is defined as:

Equation 20: $\boldsymbol{A} \equiv \mathbf{0.425}(\boldsymbol{h_4} - \boldsymbol{h_{5s}})$

Once h5 is known it can be used as input for step 1.

Validation of the methodology comparison of direct emissions reported by operators and estimated:

The data provided by several operators have been compared to the values of direct emissions calculated using the methodology described. Table A 16 below summarizes the estimated and reported emissions for several falsh and dry steam plants.

Table A 17: Plants' emissions

Plant	estimated emissions of CO2 [ton/yr]	Emissions of CO2 [ton/yr]	estimated emissions of H2S [kg/yr]	Emissions of H2S [kg/yr]
1P CHPa (not accounting for abatement)	3.5E+4	3.6E+4	1.04E+4	9.1E+3
1P CHPb	1.3E+4	1.35E+4	6.03E+3	6.4E+3
4P	2.74E+5	confidential	2.65E+5	confidential
4P CHP	2.36E+5	confidential	9.09E+4	confidential

* for 1P CHPa and 1P CHPb reported by the operator and for 4P and 4P-CHP calculated based on mean flow rate, hours of operation and hourly emissions reported by control authority.

ANNEXES III: KEY PARAMETERS AND LIFE CYCLE INVENTORIES

Key Plant Parameters

plant	type of plant	Electricity production (MWh)	Uncertainty on electricity production (MWh)	Heat production (MWh)	Uncertainty on heat production (MWh)	Running capacity (Mwe)	Running thermal capacity (MWth)	Flow rate (kg/s)	T in (°C)	T out (°C)	P inlet (bar)	P outlet (bar)	inlet enthalpy	dhf
1P-CHPa	1	2347000				303		600	178	50	9.51	0.12		0 * x
1P-CHPb	1	984000				120		230	192	50	13.01	0.12		0 * x
1P-CHPa	4			630000			133	83.3	100	60	9.51	1		0 * x
1P-CHPb	4			1203000			300	55	100	60	13.01	1		0 * x
Cluster 1P	1	682500	34125			86.1		160	180	50	12	0.12		0*x
Cluster 2P	3	85520	4200			14.1		100	170	95	8	1		0*x
Cluster 3P	0	125900	6295			16.5		38.5	177.8		9.5	0.1		0 * x
Cluster 3P-CHP	4			4500	225		2.9	38.5	100	60	9.5	1		0 * x
Cluster 4P	1	523200	5000			60		110	207.5		19	0.1		0 * x
Cluster 4P-CHP	1	530000	5000			60		110	207.5		19	0.1		0*x
Cluster 4P-CHP	3	8000	1000	32000	1600	1	21.1	18	150		8.5	1.013		0*x
Cluster 5P	3	22000	1000			3	3	50	165	70	22	20		7,5 * x + ,05 * x**2
Cluster 5P-CHP	3	22000	1000	9200	500	3	3	50	165	70	22	20		7,5 * x + ,05 * x**2
Cluster 6P	3	25000	1750			10		83	172		20			0*x
Cluster 7P	3	5400	500	43500	4000	0.9	12	45	125	50	45	42		8,5 * x + ,005 * x**2
Cluster 8P	3	30400	1520			6		122.5	137	55	15			5, * x + ,01 * x**2
Cluster 8P-CHP	3	25250	1250	44800	2250	5	22.75	112.5	129.5	55	15			5, * x + ,01 * x**2

Key Plant Parameters

plant	type of plant	Heat production (MWh)	Uncertainty on heat production (MWh)	Running thermal capacity (MWth)	Flow rate (kg/s)	T in (°C)	T out (°C)	P inlet (bar)	P outlet (bar)	dhf
Cluster 2DHC	4	180000	9000	25	85	170	70	25		8 * x + ,05 * x**2
Cluster 3DHC	3	16200	1620	6.5	20	85	40	6	1	0 * x
Cluster 4DHCa-PB	4	37540		10.3	75	69	48	9.6	22.7	4,1 * x + ,025 * x**2
Cluster 4DHCb	4	28850	1442.5	11.2	70.8	54	14.3	20	20	
Cluster 5DHC	3	48800		14	76	90.5	50	15		3 * x + ,0125 * x**2

Cluster 1P

Gas Composition [mass fraction]

CO_2	CH_4	H_2S	H_2	N_2	NH_3	As	Hg	remark
5.0E-03	2.2E-06	1.8E-04	1.1E-03	6.2E-05				data from Altamirano 2006 G-35
9.7E-04	2.3E-07	3.0E-04						data from Oskarsson et al 2013 well 1 sampling P 31,8 bar-g
1.4E-03		2.6E-04						data from Armansson 2013 well ThG-1 at 280°C
2.3E-03	7.6E-07	5.8E-04			3E-6			mean values data from Trausti Hauksson 2015
6.8E-03		1.4E-04						Ravazdezh 2015 0,7% NCG 98%CO_2 2% H_2S
1.6E-03	2.8E-07	5.6E-05			2.8E-6			primary data
6.8E-03	8.8E-07	4.9E-04	8.0E-05	4.9E-05				data from Altamirano2006 G-1
5.9E-03	8.8E-07	5.8E-04	7.8E-05	5.0E-05				data from Altamirano 2006 G-2
9.8E-03	3.2E-07	1.33E-04	9.47E-07	1.42E-04				data from Altamirano 2006 well 22
3.9E-03	1.4E-07	5.3E-05	3.8E-07	5.6E-05				data from Altamirano 2006 well 12 corrected at 1 bar
4.1E-03	1.0E-06	3.9E-04	1.8E-05	1.5E-04		1.9E-9	2.5E-11	Based on min NCG reported 0,4% by Benediktson 2011 and gas composition from Mamrosh et al, 2014; Giroud (2008) for As and Hg in the vapour phase min values for Reykjanes
8.3E-03	7.3E-06	1.1E-03	7.3E-05	3.2E-05		3.5E-10	6.1E-11	data from Hauksson 2013 LV-2013-073 mean value; Giroud (2008) for As and Hg in the vapour phase min values Krafla

CO2	CH4	H2S	H2	N2	NH3	As	Hg	remark
2.9E-03	1.7E-05	2.7E-03	2.1E-04			5E-11	3E-12	Based on gas composition Mamrosh et al., 2014 and NCG content based on Mamrosh et al, 2012; Giroud (2008) for As and Hg in the vapour phase max values Krafla
1.2E-03	1.3E-05	9.2E-04	5.4E-05	3.58E-05		3.29E-10	1.5E-11	data from Hauksson 2013 LV-2013-073 mean value; Giroud (2008) for As and Hg in the vapour phase max values Krafla

Life Cycle Inventory

Process	Flow	U.o.M.	1P	
			Min	max
Exploration	fuel	l	n.a.	n.a.
Drilling, casing, cementing	Eused	MWh	9.8E+03	2.3E+04
	fuel	l	2.1E+05	3.8E+05
	steel	kg	4.5E+06	6.7E+06
	cement	m3	2.2E+03	3.2E+03
	mud	m3	8.1E+03	1.1E+04
	cuttings	ton	7.4E+03	9.5E+03
Stimulation	Eused	MWh	n.a.	n.a.
Testing	Eused	MWh	n.a.	n.a.
	CO2	kg	n.a.	n.a.
	CH4	kg	n.a.	n.a.
	H2S	kg	n.a.	n.a.
	NH3	kg	n.a.	n.a.
	Hg	kg	n.a.	n.a.
	As	kg	n.a.	n.a.
	N2	kg	n.a.	n.a.
Surface components	stainless	kg	2.4E+05	2.7E+05
	steel	kg	6.2E+06	6.9E+06
	aluminium	kg	1.2E+05	1.4E+05
	copper	kg	4.0E+04	4.8E+04
	mineral wool	kg	1.2E+05	2.5E+05
	plastics	kg	2.3E+05	2.6E+05
	concrete	kg	7.4E+06	1.2E+07
	organic chemicals	kg	0.0E+00	0.0E+00
	titanium	kg	4.3E+04	4.7E+04
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	6.5E+05	7.2E+05
	Eth	MWh/y	nan	nan
Annual operation - Emissions	CO2	kg/y	8.1E+06	3.3E+07
	CH4	kg/y	0.0E+00	4.5E+04
	H2S	kg/y	0.0E+00	8.0E+06
	N2	kg/y	1.2E+05	5.5E+05
	NH3	kg/y	1.3E+04	1.4E+04
	Hg	kg/y	1.4E-02	2.8E-01
	As	kg/y	2.3E-01	8.7E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	2.3E+03	1.3E+04
	waste - filters disposal	kg/y	1.6E+03	9.2E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	2.1E+04	1.2E+05
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	0.0E+00	0.0E+00
Annual operation - Surface components replacement				

Cluster 1P CHPa

Gas Composition [mass fraction]

CO_2	CH_4	H_2S	H_2	N_2	remark
1.36E-03	2.29E-06	5.68E-04	1.44E-05	2.54E-05	Berstad and Nord 2016
2.92E-03	4.38E-06	7.50E-04	3.13E-05		Karlsdottir 2015
2.92E-03	4.38E-06	7.50E-04	3.13E-05		Karlsdottir pers,com 2020
2.28E-03	3.13E-06	5.68E-04	2.14E-05	2.23E-05	Geo-Cat project report

Life Cycle Inventory

Process	Flow	U.o.M.	1P CHPa	
			Min	max
Exploration	fuel	l	n.a.	n.a.
Drilling, casing, cementing	Eused	MWh	3.1E+04	6.8E+04
	fuel	l	6.4E+05	1.1E+06
	steel	kg	1.2E+07	1.8E+07
	cement	m3	5.9E+03	8.9E+03
	mud	m3	2.2E+04	3.0E+04
	cuttings	ton	2.0E+04	2.6E+04
Stimulation	Eused	MWh	n.a.	n.a.
Testing	Eused	MWh	n.a.	n.a.
	CO2	kg	n.a.	n.a.
	CH4	kg	n.a.	n.a.
	H2S	kg	n.a.	n.a.
	NH3	kg	n.a.	n.a.
	Hg	kg	n.a.	n.a.
	As	kg	n.a.	n.a.
	N2	kg	n.a.	n.a.
Surface components	stainless	kg	1.2E+06	1.4E+06
	steel	kg	5.3E+07	6.2E+07
	aluminium	kg	4.9E+05	5.8E+05
	copper	kg	1.6E+05	1.9E+05
	mineral wool	kg	5.1E+05	9.9E+05
	plastics	kg	1.0E+06	1.2E+06
	concrete	kg	5.7E+07	1.1E+08
	organic chemicals	kg	0.0E+00	0.0E+00
	titanium	kg	1.5E+05	1.7E+05
	transformer oil	kg	1.8E+05	2.2E+05
Annual operation - Production	Ee	MWh/y	2.2E+06	2.5E+06
	Eth	MWh/y	6.0E+05	6.6E+05
Annual operation - Emissions	CO2	kg/y	1.6E+07	3.4E+07
	CH4	kg/y	3.4E+04	7.1E+04
	H2S	kg/y	2.1E+06	3.1E+06
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	n.a.	n.a.
	As	kg/y	n.a.	n.a.
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	8.2E+03	4.6E+04
	waste - filters disposal	kg/y	5.7E+03	3.2E+04
	Chemicals for scaling, corrosion, fluid treatment	kg/y	7.3E+04	4.1E+05
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	0.0E+00	0.0E+00
Annual operation - Surface components replacement				

Cluster 1P CHPb

Gas Composition [mass fraction]

CO2	CH4	H2S	H2	N2	As	Hg	remark
1.92E-03	4.60E-06	8.89E-04	5.00E-05		5E-11	4E-12	Karlsdottir pers com 2020; Giroud (2008) for As and Hg in the vapour phase min values for Nesjavellir plant
1.94E-03	4.15E-06	9.6E-4	4.94E-05	47.7 E-5	1.86E-10	3.6E-11	Geo-Cat project report, Sigurðardóttir et al. (2018) and Giroud (2008) for As and Hg in the vapour phase max values for Nesjavellir plant

Process	Flow	U.o.M.	1P CHPb	
			Min	max
Exploration	fuel	l	n.a.	n.a.
Drilling, casing, cementing	Eused	MWh	8.5E+03	2.3E+04
	fuel	l	1.8E+05	3.7E+05
	steel	kg	3.5E+06	5.5E+06
	cement	m3	1.7E+03	2.6E+03
	mud	m3	6.8E+03	9.2E+03
	cuttings	ton	6.0E+03	8.0E+03
Stimulation	Eused	MWh	n.a.	n.a.
Testing	Eused	MWh	n.a.	n.a.
	CO2	kg	n.a.	n.a.
	CH4	kg	n.a.	n.a.
	H2S	kg	n.a.	n.a.
	NH3	kg	n.a.	n.a.
	Hg	kg	n.a.	n.a.
	As	kg	n.a.	n.a.
	N2	kg	n.a.	n.a.
Surface components	stainless	kg	1.1E+06	1.5E+06
	steel	kg	4.6E+07	5.4E+07
	aluminium	kg	3.2E+05	3.9E+05
	copper	kg	9.4E+04	1.2E+05
	mineral wool	kg	3.4E+05	5.6E+05
	plastics	kg	7.7E+05	1.0E+06
	concrete	kg	5.4E+07	1.1E+08
	organic chemicals	kg	0.0E+00	0.0E+00
	titanium	kg	6.0E+04	6.6E+04
	transformer oil	kg	7.2E+04	8.7E+04
Annual operation - Production	Ee	MWh/y	9.3E+05	1.0E+06
	Eth	MWh/y	1.1E+06	1.3E+06
Annual operation - Emissions	CO2	kg/y	1.1E+07	2.3E+07
	CH4	kg/y	2.0E+04	4.2E+04
	H2S	kg/y	5.5E+06	8.0E+06
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	2.7E-02	2.4E-01
	As	kg/y	3.4E-01	1.3E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	3.2E+03	1.8E+04
	waste - filters disposal	kg/y	2.3E+03	1.3E+04
	Chemicals for scaling, corrosion, fluid treatment	kg/y	2.9E+04	1.6E+05
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	0.0E+00	0.0E+00
Annual operation - Surface components replacement				

Cluster 2P

Gas Composition [Nm^3/ m^3]

CO2	CH4	H2S	NH3	N2	remark
2.67E+00	1.84E-04	3.20E-02	6.78E-02	6.84E-02	Rangel et al,2019
7.45E+00	4.58E-04	2.15E-02		2.70E-02	Carvalho et al,2006
3.24E+00	2.18E-04	9.29E-03		1.29E-02	Carvalho et al,2006 based on PV1 at under atm pressure

Life Cycle Inventory

Process	Flow	U.o.M.	2P	
			Min	max
Exploration	fuel	l	0.0E+00	0.0E+00
Drilling, casing, cementing	Eused	MWh	1.2E+03	3.2E+03
	fuel	l	2.5E+04	5.3E+04
	steel	kg	5.8E+05	8.9E+05
	cement	m3	2.8E+02	4.3E+02
	mud	m3	1.1E+03	1.5E+03
	cuttings	ton	1.0E+03	1.3E+03
Stimulation	Eused	MWh	n.a.	n.a.
Testing	Eused	MWh	n.a.	n.a.
	CO2	kg	n.a.	n.a.
	CH4	kg	n.a.	n.a.
	H2S	kg	n.a.	n.a.
	NH3	kg	n.a.	n.a.
	Hg	kg	n.a.	n.a.
	As	kg	n.a.	n.a.
	N2	kg	n.a.	n.a.
Surface components	stainless	kg	3.7E+04	5.1E+04
	steel	kg	9.4E+05	1.1E+06
	aluminium	kg	1.4E+04	1.6E+04
	copper	kg	1.3E+04	1.9E+04
	mineral wool	kg	1.7E+04	2.7E+04
	plastics	kg	2.1E+04	3.0E+04
	concrete	kg	8.4E+05	1.3E+06
	organic chemicals	kg	3.7E+04	6.2E+04
	titanium	kg	0.0E+00	0.0E+00
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	8.1E+04	9.0E+04
	Eth	MWh/y	0.0E+00	0.0E+00
Annual operation - Emissions	CO2	kg/y	7.8E+06	3.9E+07
	CH4	kg/y	2.7E+02	9.1E+02
	H2S	kg/y	3.0E+06	3.0E+06
	N2	kg/y	4.0E+04	1.2E+05
	NH3	kg/y	5.4E+04	2.9E+05
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	3.8E+02	2.2E+03
	waste - filters disposal	kg/y	2.7E+02	1.5E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	3.4E+03	1.9E+04
	ORC leak	kg/y	7.4E+01	4.2E+02
	ORC refill	kg/y	7.4E+01	4.2E+02
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 3P CHP

Gas Composition [mass fraction]

CO2	CH4	H2S	NH3	Hg	As	remark
confidential						data plant operators 2019 3PCHP plant 1 based on flow rate 131,7 t/h
confidential						3PCHP plant 2 data 2019 plant operators based on flow rate 427,9 t/h
confidential						3PCHP plant 3 data 2019 plant operator 2017 based on flow rate 394,8 t/h
3.18E-02	3.20E-04	1.03E-03	2.48E-05	5.93E-08	3.00E-09	Monteverdi 2 data from ARPAT 2018b
1.48E-02	2.00E-04	1.02E-04	4.50E-06	1.60E-07	4.50E-09	Nuova Monterotondo data from ARPAT 2017a mass flow rate 66 ton/hr and AMIS efficiency 92,5 for Hg
4.00E-02	2.07E-04	4.90E-04	7.00E-06	3.33E-08	2.50E-09	Nuova Serrazzano data from ARPAT 2017 and AMIS efficiency 92,5%
3.06E-02	3.51E-04	2.12E-03	4.01E-05	1.00E-07	3.75E-09	Sasso data from ARPAT 2018a and AMIS efficiency 92,5%

Life Cycle Inventory

Process	Flow	U.o.M.	3P CHP	
			Min	max
Exploration	fuel	l	0.0E+00	0.0E+00
Drilling, casing, cementing	Eused	MWh	1.0E+04	1.1E+04
	fuel	l	1.6E+05	1.6E+05
	steel	kg	1.7E+06	1.7E+06
	cement	m3	8.5E+02	1.2E+03
	mud	m3	3.2E+03	3.2E+03
	cuttings	ton	2.8E+03	3.1E+03
Stimulation	Eused	MWh	0.0E+00	0.0E+00
Testing	Eused	MWh	0.0E+00	0.0E+00
	CO2	kg	5.3E+03	1.6E+04
	CH4	kg	2.2E+01	2.4E+02
	H2S	kg	3.7E+01	7.6E+02
	NH3	kg	1.2E+01	1.9E+02
	Hg	kg	3.8E-03	5.8E-02
	As	kg	9.0E-04	2.5E-03
	N2	kg	0.0E+00	0.0E+00
Surface components	stainless	kg	6.4E+04	7.3E+04
	steel	kg	9.8E+05	1.1E+06
	aluminium	kg	2.9E+04	3.4E+04
	copper	kg	9.7E+03	1.2E+04
	mineral wool	kg	3.1E+04	6.1E+04
	plastics	kg	5.7E+04	6.7E+04
	concrete	kg	1.4E+06	2.2E+06
	organic chemicals	kg	0.0E+00	0.0E+00
	titanium	kg	9.9E+03	1.1E+04
	transformer oil	kg	1.2E+04	1.5E+04
Annual operation - Production	Ee	MWh/y	1.2E+05	1.3E+05
	Eth	MWh/y	4.6E+03	5.1E+03
Annual operation - Emissions	CO2	kg/y	1.6E+07	4.6E+07
	CH4	kg/y	6.4E+04	7.0E+05
	H2S	kg/y	8.1E+03	1.7E+05
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	4.8E+03	7.3E+04
	Hg	kg/y	8.3E-01	1.3E+01
	As	kg/y	2.6E+00	7.3E+00
	SO2	kg/y	1.0E+02	1.7E+02
Annual operation - Mainteinance	lubricant oil	kg/y	4.4E+02	2.5E+03
	waste - filters disposal	kg/y	3.1E+02	1.8E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	4.0E+03	2.2E+04
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	0.0E+00	0.0E+00
Annual operation - Surface components replacement				

Cluster 4P

Gas Composition [mass fraction]

CO_2	CH_4	H_2S	NH_3	Hg	As	remark
confidential						data plant operator
6.75E-02	2.27E-03	1.30E-03	2.07E-03	5.75E-07	6.25E-09	data from ARPAT 2019 based on 400t/h mean flow rate

Life Cycle Inventory

Process	Flow	U.o.M.	4P	
			Min	max
Exploration	fuel	l	0.0E+00	0.0E+00
Drilling, casing, cementing	Eused	MWh	2.0E+04	3.5E+04
	fuel	l	3.8E+05	6.1E+05
	steel	kg	5.3E+06	8.4E+06
	cement	m3	2.6E+03	4.1E+03
	mud	m3	9.1E+03	1.2E+04
	cuttings	ton	8.3E+03	1.1E+04
Stimulation	Eused	MWh	0.0E+00	0.0E+00
Testing	Eused	MWh	0.0E+00	0.0E+00
	CO2	kg	4.5E+05	4.6E+05
	CH4	kg	7.1E+03	7.2E+03
	H2S	kg	6.9E+03	8.6E+03
	NH3	kg	5.0E+03	1.8E+04
	Hg	kg	1.3E+00	2.2E+00
	As	kg	2.3E-02	5.5E-02
	N2	kg	0.0E+00	0.0E+00
Surface components	stainless	kg	1.7E+05	1.9E+05
	steel	kg	3.8E+06	4.1E+06
	aluminium	kg	8.3E+04	9.8E+04
	copper	kg	2.8E+04	3.4E+04
	mineral wool	kg	8.7E+04	1.8E+05
	plastics	kg	1.6E+05	1.8E+05
	concrete	kg	4.6E+06	7.4E+06
	organic chemicals	kg	0.0E+00	0.0E+00
	titanium	kg	3.0E+04	3.3E+04
	transformer oil	kg	3.6E+04	4.4E+04
Annual operation - Production	Ee	MWh/y	5.2E+05	5.3E+05
	Eth	MWh/y	0.0E+00	0.0E+00
Annual operation - Emissions	CO2	kg/y	2.7E+08	2.8E+08
	CH4	kg/y	4.3E+06	4.3E+06
	H2S	kg/y	2.4E+05	2.9E+05
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	5.1E+04	1.9E+05
	Hg	kg/y	6.2E+01	1.0E+02
	As	kg/y	5.5E-01	1.3E+00
	SO2	kg/y	1.0E+03	1.3E+03
Annual operation - Mainteinance	lubricant oil	kg/y	1.6E+03	9.2E+03
	waste - filters disposal	kg/y	1.1E+03	6.4E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	1.4E+04	8.2E+04
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	0.0E+00	0.0E+00
Annual operation - Surface components replacement				

Cluster 4P CHP

Gas Composition [mass fraction]

CO2	CH4	H2S	NH3	Hg	As	remark
8.02E-02	1.23E-03	3.41E-03	5.33E-05	1.01E-06	9.50E-09	data from ARPAT 2019
confidential						data plant operator modif H2S, Hg and NH3 based on outlet and abatement

Life Cycle Inventory

Process	Flow	U.o.M.	4P CHP	
			Min	max
Exploration	fuel	l	0.0E+00	0.0E+00
Drilling, casing, cementing	Eused	MWh	8.9E+03	1.6E+04
	fuel	l	1.7E+05	2.8E+05
	steel	kg	2.4E+06	3.8E+06
	cement	m3	1.2E+03	1.8E+03
	mud	m3	4.2E+03	5.6E+03
	cuttings	ton	3.8E+03	5.0E+03
Stimulation	Eused	MWh	0.0E+00	0.0E+00
Testing	Eused	MWh	0.0E+00	0.0E+00
	CO2	kg	3.9E+05	3.9E+05
	CH4	kg	1.1E+04	1.3E+04
	H2S	kg	7.5E+03	7.5E+03
	NH3	kg	1.2E+04	1.2E+04
	Hg	kg	7.5E-01	7.7E-01
	As	kg	1.7E-02	3.6E-02
	N2	kg	0.0E+00	0.0E+00
Surface components	stainless	kg	2.3E+05	2.7E+05
	steel	kg	4.2E+06	4.6E+06
	aluminium	kg	9.5E+04	1.1E+05
	copper	kg	3.1E+04	3.9E+04
	mineral wool	kg	1.0E+05	1.9E+05
	plastics	kg	1.9E+05	2.3E+05
	concrete	kg	5.9E+06	9.5E+06
	organic chemicals	kg	2.6E+03	4.4E+03
	titanium	kg	3.0E+04	3.3E+04
	transformer oil	kg	3.6E+04	4.4E+04
Annual operation - Production	Ee	MWh/y	5.3E+05	5.4E+05
	Eth	MWh/y	3.0E+04	3.4E+04
Annual operation - Emissions	CO2	kg/y	2.4E+08	2.4E+08
	CH4	kg/y	6.5E+06	7.9E+06
	H2S	kg/y	8.7E+04	8.7E+04
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	3.8E+05	3.8E+05
	Hg	kg/y	6.0E+01	6.2E+01
	As	kg/y	1.0E+01	2.2E+01
	SO2	kg/y	3.1E+02	3.1E+02
Annual operation - Mainteinance	lubricant oil	kg/y	1.6E+03	9.3E+03
	waste - filters disposal	kg/y	1.1E+03	6.4E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	1.0E+06	3.0E+06
	ORC leak	kg/y	4.9E+00	2.8E+01
	ORC refill	kg/y	4.9E+00	2.8E+01
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 5P

Gas Composition [Nm^3/ m^3]

CO2	CH4	N2	remark
9.37E-01	2.06E-02	7.21E-02	Landau idem Soultz
9.37E-01	2.06E-02	7.21E-02	Soultz-sous-Forets Mouchot et al, 2018
1.08E+00	2.40E-02	8.40E-02	Rittershoffen Mouchot et al, 2018
1.44E+00	1.60E-02	1.42E-01	Bruchsal Mergner et al, 2013
8.97E-01	3.25E-02	6.04E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1
8.62E-01	2.28E-02	9.85E-02	Soultz-sous-Forets Sanjuan et al, 2016 with GLR 1:1
8.63E-01	2.19E-02	8.27E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.08E+00	3.90E-02	7.25E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1,2
1.03E+00	2.74E-02	1.18E-01	Soultz-sous-Forets Sanjuan et al, 2016 with GLR 1:1,2
1.04E+00	2.63E-02	9.92E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2
8.53E-01	2.25E-02	8.90E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.02E+00	2.25E-02	8.90E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2

Life Cycle Inventory

Process	Flow	U.o.M.	5P	
			Min	max
Exploration	fuel	l	3.4E+04	5.0E+04
Drilling, casing, cementing	Eused	MWh	2.2E+03	3.7E+03
	fuel	l	4.2E+04	6.5E+04
	steel	kg	5.5E+05	8.7E+05
	cement	m3	2.7E+02	4.2E+02
	mud	m3	9.1E+02	1.2E+03
	cuttings	ton	8.4E+02	1.1E+03
Stimulation	Eused	MWh	1.1E+01	1.3E+01
	Acid stimulations	n° of treatments	2	
	Thermal stimulation	n° of treatments	1	
	Hydraulic stimulation (hydrothermal)	n° of treatments	0	
	Hydraulic stimulation (EGS)	n° of treatments	1	
Testing	Eused	MWh	9.7E+00	1.2E+01
	CO2	kg	2.4E+04	3.3E+04
	CH4	kg	2.1E+02	3.3E+02
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	5.0E+02	8.8E+02
Surface components	stainless	kg	7.9E+03	1.1E+04
	steel	kg	2.1E+05	2.4E+05
	aluminium	kg	3.7E+03	4.2E+03
	copper	kg	2.9E+03	4.1E+03
	mineral wool	kg	4.6E+03	8.0E+03
	plastics	kg	4.5E+03	6.4E+03
	concrete	kg	1.6E+05	2.7E+05
	organic chemicals	kg	7.8E+03	1.3E+04
	titanium	kg	0.0E+00	0.0E+00
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	2.1E+04	2.3E+04
	Eth	MWh/y	nan	nan
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	8.1E+01	4.6E+02
	waste - filters disposal	kg/y	5.7E+01	3.2E+02
	Chemicals for scaling, corrosion, fluid treatment	kg/y	7.2E+02	4.1E+03
	ORC leak	kg/y	1.6E+01	8.9E+01
	ORC refill	kg/y	1.6E+01	8.9E+01
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 5P CHP

Gas Composition [Nm^3/ m^3]

CO2	CH4	N2	remark
9.37E-01	2.06E-02	7.21E-02	Landau idem Soultz
9.37E-01	2.06E-02	7.21E-02	Soultz-sous-Forets Mouchot et al, 2018
1.08E+00	2.40E-02	8.40E-02	Rittershoffen Mouchot et al, 2018
1.44E+00	1.60E-02	1.42E-01	Bruchsal Mergner et al, 2013
8.97E-01	3.25E-02	6.04E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1
8.62E-01	2.28E-02	9.85E-02	Soultz-sous-Forets Sanjuan et al, 2016 with GLR 1:1
8.63E-01	2.19E-02	8.27E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.08E+00	3.90E-02	7.25E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1,2
1.03E+00	2.74E-02	1.18E-01	Soultz-sous-Forets Sanjuan et al, 2016 with GLR 1:1,2
1.04E+00	2.63E-02	9.92E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2
8.53E-01	2.25E-02	8.90E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.02E+00	2.25E-02	8.90E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2
9.37E-01	2.06E-02	7.21E-02	Landau idem Soultz
9.37E-01	2.06E-02	7.21E-02	Soultz-sous-Forets Mouchot et al, 2018
1.08E+00	2.40E-02	8.40E-02	Rittershoffen Mouchot et al, 2018
1.44E+00	1.60E-02	1.42E-01	Bruchsal Mergner et al, 2013
8.97E-01	3.25E-02	6.04E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1
8.62E-01	2.28E-02	9.85E-02	Soultz-sous-Forets Sanjuan et al, 2016 with GLR 1:1
8.63E-01	2.19E-02	8.27E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.08E+00	3.90E-02	7.25E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1,2
1.03E+00	2.74E-02	1.18E-01	Soultz-sous-Forets Sanjuan et al, 2016 with GLR 1:1,2
1.04E+00	2.63E-02	9.92E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2
8.53E-01	2.25E-02	8.90E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.02E+00	2.25E-02	8.90E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2

Life Cycle Inventory

Process	Flow	U.o.M.	5P CHP	
			Min	max
Exploration	fuel	l	3.4E+04	5.0E+04
Drilling, casing, cementing	Eused	MWh	2.2E+03	3.7E+03
	fuel	l	4.2E+04	6.5E+04
	steel	kg	5.5E+05	8.7E+05
	cement	m3	2.7E+02	4.2E+02
	mud	m3	9.1E+02	1.2E+03
	cuttings	ton	8.4E+02	1.1E+03
Stimulation	Eused	MWh	1.1E+01	1.3E+01
	Acid stimulations	n° of treatments	2	
	Thermal stimulation	n° of treatments	1	
	Hydraulic stimulation (hydrothermal)	n° of treatments	0	
	Hydraulic stimulation (EGS)	n° of treatments	1	
Testing	Eused	MWh	9.7E+00	1.2E+01
	CO2	kg	2.4E+04	3.3E+04
	CH4	kg	2.1E+02	3.3E+02
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	5.0E+02	8.8E+02
Surface components	stainless	kg	1.4E+04	2.0E+04
	steel	kg	2.1E+05	2.4E+05
	aluminium	kg	3.6E+03	4.3E+03
	copper	kg	2.8E+03	4.2E+03
	mineral wool	kg	4.0E+03	8.8E+03
	plastics	kg	7.1E+03	1.0E+04
	concrete	kg	1.6E+05	2.7E+05
	organic chemicals	kg	7.8E+03	1.3E+04
	titanium	kg	0.0E+00	0.0E+00
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	2.1E+04	2.3E+04
	Eth	MWh/y	8.7E+03	9.7E+03
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	8.1E+01	4.6E+02
	waste - filters disposal	kg/y	5.7E+01	3.2E+02
	Chemicals for scaling, corrosion, fluid treatment	kg/y	7.2E+02	4.1E+03
	ORC leak	kg/y	1.6E+01	8.9E+01
	ORC refill	kg/y	1.6E+01	8.9E+01
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 6P

Gas composition [Nm^3/ m^3]

CO2	remark
2.99E+01	based on 30Nm^3/m^3 and 99,5% CO2 from Maljković and Guðmundsson, 2017
2.70E+01	based on 27Nm^3/m^3 and 100% CO2 from Cubric, 2012

Life Cycle Inventory

Process	Flow	U.o.M.	6P	
			Min	max
Exploration	fuel	l	1.8E+04	2.2E+04
Drilling, casing, cementing	Eused	MWh	1.7E+03	3.6E+03
	fuel	l	3.5E+04	6.0E+04
	steel	kg	7.0E+05	1.0E+06
	cement	m3	3.4E+02	5.0E+02
	mud	m3	1.2E+03	1.7E+03
	cuttings	ton	1.1E+03	1.4E+03
Stimulation	Eused	MWh	n.a.	n.a.
	Stimulations	n° of treatments	n.a.	n.a.
Testing	Eused	MWh	n.a.	n.a.
	CO_2	kg	n.a.	n.a.
	CH_4	kg	n.a.	n.a.
	H_2S	kg	n.a.	n.a.
	NH_3	kg	n.a.	n.a.
	Hg	kg	n.a.	n.a.
	As	kg	n.a.	n.a.
	N_2	kg	n.a.	n.a.
Surface components	stainless	kg	2.6E+04	3.6E+04
	steel	kg	6.4E+05	7.2E+05
	aluminium	kg	9.5E+03	1.1E+04
	copper	kg	9.5E+03	1.4E+04
	mineral wool	kg	1.2E+04	1.8E+04
	plastics	kg	1.5E+04	2.1E+04
	concrete	kg	5.7E+05	9.3E+05
	organic chemicals	kg	2.6E+04	4.4E+04
	titanium	kg	0.0E+00	0.0E+00
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	3.1E+04	3.5E+04
	Eth	MWh/y	0.0E+00	0.0E+00
Annual operation - Emissions	CO_2	kg/y	9.3E+07	1.1E+08
	CH_4	kg/y	0.0E+00	0.0E+00
	H_2S	kg/y	0.0E+00	0.0E+00
	N_2	kg/y	0.0E+00	0.0E+00
	NH_3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO_2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	3.0E+02	1.7E+03
	waste - filters disposal	kg/y	1.9E+02	1.1E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	2.4E+03	1.4E+04
	ORC leak	kg/y	5.3E+01	3.0E+02
	ORC refill	kg/y	5.3E+01	3.0E+02
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 7P CHP

Gas compo sition [Nm^3/ m^3]

CO2	CH4	N2	remark
1.977	0.21	0.061	based on pers. com. VITO
1.813	0.202	0.096	based on pers. com. VITO
2.19	0.122	0.054	based on pers. com. VITO

Process	Flow	U.o.M.	7P CHP	
			Min	max
Exploration	fuel	l	1.5E+04	2.5E+04
Drilling, casing, cementing	Eused	MWh	3.3E+03	5.2E+03
	fuel	l	5.8E+04	9.5E+04
	steel	kg	6.3E+05	1.0E+06
	cement	m3	3.1E+02	5.0E+02
	mud	m3	1.0E+03	1.4E+03
	cuttings	ton	9.4E+02	1.3E+03
Stimulation	Eused	MWh	4.1E+00	5.1E+00
	Acid stimulations	n° of treatments	3	
	Thermal stimulation	n° of treatments	0	
	Hydraulic stimulation (hydrothermal)	n° of treatments	0	
	Hydraulic stimulation (EGS)	n° of treatments	0	
Testing	Eused	MWh	6.4E+00	7.9E+00
	CO2	kg	3.1E+04	3.8E+04
	CH4	kg	8.1E+02	1.4E+03
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	2.0E+02	4.4E+02
Surface components	stainless	kg	3.3E+04	4.6E+04
	steel	kg	2.7E+05	3.1E+05
	aluminium	kg	8.3E+03	1.0E+04
	copper	kg	2.2E+03	3.3E+03
	mineral wool	kg	9.3E+03	1.4E+04
	plastics	kg	1.9E+04	2.7E+04
	concrete	kg	7.0E+05	1.1E+06
	organic chemicals	kg	2.3E+03	4.0E+03
	titanium	kg	0.0E+00	0.0E+00
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	4.9E+03	5.9E+03
	Eth	MWh/y	4.0E+04	4.8E+04
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	3.3E+04
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	2.4E+01	1.4E+02
	waste - filters disposal	kg/y	1.7E+01	9.6E+01
	Chemicals for scaling, corrosion, fluid treatment	kg/y	2.2E+02	1.2E+03
	ORC leak	kg/y	4.7E+00	2.7E+01
	ORC refill	kg/y	4.7E+00	2.7E+01
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 8P

Gas composition [Nm^3/ m^3]

CO2	CH4	N2	remark
5.60E-02	1.60E-02	8.00E-03	based on mean values of 0,08Nm^3/m^3 and compo 70, 20 & 10% from Schreiber et al, 2016
8.40E-02	2.40E-02	1.20E-02	based on mean values of 0,12Nm^3/m^3 and compo 70, 20 & 10% from Schreiber et al, 2016
7.00E-02	3.17E-02	1.40E-02	based on mean values of 0,118Nm^3/m^3 and compo 59,4, 26,9 & 12,4% from mean values Wanner et al., 2017 (CO2, CH4 and N2)

Life Cycle Inventory

Process	Flow	U.o.M.	8P	
			Min	max
Exploration	fuel	l	1.5E+04	2.5E+04
Drilling, casing, cementing	Eused	MWh	4.9E+03	7.9E+03
	fuel	l	8.3E+04	1.5E+05
	steel	kg	7.4E+05	1.2E+06
	cement	m3	3.6E+02	6.0E+02
	mud	m3	1.2E+03	1.6E+03
	cuttings	ton	1.1E+03	1.5E+03
Stimulation	Eused	MWh	4.2E+00	4.8E+00
	Acid stimulations	n° of treatments	5	
	Thermal stimulation	n° of treatments	0	
	Hydraulic stimulation (hydrothermal)	n° of treatments	0	
	Hydraulic stimulation (EGS)	n° of treatments	0	
Testing	Eused	MWh	1.9E+01	2.4E+01
	CO2	kg	4.7E+03	5.7E+03
	CH4	kg	3.3E+02	5.4E+02
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	0.0E+00	5.9E+01
Surface components	stainless	kg	1.6E+04	2.2E+04
	steel	kg	3.6E+05	4.1E+05
	aluminium	kg	5.3E+03	6.1E+03
	copper	kg	5.7E+03	8.1E+03
	mineral wool	kg	6.4E+03	9.9E+03
	plastics	kg	9.1E+03	1.3E+04
	concrete	kg	3.3E+05	5.4E+05
	organic chemicals	kg	1.6E+04	2.6E+04
	titanium	kg	0.0E+00	0.0E+00
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	2.9E+04	3.2E+04
	Eth	MWh/y	nan	nan
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	1.6E+02	9.2E+02
	waste - filters disposal	kg/y	1.1E+02	6.4E+02
	Chemicals for scaling, corrosion, fluid treatment	kg/y	1.4E+03	8.2E+03
	ORC leak	kg/y	9.8E+00	5.6E+01
	ORC refill	kg/y	9.8E+00	5.6E+01
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 8P CHP

Gas composition [Nm^3/ m^3]

CO2	CH4	remark
5.60E-02	1.60E-02	based on mean values of 0,08Nm^3/m^3 and compo 70, 20 & 10% from Schreiber et al, 2016
8.40E-02	2.40E-02	based on mean values of 0,12Nm^3/m^3 and compo 70, 20 & 10% from Schreiber et al, 2016
7.00E-02	3.17E-02	based on mean values of 0,118Nm^3/m^3 and compo 59,4, 26,9 & 12,4% from mean values Wanner et al., 2017 (CO2, CH4 and N2)

Process	Flow	U.o.M.	8P CHP	
			Min	max
Exploration	fuel	l	1.5E+04	2.5E+04
Drilling, casing, cementing	Eused	MWh	4.9E+03	7.9E+03
	fuel	l	8.3E+04	1.5E+05
	steel	kg	7.4E+05	1.2E+06
	cement	m3	3.6E+02	6.0E+02
	mud	m3	1.2E+03	1.6E+03
	cuttings	ton	1.1E+03	1.5E+03
Stimulation	Eused	MWh	4.2E+00	4.8E+00
	Acid stimulations	n° of treatments	5	
	Thermal stimulation	n° of treatments	0	
	Hydraulic stimulation (hydrothermal)	n° of treatments	0	
	Hydraulic stimulation (EGS)	n° of treatments	0	
Testing	Eused	MWh	2.0E+01	2.4E+01
	CO2	kg	4.7E+03	5.7E+03
	CH4	kg	3.3E+02	5.4E+02
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	0.0E+00	5.8E+01
Surface components	stainless	kg	7.0E+04	9.8E+04
	steel	kg	6.6E+05	7.6E+05
	aluminium	kg	1.4E+04	1.7E+04
	copper	kg	6.9E+03	1.0E+04
	mineral wool	kg	1.6E+04	2.2E+04
	plastics	kg	3.9E+04	5.5E+04
	concrete	kg	1.4E+06	2.3E+06
	organic chemicals	kg	1.3E+04	2.2E+04
	titanium	kg	0.0E+00	0.0E+00
	transformer oil	kg	0.0E+00	0.0E+00
Annual operation - Production	Ee	MWh/y	2.4E+04	2.7E+04
	Eth	MWh/y	4.3E+04	4.7E+04
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	1.4E+02	7.7E+02
	waste - filters disposal	kg/y	9.5E+01	5.4E+02
	Chemicals for scaling, corrosion, fluid treatment	kg/y	1.2E+03	6.8E+03
	ORC leak	kg/y	2.6E+01	1.5E+02
	ORC refill	kg/y	2.6E+01	1.5E+02
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 2DHC

Gas composition [Nm^3/ m^3]

CO2	CH4	remark
9.37E-01	2.06E-02	Soultz-sous-Forêts Mouchot et al, 2018
1.08E+00	2.40E-02	Rittershoffen Mouchot et al, 2018
1.44E+00	1.60E-02	Bruchsal Mergner et al, 2013
8.97E-01	3.25E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1
8.62E-01	2.28E-02	Soultz-sous-Forêts Sanjuan et al, 2016 with GLR 1:1
8.63E-01	2.19E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.08E+00	3.90E-02	Bruschal Sanjuan et al, 2016 with GLR 1:1,2
1.03E+00	2.74E-02	Soultz-sous-Forêts Sanjuan et al, 2016 with GLR 1:1,2
1.04E+00	2.63E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2
8.53E-01	2.25E-02	Insheim Sanjuan et al, 2016 with GLR 1:1
1.02E+00	2.25E-02	Insheim Sanjuan et al, 2016 with GLR 1:1,2

Life Cycle Inventory

Process	Flow	U.o.M.	2DHC	
			Min	max
Exploration	fuel	l	1.5E+04	2.5E+04
Drilling, casing, cementing	Eused	MWh	1.4E+03	2.6E+03
	fuel	l	2.8E+04	4.4E+04
	steel	kg	4.5E+05	6.8E+05
	cement	m3	2.2E+02	3.3E+02
	mud	m3	7.6E+02	1.0E+03
	cuttings	ton	7.0E+02	9.0E+02
Stimulation	Eused	MWh	1.1E+01	1.3E+01
	Acid stimulations	n° of treatments	2	
	Thermal stimulation	n° of treatments	1	
	Hydraulic stimulation (hydrothermal)	n° of treatments	0	
	Hydraulic stimulation (EGS)	n° of treatments	1	
Testing	Eused	MWh	1.3E+02	1.5E+02
	CO2	kg	1.6E+05	2.2E+05
	CH4	kg	1.4E+03	2.3E+03
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	3.4E+03	6.0E+03
Surface components	stainless	kg	6.6E+04	9.1E+04
	steel	kg	5.1E+05	5.8E+05
	mineral wool	kg	1.6E+04	2.0E+04
	plastics	kg	3.8E+04	5.3E+04
	concrete	kg	1.6E+06	2.5E+06
	copper	kg	3.1E+03	4.7E+03
	aluminium	kg	1.4E+04	1.7E+04
Annual operation - Production	Ee	MWh/y	1.7E+05	1.9E+05
	Eused	MWh/y	5.0E+03	6.3E+03
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	6.5E+02	3.7E+03
	waste - filters disposal	kg/y	4.5E+02	2.6E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	5.8E+03	3.3E+04
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 3DHC

Gas composition [Nm^3/ m^3]

CO2	CH4	remark
6.76E-02	4.52E-01	based on mean values of 520 l/m³ and compo 87%CH4 rest CO2 13% from SETIS 2015
0.00E+00	3.00E+00	based on mean values of 3Nm³/m³ and compo CH4 % Rosca et al. 2016.
1.67E-01	9.58E-01	based on mean values in Varga et al., 2019 for production wells
1.99E-01	8.09E-01	based on mean values in Varga et al., 2019 for production wells
5.00E-03	3.03E-01	based on mean values in Varga et al., 2019 for injection wells
7.20E-02	1.06E-01	based on mean values in Varga et al., 2019 for injection wells
3.80E-02	8.40E-02	based on mean values in Varga et al., 2019 for injection wells
2.50E-01	0.00E+00	based on mean values in Pannergy, 2013 0,5 m³/m³
1.50E-02	7.00E-03	30-1650 l / m3 with methane contents of 7-109 l / m3 considering at least 50% of the GWR is CO2, rest N2 from Szöcs et al, 2017
8.25E-01	1.09E-01	30-1650 l / m3 with methane contents of 7-109 l / m3 considering at least 50% of the GWR is CO2, rest N2 from Szöcs et al, 2017
2.00E-02	3.60E-02	80-2602 l / m3 with methane contents of 36-659 l / m3 considering at least 25% of the GWR is CO2, rest N2 from Szöcs et al, 2017
6.50E-01	6.60E-01	80-2602 l / m3 with methane contents of 36-659 l / m3 considering at least 25% of the GWR is CO2, rest N2 from Szöcs et al, 2017
1.50E-02	0.00E+00	30-332 l / m3 with methane contents of 0-293 l / m3 considering at least 50% N2 rest CO2 from Szöcs et al, 2017

Highlight: Many Hungarian wells produce thermal water with significant dissolved gas content (methane, nitrogen, CO2, H2S). Degasification units are often installed next to the production wells and in some cases the separated gas (methane) is used in auxiliary equipment, however often the gas is just released to the atmosphere (Opera 2016). The re-use of methane is not accounted in this study.

Life Cycle Inventory

Process	Flow	U.o.M.	3DHC	
			Min	max
Exploration	fuel	l	1.5E+04	2.5E+04
Drilling, casing, cementing	Eused	MWh	7.9E+02	2.0E+03
	fuel	l	1.7E+04	3.2E+04
	steel	kg	3.8E+05	5.7E+05
	cement	m3	1.8E+02	2.7E+02
	mud	m3	7.1E+02	9.5E+02
	cuttings	ton	6.4E+02	8.2E+02
Stimulation	Eused	MWh	0.0E+00	0.0E+00
Testing	Eused	MWh	0.0E+00	0.0E+00
	CO2	kg	0.0E+00	2.7E+04
	CH4	kg	0.0E+00	2.5E+04
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	0.0E+00	1.2E+04
Surface components	stainless	kg	1.7E+04	2.4E+04
	steel	kg	1.3E+05	1.5E+05
	mineral wool	kg	5.5E+03	9.2E+03
	plastics	kg	9.8E+03	1.4E+04
	concrete	kg	3.6E+05	5.9E+05
	copper	kg	8.2E+02	1.2E+03
	aluminium	kg	5.0E+03	5.9E+03
Annual operation - Production	Ee	MWh/y	1.5E+04	1.8E+04
	Eused	MWh/y	0.0E+00	9.3E+01
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	2.7E+05
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	1.3E+05
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	1.2E+03	7.0E+03
	waste - filters disposal	kg/y	8.7E+02	4.9E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	1.1E+04	6.3E+04
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 4DHCa

Gas composition [Nm^3/ m^3]

CO_2	CH_4	H_2S	N_2	remark
2,16E-02	4,72E-02		4,18E-02	average of all data from Paris basin (source of the data from: Criaud et al. (1987), Lemale (2012), database BRGM)
3,06E-03	1,31E-02	0,00E+00	1,74E-02	min
6,59E-02	6,56E-02	5,88E-03	8,53E-02	max

Process	Flow	U.o.M.	4DHCa	
			Min	max
Exploration	fuel	l	n.a.	n.a.
Drilling, casing, cementing	Eused	MWh	6.3E+02	1.5E+03
	fuel	l	1.3E+04	2.4E+04
	steel	kg	2.9E+05	4.3E+05
	cement	m3	1.4E+02	2.1E+02
	mud	m3	5.2E+02	7.1E+02
	cuttings	ton	4.8E+02	6.1E+02
Stimulation	Eused	MWh	0.0E+00	0.0E+00
Testing	Eused	MWh	2.0E+00	3.3E+00
	CO2	kg	6.5E+02	1.1E+03
	CH4	kg	1.2E+02	1.9E+02
	H2S	kg	8.4E+02	1.4E+03
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	7.9E+01	1.3E+02
Surface components	stainless	kg	2.7E+04	3.7E+04
	steel	kg	1.7E+05	2.0E+05
	mineral wool	kg	7.2E+03	9.9E+03
	plastics	kg	1.6E+04	2.2E+04
	concrete	kg	5.9E+05	9.6E+05
	copper	kg	1.3E+03	1.9E+03
	aluminium	kg	6.5E+03	7.7E+03
Annual operation - Production	Ee	MWh/y	3.6E+04	3.9E+04
	Eused	MWh/y	4.4E+03	5.4E+03
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	3.7E+02	2.1E+03
	waste - filters disposal	kg/y	2.6E+02	1.5E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	3.3E+03	1.9E+04
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 4DHCb

Gas composition [Nm^3/m^3]

CO2	CH4	remark
1.47E-01	8.00E-04	mean values Veldkamp 2016
9.80E-03	7.00E-03	Veldkamp 2016

Life Cycle Inventory

Process	Flow	U.o.M.	4DHCb	
			Min	max
Exploration	fuel	l	n.a.	n.a.
Drilling, casing, cementing	Eused	MWh	7.7E+02	1.7E+03
	fuel	l	1.6E+04	2.8E+04
	steel	kg	3.3E+05	4.9E+05
	cement	m3	1.6E+02	2.4E+02
	mud	m3	5.8E+02	7.9E+02
	cuttings	ton	5.3E+02	6.8E+02
Stimulation	Eused	MWh	0.0E+00	0.0E+00
Testing	Eused	MWh	n.a.	n.a.
	CO2	kg	n.a.	n.a.
	CH4	kg	n.a.	n.a.
	H2S	kg	n.a.	n.a.
	NH3	kg	n.a.	n.a.
	Hg	kg	n.a.	n.a.
	As	kg	n.a.	n.a.
	N2	kg	n.a.	n.a.
Surface components	stainless	kg	2.9E+04	4.1E+04
	steel	kg	1.9E+05	2.1E+05
	mineral wool	kg	7.8E+03	1.1E+04
	plastics	kg	1.7E+04	2.4E+04
	concrete	kg	6.5E+05	1.0E+06
	copper	kg	1.4E+03	2.1E+03
	aluminium	kg	7.0E+03	8.3E+03
Annual operation - Production	Ee	MWh/y	2.7E+04	3.0E+04
	Eused	MWh/y	2.8E+02	3.4E+02
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	2.9E+02	1.6E+03
	waste - filters disposal	kg/y	2.0E+02	1.1E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	2.6E+03	1.4E+04
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

Cluster 5DHC

Gas composition [Nm^3/ m^3]

CO2	CH4	remark
5.60E-02	1.60E-02	based on mean values of 0,08Nm^3/m^3 and compo 70, 20 & 10%
8.40E-02	2.40E-02	based on mean values of 0,12Nm^3/m^3 and compo 70, 20 & 10%
7.00E-02	3.17E-02	based on mean values of 0,118Nm^3/m^3 and compo 59,4, 26,9 & 12,4% from mean values Wanner et al., 2017 (CO2, CH4 and N2)
1.75E-01	5.00E-02	based on mean values of 0,25Nm^3/m^3 (dissertation Welter 2018) and compo 70, 20 & 10%

Life Cycle Inventory

Process	Flow	U.o.M.	5DHC	
			Min	max
Exploration	fuel	l	1.5E+04	2.5E+04
Drilling, casing, cementing	Eused	MWh	1.8E+03	3.1E+03
	fuel	l	3.4E+04	5.2E+04
	steel	kg	5.0E+05	7.7E+05
	cement	m3	2.4E+02	3.8E+02
	mud	m3	8.4E+02	1.1E+03
	cuttings	ton	7.7E+02	1.0E+03
Stimulation	Eused	MWh	3.0E+00	3.4E+00
	Acid stimulations	n° of treatments	5	
	Thermal stimulation	n° of treatments	0	
	Hydraulic stimulation (hydrothermal)	n° of treatments	0	
	Hydraulic stimulation (EGS)	n° of treatments	0	
Testing	Eused	MWh	1.4E+01	1.6E+01
	CO2	kg	4.2E+03	8.1E+03
	CH4	kg	3.3E+02	7.1E+02
	H2S	kg	0.0E+00	0.0E+00
	NH3	kg	0.0E+00	0.0E+00
	Hg	kg	0.0E+00	0.0E+00
	As	kg	0.0E+00	0.0E+00
	N2	kg	5.6E+01	1.4E+02
Surface components	stainless	kg	3.7E+04	5.1E+04
	steel	kg	2.4E+05	2.7E+05
	mineral wool	kg	9.4E+03	1.2E+04
	plastics	kg	2.1E+04	3.0E+04
	concrete	kg	8.3E+05	1.3E+06
	copper	kg	1.8E+03	2.6E+03
	aluminium	kg	8.5E+03	1.0E+04
Annual operation - Production	Ee	MWh/y	4.6E+04	5.1E+04
	Eused	MWh/y	1.1E+03	1.4E+03
Annual operation - Emissions	CO2	kg/y	0.0E+00	0.0E+00
	CH4	kg/y	0.0E+00	0.0E+00
	H2S	kg/y	0.0E+00	0.0E+00
	N2	kg/y	0.0E+00	0.0E+00
	NH3	kg/y	0.0E+00	0.0E+00
	Hg	kg/y	0.0E+00	0.0E+00
	As	kg/y	0.0E+00	0.0E+00
	SO2	kg/y	0.0E+00	0.0E+00
Annual operation - Mainteinance	lubricant oil	kg/y	4.6E+02	2.6E+03
	waste - filters disposal	kg/y	3.2E+02	1.8E+03
	Chemicals for scaling, corrosion, fluid treatment	kg/y	4.1E+03	2.3E+04
	ORC leak	kg/y	0.0E+00	0.0E+00
	ORC refill	kg/y	0.0E+00	0.0E+00
	cleaning hX	n treatments/year	1.8E-01	1.0E+00
Annual operation - Surface components replacement				

ANNEX IV: GHG EMISSIONS INVENTORY

GHG Emissions Inventory (P-clusters 1/2)

Flow	Ref. unit	GHG EF [$kgCO_2e$/Ref. unit]	Sub-Surface Construction							
			Exploration		Drilling, casing, cementing		Stimulation		Testing	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Energy from fuel	MJ	0.09	0.0E+00	5.3E-01	7.6E-02	1.1E+00	0.0E+00	1.5E-05	0.0E+00	2.0E-05
Steel	kg	1.62	0.0E+00	0.0E+00	3.7E-04	2.1E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cement	m^3	845.93	0.0E+00	0.0E+00	9.4E-05	5.3E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Drilling mud	m^3	126.70	0.0E+00	0.0E+00	5.3E-05	2.3E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cuttings	t	9.98	0.0E+00	0.0E+00	3.8E-06	1.6E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Stainless steel	kg	3.39	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Aluminium	kg	9.86	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Copper	kg	1.73	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Titanium	kg	4.72	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Mineral wool	kg	1.12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Plastics	kg	3.48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Oil	kg	1.11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Concrete	kg	0.01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Organic chemicals	kg	2.02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Flow	Ref. unit	GHG EF [kgCO_2e / Ref. unit]	Sub-Surface Construction							
			Exploration		Drilling, casing, cementing		Stimulation		Testing	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
CO2	kg	1.00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	7.7E-05
CH4	kg	36.80	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4.1E-05
Lubricant oil	kg	1.11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Waste disposal	kg	2.44	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Inorganic chemicals	kg	1.89	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Acid for stimulations	kg	0.42	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	9.8E-07	0.0E+00	0.0E+00

GHG Emissions Inventory (P-clusters, 2/2)

Flow	Ref. unit	GHG EF [kgCO_2e / Ref. unit]	Surface Construction		Core processes			
			Equipment, building		Operation		Maintenance	
			Min.	Max.	Min.	Max.	Min.	Max.
Energy from fuel	MJ	0.09	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.6E-01	2.5E+00
Steel	kg	1.62	3.9E-04	1.1E-03	0.0E+00	0.0E+00	8.4E-06	1.1E-03
Cement	m^3	845.93	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Drilling mud	m^3	126.70	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cuttings	t	9.98	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Stainless steel	kg	3.39	3.7E-05	1.2E-04	0.0E+00	0.0E+00	8.6E-07	1.1E-04
Aluminium	kg	9.86	5.2E-05	1.0E-04	0.0E+00	0.0E+00	2.8E-06	1.0E-04
Copper	kg	1.73	3.1E-06	2.3E-05	0.0E+00	0.0E+00	1.9E-07	2.0E-05
Titanium	kg	4.72	0.0E+00	1.0E-05	0.0E+00	0.0E+00	0.0E+00	1.0E-05
Mineral wool	kg	1.12	6.3E-06	2.0E-05	0.0E+00	0.0E+00	8.6E-08	1.7E-05
Plastics	kg	3.48	2.5E-05	7.1E-05	0.0E+00	0.0E+00	3.3E-07	6.4E-05
Oil	kg	1.11	0.0E+00	3.1E-06	0.0E+00	0.0E+00	0.0E+00	2.9E-06
Concrete	kg	0.01	2.8E-06	9.8E-06	0.0E+00	0.0E+00	6.5E-08	8.3E-06
Organic chemicals	kg	2.02	0.0E+00	8.5E-05	0.0E+00	0.0E+00	0.0E+00	7.1E-05
CO2	kg	1.00	0.0E+00	0.0E+00	0.0E+00	9.4E+01	0.0E+00	0.0E+00
CH4	kg	36.80	0.0E+00	0.0E+00	0.0E+00	9.9E+00	0.0E+00	0.0E+00

Flow	Ref. unit	GHG EF [$kgCO_2e$ / Ref. unit]	Surface Construction		Core processes			
			Equipment, building		Operation		Maintenance	
			Min.	Max.	Min.	Max.	Min.	Max.
Lubricant oil	kg	1.11	0.0E+00	0.0E+00	7.3E-05	1.0E-03	0.0E+00	0.0E+00
Waste disposal	kg	2.44	0.0E+00	0.0E+00	0.0E+00	6.3E-04	0.0E+00	0.0E+00
Inorganic chemicals	kg	1.89	0.0E+00	0.0E+00	0.0E+00	2.5E-06	0.0E+00	0.0E+00
Acid for stimulations	kg	0.42	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

GHG Emissions Inventory (DHC-clusters 1/2)

Flow	Ref. unit	GHG EF [kgCO2e / Ref. unit]	Exploration		Drilling, casing, cementing		Stimulation		Testing	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Energy from fuel	MJ	0.09	0.0E+00	3.4E-01	4.0E-02	4.5E-01	0.0E+00	1.8E-06	0.0E+00	2.2E-05
Electricity Consumption	MWh	418	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Steel	Kg	1.62	0.0E+00	0.0E+00	1.4E-04	1.7E-03	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cement	m^3	845.93	0.0E+00	0.0E+00	3.6E-05	4.3E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Drilling mud	m^3	126.70	0.0E+00	0.0E+00	1.9E-05	2.3E-04	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cuttings	T	9.98	0.0E+00	0.0E+00	1.4E-06	1.5E-05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Stainless steel	Kg	3.39	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Aluminium	Kg	9.86	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Copper	Kg	1.73	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Mineral wool	Kg	1.12	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Plastics	Kg	3.48	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Oil	Kg	1.11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Concrete	Kg	0.01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Organic chemicals	Kg	2.02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
CO2	Kg	1.00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	5.0E-05

Flow	Ref. unit	GHG EF [kgCO2e / Ref. unit]	Exploration		Drilling, casing, cementing		Stimulation		Testing	
			Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
CH4	Kg	36.80	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	1.7E-03
Lubricant oil	Kg	1.11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Waste disposal	Kg	2.44	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Inorganic chemicals	Kg	1.89	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Acid for stimulations	Kg	0.42	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	6.1E-07	0.0E+00	0.0E+00

GHG Emissions Inventory (DHC-clusters, 2/2)

Flow	Ref. unit	GHG EF [$kgCO_2e$ / Ref. unit]	Surface Construction		Core processes			
			Equipment, building		Operation		Maintenance	
			Min.	Max.	Min.	Max.	Min.	Max.
Energy from fuel	MJ	0.09	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2.0E-01	2.0E+01
Electricity consumption	MWh	418	0.0E+00	0.0E+00	0.0E+00	5.7E-02	0.0E+00	0.0E+00
Steel	kg	1.62	1.6E-04	4.8E-04	0.0E+00	0.0E+00	6.0E-05	4.4E-04
Cement	m^3	845.93	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Drilling mud	m^3	126.70	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Cuttings	t	9.98	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Stainless steel	kg	3.39	4.3E-05	1.5E-04	0.0E+00	0.0E+00	1.8E-05	1.4E-04
Aluminium	kg	9.86	2.7E-05	1.1E-04	0.0E+00	0.0E+00	1.4E-03	9.7E-03
Copper	kg	1.73	1.3E-05	4.0E-06	0.0E+00	0.0E+00	5.4E-06	4.1E-05
Mineral wool	kg	1.12	3.5E-06	1.9E-05	0.0E+00	0.0E+00	1.2E-06	1.2E-05
Plastics	kg	3.48	2.6E-05	9.1E-05	0.0E+00	0.0E+00	9.3E-07	7.0E-06
Oil	kg	1.11	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Concrete	kg	0.01	3.4E-06	1.3E-05	0.0E+00	0.0E+00	2.9E-09	1.6E-07
Organic chemicals	kg	2.02	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
CO2	kg	1.00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

Flow	Ref. unit	GHG EF [$kgCO_2e$ / Ref. unit]	Surface Construction		Core processes			
			Equipment, building		Operation		Maintenance	
			Min.	Max.	Min.	Max.	Min.	Max.
CH4	kg	36.80	0.0E+00	0.0E+00	0.0E+00	1.7E+01	0.0E+00	0.0E+00
Lubricant oil	kg	1.11	0.0E+00	0.0E+00	0.0E+00	9.2E-03	0.0E+00	0.0E+00
Waste disposal	kg	2.44	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Inorganic chemicals	kg	1.89	0.0E+00	0.0E+00	0.0E+00	3.2E-06	0.0E+00	0.0E+00
Acid for stimulations	kg	0.42	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00

REFERENCES

Abdel-Ghany M., Siso S., Hassan A., Pierpaolo P. & Roberto C. (2011). New technology application, radial drilling petrobel, first well in Egypt. In: Offshore Mediterranean conference and exhibition, 23e25 March, Ravenna, Italy. Offshore Mediterranean conference; 2011. OMC-2011-163.

Aiuppa A., Caleca A., Federico C., Gurrieri S. & Valenza M., 2004: Diffuse degassing of carbon dioxide at Somma-Vesuvius volcanic complex (Southern Italy) and its relation with regional tectonics. Journal of Volcanology and Geothermal Research 133: 55-79.

Akin, S., Yildirim, N., Yazman, M., Karadag, M., Seckin, C., Tonguc, E., et al. (2015). Coiled Tubing Acid Stimulation of Alaşehir Geothermal Field, Turkey. Proceedings World Geothermal Congress 2015, pp. 1-6). Melbourne, Australia.

Allard P., Carbonnelle J., Dallevic D., Le Bronec J., Morel P., Robe M. C., Maurenas J. M., Faivre-Pierret R., Martioni D., Sabroux J. C. & Zettwoog P., 1991: Eruptive and diffuse emissions of CO2 from Mount Etna. Lettres to Nature 351: 387-391.

Altamirano J., “Sampling and analyses of geothermal steam and geothermometer applications in Krafla, Theistareykir, Reykjanes and Svartsengi, iceland”, Tech. Rep. 13, 2006, pp. 153–169.

Andrade C., Viveiros F., Cruz J. V., Branco R., Moreno L., Silva C., Coutinho R. & Pacheco J., 2019: Diffuse CO2 flux emission in two maar crater lakes from Sao Miguel Island (Azores, Portugal). Journal of Volcanology and Geothermal Research 369: 188-202.

Aradottir E. S. P., Gunnarsson I., Sigfusson B., Gunnarsson G., Juliusson B., Gunnglaugsson E., Sigurdardottir H., Arnarson M. T. & Sonnethal E., 2015. Toward Cleaner Geothermal Energy Utilisation: Capturing and Sequestering CO2 and H2S Emissions from Geothermal Power Plants. Transport in Porous Media 108: 61-84.

Aradóttir, E.S.P., Gunnarsson, I., Sigfusson, B. et al. (2015). Towards Cleaner Geothermal Energy: Subsurface Sequestration of Sour Gas Emissions from Geothermal Power Plants. Proceedings World Geothermal Congress 2015, Melbourne, Australia, 19-25 April 2015.

Armannsson H., Fridriksson T., Benjaminsson J. & Hauksson T., 2013. History of gas in geothermal fluids, Krafla, northeast Iceland. Procedia Earth and Planetary Science 7, 23 – 26.

Armannsson H., Fridriksson T. & Kristjansson B. R., 2005: CO2 emissions from geothermal power plants and natural geothermal activity in Iceland. Geothermics 34: 286-296.

Ármannsson, H. (2016). The fluid geochemistry of Icelandic high temperature geothermal areas. Appl. Geochem. 66, 14–64.

Armannsson H., 2017: Carbon dioxide emissions from Icelandic geothermal areas. Procedia Earth and Planetary Science 17: 104-107.

Arnorsson, S., 1986.Chemistry of gases associated with geothermal activity and volcanism in Iceland: A review January 1986Journal of Geophysical Research Atmospheres 911(B12):12261-12268 DOI: 10.1029/JB091iB12p12261

Arnorsson S., 1995: Geothermal Systems in Iceland: Structure and conceptual models. High temperature areas. Geothermics 24 (5-6): 561-602.

ARPAT, 2017. Monitoraggio delle aree geotermiche toscane Anno 2015. Arpat Annual report.

ARPAT, 2018a. Monitoraggio delle aree geotermiche toscane Anno 2016. Arpat Annual report.

ARPAT, 2018b. Monitoraggio delle aree geotermiche toscane Anno 2017. Arpat Annual report.

ARPAT, 2019. Monitoraggio delle aree geotermiche toscane Anno 2018. Arpat Annual report.

Axtmann, R. C., 1975. Environmental impact of a geothermal power plant. Science 187: 975–803.

Bacci E., Gaggi C., Lanzillotti E., Ferrozzi S. & Valli L., 2000: Geothermal power plants at Mt. Amiata (Tuscany-Italy): mercury and hydrogen sulphide deposition revealed by vegetation. Chemosphere 40: 907-911.

Baldacci A., 2001. Italian Patent #01305033 dated 10 April 2001 (applied for 16 October 1998).

Baldacci, A., 2004. AMIS: an innovative technology for hydrogen sulphide and mercury abatement from geothermal gases. GRC Trans. 28, 511–514.

Baujard, C., A. Genter, E. Dalmais, V. Maurer, R. Hehn, R. Rosillette, J. Vidal, J. Schmittbuhl Hydrothermal characterisation of wells GRT-1 and GRT-2 in Rittershoffen, France: implications on the understanding of natural flow systems in the Rhine graben. Geothermics, 65 (2017), pp. 255-268, 10.1016/j.geothermics.2016.11.001

Barber Nichols Home Page. http://www.barber-nichols.com/products/blowers_and_compressors/turbocompressors/default.asp

Barelli, A., Cappetti, G., Manetti, G., Peano, A., 1985. Well stimulation in Latera Field. Geothermal resources Council Transactions 9, 213–219

Barelli A., Ceccarelli A., Dini I., Fiordelisi A., Giogi N., Lovari F. & Romagnoli P., 2010: A Review of the Mt. Amiata Geothermal System (Italy). Proceedings World Geothermal Congress 2010. Bali, Indonesia.

Bargagli R., Cateni D., Nelli L., Olmanstroni S. & Zagarese B., 1997: Environmental Impact of Trace Element Emissions from Geothermal Power Plants. Archives of Environmental Contamination and Toxicology 33: 172-181.

Barrios L., Guerra E., Jacobo P., and Mayorga H., (2012). Acid stimulation of geothermal reservoirs. Short Course on Geothermal Development and Geothermal Wells, UNU-GTP and LaGeo, in Santa Tecla, El Salvador, March 11-17, 2012.

Basciotti D., Judex F., Pol O., Schmidt R., (2011). Sensible heat storage in district heating networks: a novel control strategy using the network as storage.

Baubron J. C., Allard P. & Toutain J. P., 1990: Diffuse volcanic emissions of carbon dioxide from Vulcano Island, Italy. Letters to Nature 344: 51-53.

Bebout, D.G. and Bachman, A.L., 1981. A correlation of published data on the solubility of methane in H2O-NaCl solutions. Proceedings of the fifth Geopressured - geothermal Energy conference. Louisiana State University, 13 - 15 October 1981.

Bello and Teodoriu, 2012; Development of a Model To Calculate Rig Power Requirements for Geothermal Applications. ISBN: 978-1-61399-210-4. Society of Petroleum Engineers

Berstad, D., & Nord, L.O. (2016). Acid Gas Removal in Geothermal Power Plant in Iceland. Energy Procedia 86, 32 – 40

Bertani, R., and I. Thain. 2002. "Geothermal Power Generating Plant CO2 Emission Survey." International Geothermal Association Newsletter 49 (July-September 2002): 1–3.

Bertani, R.. 2017. Perspective for geothermal energy in Europe.

Bidini, G.; Desideri, F.; Di Maria, F. A Single Flash Integrated Gas Turbine - Geothermal Power Plant With Non Condensable Gasses Combustion, Geothermics, 28, (1999), 1131-150.

Blanc I., Damen L., Douziech M., Fiaschi D., Harcouët-Menou V., Manfrida G., Mendecka B., Parisi M. L., Perez Lopez P., Ravier G., Tosti L., 2020. LCA Guidelines for geothermal installations – Deliverable 3.2. GEOENVI, GA n° 818242 under European Union's Horizon 2020 programme.

Blanco Ilzarbe JM, Malpartida JG and Rojí Chandro E: Recent Patents On Geothermal Power extraction Devices. Recent Patents on Engineering 7 (2–24). DOI:10.2174/10002

Bogarin Chaves, R., 1996: Geothermal gases as a source of commercial extraction of CO2, in Miravalles, Costa Rica and Haedarendi, Iceland. Report 3 in: Geothermal training in Iceland 1996. UNU-GTP, Iceland, 23-44.

Bonafin J., Pietra C., Bonzanini A., Bombarda P. (2019). CO_2 emissions from geothermal power plants: evaluation of technical solutions for CO_2 reinjection. European Geothermal Congress 2019 Den Haag, The Netherlands, 11-14 June 2019.

Bozza, G., 1961: On the origin of thermality in underground waters and endogenous steam. Privately printed by Larderello Ld., Pisa, Italy, pp. 1-60.

Bravi M. & Basosi R., 2014: Environmental impact of electricity from selected geothermal power plants in Italy. Journal of Cleaner Production 66: 301-308.

Brombach T. & Hunziker J., 2001: Soil diffuse degassing and thermal energy fluxes from the southern Lakki Plain, Nisyros (Greece). Geophysical Research Letters 28 (1): 69-72.

Bruni MA, Biasotti JH, Salomone GD. Radial drilling in Argentina. In: Latin American & Caribbean petroleum engineering conference, 15e18 April, Buenos Aires, Argentina. Society of Petroleum Engineers; 2007. https://doi.org/10.2118/ 107382-MS. SPE-107382-MS.

Bruscoli, L., Fiaschi, D., Manfrida, G., Tempesti, D., 2015. Improving the Environmental Sustainability of Flash Geothermal Power Plants—A Case Study. Sustainability 2015, 7(11), 15262-15283; https://doi.org/10.3390/su71115262.

Buonocore, Elvira; Vanoli, Laura; Carotenuto, Alberto; Ulgiati, Sergio (2015): Integrating life cycle assessment and emergy synthesis for the evaluation of a dry steam geothermal power plant in Italy. In Energy 86, pp. 476–487. DOI: 10.1016/j.energy.2015.04.048.

Buset, P., Riiber, M., Eek, A. (2001). "Jet Drilling Tool: Cost-Effective Lateral Drilling Technology for Enhanced Oil Recovery". SPE/ICoTA Coiled Tubing Roundtable, Houston, Texas, 7-8 March.

Bustaffa, Elisa; Minichilli, Fabrizio; Nuvolone, Daniela; Voller, Fabio; Cipriani, Francesco; Bianchi, Fabrizio (2017): Mortality of populations residing in geothermal areas of Tuscany during the period 2003-2012. In *Annali dell'Istituto superiore di sanita* 53 (2), pp. 108–117. DOI: 10.4415/ANN_17_02_06.

Bustaffa, Elisa; Cori, Liliana; Manzella, Adele; Nuvolone, Daniela; Minichilli, Fabrizio; Bianchi, Fabrizio; Gorini, Francesca (2020): The health of communities living in proximity of geothermal plants generating heat and electricity: A review. In The Science of the total environment 706, p. 135998. DOI: 10.1016/j.scitotenv.2019.135998.

Carlsen, Hanne Krage; Zoëga, Helga; Valdimarsdóttir, Unnur; Gíslason, Thórarinn; Hrafnkelsson, Birgir (2012): Hydrogen sulfide and particle matter levels associated with increased dispensing of anti-asthma drugs in Iceland's capital. In Environmental research 113, pp. 33–39. DOI: 10.1016/j.envres.2011.10.010.

Carvalho M.R., Forjaz V. H., & Almeida A., 2006. Chemical composition of deep hydrothermal fluids in the Ribeira Grande geothermal field (São Miguel, Azores). Journal of Volcanology and Geothermal Research 156, 116–134.

Cataldi, R., Stefani, G.C. and Tongiorgi, E., 1963. Geology of Larderello region (Tuscany); contribution to the study of the geothermal basin. In: E. Tongiorgi (Editor), Nuclear Geology on Geothermal Areas. Proc. Int. Syrup., Spoleto, Italy, pp. 235-265.

Chemwotei, S.C., 2011: Geothermal drilling fluids, Kenya. Report 10 in: Geothermal Training in Iceland 2011. UNU-GTP, Iceland, 149-177.

Chiavetta, Cristian; Tinti, Francesco; Bonoli, Alessandra (2011): Comparative life cycle assessment of renewable energy systems for heating and cooling. In Procedia Engineering 21, pp. 591–597. DOI: 10.1016/j.proeng.2011.11.2054.

Chiodini G., Frondini F. & Ponziani F., 1995: Deep structures and carbon dioxide degassing in central Italy. Geothermics 24 (1): 81-94.

Chiodini G., Cioni R., Guidi M., Raco B. & Martini L., 1998: Soil CO2 flux measurements in volcanic and geothermal areas. Applied Geochemistry 13 (5): 543-552.

Chiodini G., Frondini F., Kerrick D. M., Rogie J., Parello F., Peruzzi L. & Zanzari A. R., 1999: Quantification of deep CO2 fluxes from central Italy. Examples of carbon balance for regional aquifers and of soil diffuse degassing. Chemical Geology 159: 205-222.

Chiodini G., Frondini F., Cardellini C. Parello F. & Reruzzi L., 2000: Rate of diffuse carbon dioxide Earth deghassing estimated from carbon balance of regional aquifers: The case of central Apennine, Italy. Journal of Geophysical Research 105 (B4): 8423-8434.

Chiodini G., Frondini F., Cardellini C., Granieri D., Marini L. & Ventura G., 2001: CO2 degassing and energy release at Solfatara volcano, Campi Flegrei, Italy. Journal of Geophysical Research 106 (B8): 16,213-16,221

Chiodini G., Cardellini C., Amato A., Boschi E., Caliro S. & Frondini F., 2004: Carbon dioxide Earth degassing and seismogenesis in central and southern Italy. Geophysical Research Letters 31: L07615, doi:10.1029/2004GL019480, 2004.

Chiodini G., Granieri D., Avino R., Caliro S., Costa A. & Werner C., 2005: Carbon dioxide diffuse degassing and estimation of heat release from volcanic and hydrothermal systems. Journal of Geophysical Research 110: B08204, doi:10.1029/2004JB003542, 2005.

Chiodini G., Baldini A., Barberi F., Carapezza M. L., Cardellini C., Frondini F., Granieri D. & Ranaldi M., 2007: Carbon dioxide degassing at Latera caldera (Italy): Evidence of geothermal reservoir and evaluation of its potential energy. Journal of Geophysical Research 112: B12204, doi:10.1029/2006JB004896, 2007.

Cinelli SD, Kamel AH. Novel technique to drill horizontal laterals revitalizes aging field. In: SPE/IADC drilling conference society of petroleum engineers, 5e7 March, Amsterdam. The Netherlands; 2013. https://doi.org/10.2118/163405-MS. SPE-163405-MS.

Cirigliano RA, Talavera Blacutt JF. First experience in the application of radial perforation technology in deep wells. In: Latin American & Caribbean petroleum engineering conference, 15e18 April, Buenos Aires, Argentina. Society of Petroleum Engineers; 2007. https://doi.org/10.2118/107182-MS. SPE- 107182-MS.

Clark, C., C. Harto, J. Sullivan, and M. Wang. 2011. Water Use in the Development and Operation of Geothermal Power Plants. Environmental Science Division, Argonne National Laboratory. ANL/EVS/R-10/5.

Craig, H., 1963: The isotope geochemistry of water and carbon in geothermal areas. In: E. Tongiorgi (Editor), Nuclear Geology on Geothermal Areas. Proc. Int. Symp., Spoleto, Italy, pp. 17-54.

Criaud A., Fouillac C., Marty B., Brach M., Wei H.F., 1987 Gas geochemistry of the Dogger geothermal aquifer (Paris Basin, France). Proceedings, 12th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, Januray 20-22, 1987. SGP-TR-109.

Cruz J. V., Coutinho R. M., Crvalho M. R., Oskarsson N. & Gislason S. R., 1999: Chemistry of waters from Furnas cvolcano, Sao Miguel, Azores: fluxes of volcanic carbon dioxide and leaches material. Journal of Volcanology and Geothermal Research 92: 151-167.

Čubrić S., 2012. Basic characteristics of hydraulic model for the Velika Ciglena geothermal reservoir, NAFTA 63 (5-6) 173-179.

Dall' Aglio M. & Ferrara G. C., 1986: Impatto ambientale dell' energia geotermica. Acqua - Aria 10: 1091-1101.

Demir H., Mobedi M., Ulku S. 2008. A review on adsorption heat pump: Problems and solutions. Renewable and Sustainable Energy Reviews 16:5207–5224.

Dereinda F. H., 2008: CO2 emissions from the Krafla Geothermal area, Iceland. United Nations University. Geothermal Training Programme. Orkustofnun Reports 15: 177-188.

DiPippo (2012). DiPippo, R.: Geothermal Power Plants. Principles, Applications, Case Studies and Environmental Impact. Butterworth-Heinemann, Oxford 2012

Di Pippo (2016). Geothermal Power Plants (Fourth Edition), 2016.

Duan, Zhenhao; Mao, Shide (2006): A thermodynamic model for calculating methane solubility, density and gas phase composition of methane-bearing aqueous fluids from 273 to 523K and from 1 to 2000bar. In *Geochimica et Cosmochimica Acta* 70 (13), pp. 3369–3386. DOI: 10.1016/j.gca.2006.03.018.

Dumas et al. (2013). Dumas, P., Antics, M., Ungemach, P.: GeoELEC - Report on Geothermal Drilling. (35) 2013.

Eberle A., Heath G., Carpenter A., Nicholson S. (2017). Systematic Review of Life Cycle Greenhouse Gas Emissions from Geothermal Electricity. National Renewable Energy Laboratory.

EGEC Geothermal Market Report 2017: Geothermal market report. EGEC website: www.egec.org

EGEC Geothermal Market Report 2018: Geothermal market report. EGEC website: www.egec.org

Elliott S. Coiled-tubing method drills radial laterals to improve oil production from a depleted reservoir. World Oil Magazine 2011.

Epperson, I.J., 1983. Beowawe acid stimulation. Geothermal Resources Council Transactions 7, 409–411.

ETIP vision document 2018. https://www.etip-dg.eu/

European Commission. Developer - Environmental Footprint reference packages, available at: https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance. First edition March 2010. EUR 24708 EN. Luxembourg. Publications Office of the European Union; 2010.

European Commission (2017). COMMISSION DECISION (EU) 2017/2285 of 6 December 2017 Amending the user's guide setting out the steps needed to participate in EMAS, under Regulation (EC) No 1221/2009 of the European Parliament and of the Council on the voluntary participation by organisations in a Community eco-management and audit scheme (EMAS) (notified under document C(2017) 8072) (Text with EEA relevance)

European Committee for Standardisation, (2017). EN 15316-4-5:2017 Energy performance of buildings - Method for calculation of system energy requirements and system efficiencies - Part 4-5: District heating and cooling.

European Parliament and Couclil of the European Union (2005). DIRECTIVE 2004/107/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 15 December 2004 relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air.

European Union Technical Expert Group on Sustainable Finance (2020). Taxonomy report: Technical Annex – Updated methodology and updated screening criteria.

Fantke P., (2015). USEtox® 2.0 User Manual (Version 2)

Favara R., Giammanco S., Inguaggiato S. & Pecoraino G., 2001: Preliminary estimate of CO2 output from Pantelleria Island volcano (Sicily, Italy): evidence of active mantle degassing. Applied Geochemistry 16: 883-894.

Fazio, S. Castellani, V. Sala, S. Schau, EM.Secchi, M. Zampori, L., Diaconu E. (2018). Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method. Joint Research Centre.

Febrianto R., Bydder J., Hochwimmer A., Ussher G., and Libbey R. 2019. Developing low temperature Geothermal projects in Indonesia using pumped well technology. IOP Conf. Ser.: Earth Environ. Sci. 254 012021.

Ferrara R., Biancaelena M., Petrosino A. & Bargagli R., 1986: Mercury levels in rain and air and the subsequent washout mechanism in a central Italian region. Atmospheric Environment 20 (1): 125-128.

Ferrara, G.C., Gonfiantini R. and Panichi, C., 1965: La composizione isotopica del vapore di alcuni soffioni di Larderello e dell'acqua di alcune sorgenti e mofete della Toscana. Atti Soc. Tosc. Sc. Nat.

Ferrara N., Tosti L., Basosi R., Parisi M. L., (2019). La tossicità dei metalli pesanti nei metodi LCIA: gli effetti delle incertezze sui fattori di caratterizzazione. Il Life Cycle Thinking a supporto delle strategie di mitigazione e adattamento ai cambiamenti climatici. Atti del XIII Convegno della Rete Italiana LCA -VIII Convegno dell'Associazione Rete Italiana LCA Roma, 13-14 giugno 2019

Finnbjornsdottir, Ragnhildur Gudrun; Oudin, Anna; Elvarsson, Bjarki Thor; Gislason, Thorarinn; Rafnsson, Vilhjalmur (2015): Hydrogen sulfide and traffic-related air pollutants in association with increased mortality: a case-crossover study in Reykjavik, Iceland. In BMJ open 5 (4), e007272. DOI: 10.1136/bmjopen-2014-007272.

Flores, M., Davies, D., Couples, G., & Palsson, B. (2005). Stimulation of Geothermal Wells, Can We Afford It? World Geothermal Congress 2005, (pp. 1-8).

Frick, S., M. Kaltschmitt, and G. Schroder. 2010. “Life Cycle Assessment of Geothermal Binary Power Plants Using Enhanced Low-Temperature Reservoirs.” Energy 35 (5): 2281–94. doi:10.1016/j.energy.2010.02.016.

Fridriksson, T., Mateos, A., Audinet, P., Orucu, Y.,. 2016. Greenhouse Gases from Geothermal Power Production. Energy Sector Management Assistance Program (ESMAP) Technical Report 09/16.World Bank, Washington, DC. © World Bank. License: CC BY 3.0 IGO. https://openknowledge.worldbank.org/handle/10986/24691

Fridriksson T., Kristjansson B. R., Armannsson H., Margertardottir E., Olafsdottir S. & Chiodini G., 2006: CO2 emissions and heat flow through soil, fumaroles, and steam heated mud pools at Reykjanes geothermal area, SW Iceland. Apllies Geochemistry 21: 1551-1569.

Fridriksson T.: 2009: Diffuse CO2 degassing through soil and geothermal exploration. United Nations University. Geothermal Training Programme. Presented at “Short Course on Surface Exploration for Geothermal Resources”, organized by UNU-GTP and LaGeo, in Ahuachapan and Santa Tecla, El Salvador, 17-30 October, 2009.

Fridriksson T., Oladottir A. A., Jonsson P. I. Eyjolfsdottir E. I., 2010: The Response of the Reykjanes Geothermal System to 100MWe Power Production: Fluid Chemistry and Surface activity. Proceedings World Geothermal Congress 2010. Bali, Indonesia.

Fridriksson T., 2016: Gases in Geothermal Fluids and Gas Emissions from Geothermal Power Plants. ESMAP, World Bank, Global Geothermal Roundtable III, Reykjavik, April 26, 2016.

Fridriksson T., Mateos A., Audinet P. & Orucu Y., 2016: Greenshouse gases from geothermal power production. ESMAP Technical Report 009/16. World Bank, Washington, USA.

Fridriksson T., Mateos A., Orucu Y., Audinet P. (2016). Greenshouse gases from geothermal power production. PROCEEDINGS, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, 2017 SGP-TR-212.

Frondini F., Chiodini G., Caliro S., Cardellini C., Granieri D. & Ventura G., 2004: Diffuse degassing at Vesuvio, Italy: Bulletin of Volcanology 66: 642-651.

Frondini F., Caliro S., Cardellini C., Chiodini G., Morgantini N. & Parello F., 2008: Carbon dioxide degassing from Tuscany and Northern Latium (Italy). Global and Planetary Change 61: 89-102.

Frondini F., Caliro S., Cardellini C., Chiodini G. & Morgantini N., 2009: Carbon dioxide degassing and thermal energy release in Monte Amiata volcanic-geothermal area (Italy). Applies Geochemistry 24: 860-875.

Gadd, Henrik; Werner, Sven (2014): Achieving low return temperatures from district heating substations. In *Applied Energy* 136, pp. 59–67. DOI: 10.1016/j.apenergy.2014.09.022.

Gallup, D. (1992): “BIOX” – A New Hydrogen Sulfide Abatement Technology for the Geothermal Industry. Geothermal Resources Council Transactions, 16, (1992), 591-596.

Gambardella B., Cardellini C., Chiodini G., Frondini F., Marini L., Ottonello G. & Zuccolini M. V., 2004: Fluxes of deep CO2 in the volcanic areas of central-southern Italy. Journal of Volcanology and Geothermal Research 136: 31-52.

Gavriliuc R., Rosca M., Polizu R., Cucueteanu D., 2016. Romania Geothermal Energy Use. European Geothermal Congress 2016.

Gerber L. & Marechal F.. 2012. "Environomic Optimal Configurations of Geothermal Energy Conversion Systems: Application to the Future Construction of EnhancedGeothermal Systems in Switzerland." Energy 45 (1): 908–23. doi:10.1016/j.energy.2012.06.068.

Gerbinet S., Van Stappen F., Belboom S., Pezennec E., Léonard A. (2019). Impact of heavy metals on human toxicity using LCA: The case study of Walloon corn. Matériaux & Techniques Volume 107, Number 1, 2019 Society and Materials (SAM12).

Gervet, 2007. Gas Flaring Emission Contributes to Global Warming. Renewable Energy Research Group Division of Architecture and Infrastructure Luleå University of Technology SE-97187 Luleå, Sweden

Giggenbach WF (1980) Geothermal gas equilibria. Geochim Cosmochim Acta 44:2021-2032.

Giroud N., 2008. A Chemical Study of Arsenic, Boron and Gases in High-Temperature Geothermal Fluids in Iceland. Dissertation for the Degree of Doctor of Philosophy. FACULTY OF SCIENCE - UNIVERSITY OF ICELAND.

Gislason G., 2000. Nesjavellir co-generation plant, Iceland flowof geothermal steam and non-condensable gases. Proceedings World Geothermal Congress 2000.

Goff S. J., Brophy P., Goff F., Environmental Effects of Geothermal Power. Interaction Energy-Environment. Encyclopedia of Life Support Systems.

Goldstein, B., G. Hiriart, R. Bertani, C. Bromley, L. Gutiérrez-Negrín, E. Huenges, H. Muraoka, A. Ragnarsson, J. Tester, V. Zui, (2011). Geothermal Energy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Granieri D., Crarpezza M. L., Chiodini G., Avino R., Caliro S., Ranaldi M., Ricci T. & Tarchini L., 2006: Correlatde increase in CO2 fumarolic content and diffuse emission from La Fossa crater (Vulcano, Italy): Evidence of volcanic unrest or increasing gas release from a stationary deep magma body? Geophysical Research Letters 33: L13316, doi:10.1029/2006GL026460, 2006.

Grant, M.A., 2012 "Thermal stimulation: the easiest and least recognised mechanism of permeability change" Paper presented at US/NZ geothermal workshop

Guan, Z., Hooman, K., Gurgenci. (2016). Dry Cooling Towers for Geothermal Power Plants. In alternative Energy and Shale Gas Encyclopedia, Chapter 32. Wiley Online library. https://doi.org/10.1002/9781119066354.ch32.

Guidotti, Tee L. (2010): Hydrogen sulfide: advances in understanding human toxicity. In International journal of toxicology 29 (6), pp. 569–581. DOI: 10.1177/1091581810384882.

Gunnarsson, G., 2011: Mastering reinjection in the Hellisheidi field, SW-Iceland: A story of successes and failures. Proceedings Thirty-Sixth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, USA, 8 pp.

Gunnarsson I., Sigfusson B., Stefánsson A., Arnórsson S., Scott S. W., Gunnlaugsson E. (2011). Injection of H2S from hellisheiði power plant, Iceland. PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 31 - February 2, 2011 SGP-TR-191

Gunnarsson I., Aradottir E. S., Sigfusson B., Gunnglaugsson E. & Juliusson B. M., 2013: Geothermal Gas Emission From Hellisheidi and Nesjavellir Power Plants, Iceland. GRC Transactions 37: 785-789.

Gunnarsson, I., Júlíusson, B.M., Aradóttir, E.S.P. and Arnarson, M.Th (2015). Pilot scale geothermal gas separation, Hellisheiði Power Plant, Iceland, Proceedings, World Geothermal Congress, (2015).

Gunnglaugsson E., 2016: Environmental management and monitoring in Iceland: Reinjection and gas sequestration at the Hellisheidi power plant. Presentation at “SDG Short Course I on Sustainability and Environmental Management of Geothermal Resource Utilisation and the Role of Geothermal in Combating Climate Change”, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, September 4-10, 2016.

Haraldsson I. G. (2011). Environmental monitoring of geothermal power plants in operation. Presented at “Short Course on Geothermal Drilling, Resource Development and Power Plants”, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, January 16-22, 2011.

Häring M.O., Schanz U., Ladner F. & Dyer B. C. (2008). Characterisation of the Basel 1 enhanced geothermal system. Geothermics, 37(5), 469-495.

Hauksson T., 2013. Krafla og Bjarnarflag. Afkost borholum og vinnslurds iirid borhola og efnainnihald vatns og gufu i 20L2.. Landsvirkjun. LV-2013-073.

Hauksson T., 2015. Þeistareykjavirkjun. Vinnslueiginleikar gugu og vatns úr borholum. Uppfærð skýrsla með nújum gögnum. Landsvirkjun. LV-2015-003.

Hernandez P. A., Perez N. M., Salazar J. M., Nakai S. N., Notsu K. & Wakita H., 1998: Diffuse emission of carbon dioxide, methane, and helium-3 from Teide volcano, Tenerife, Canary Islands. Geophysical Research Letters, 25 (17): 3311-3314.

Holbein B., Isele J., Spatafora L., Hagenmeyer V (2016). Heating & Cooling with Geothermal Energy Heat Management in an experimental Holistic Energy Grid. PROCEEDINGS, 41st Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 22-24, 2016 SGP-TR-209

International Organisation for Standardisation ISO (2018), ISO 14067:2018 Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification.

IPCC, 2011: Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jóhannesson, Th., and Chatenay, C., 2014: Direct use of geothermal resources.

Josifovic, A., Roberts, J., Corney, J., Davies, B., Shipton, Z. (2016). Reducing the environmental impact of hydraulic fracturing through design optimisation of positive displacement pumps. Energy, 115 (1). pp. 1216-1233. ISSN 1873-6785 , http://dx.doi.org/10.1016/j.energy.2016.09.016.

Juliusson B. M., Gunnarsson I., Matthiasdottir V. K., Markusson S. H., Bjarnason B., Sveinsson O. G., Gislason T., Thorsteinsson H. H. (2015). Tackling the challenge of h2s emissions. Proceedings World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015

Ilyinskaya E., Mobbs S., Burton R., Burton M., Pardini F., Pfeffer M. A., Purvis R., Lee J., Bauguitte S., Brooks B., Cofescu I., Petersen G. N., Wellpot A. & Bergsson B., 2018: Globally significant CO2 emissions from Katla, a subglacial volcano in Iceland. Geophysical Research Letters 45 (19): 10332-10341.

Inguaggiato S., Mazot A., Diliberto I. S., Inguaggiato C., Madonia P., Rouwet D. & Vita F., 2012: Total CO2 output from Vulcano island (Aeolian Islands, Italy). G3, Geochemistry, Geophysics, Geosystems 13 (2): Q02012, doi:10.1029/2011GC003920.

Kagel A., Bates D., Gawell K. (2007). A Guide to Geothermal Energy and the Environment.

Karlsdóttir M. R., Lew J. B., Palsson H. P., P. Palsson O. (2014). Geothermal district heating system in iceland: a life cycle perspective with focus on primary energy efficiency and CO2 emissions. The 14th International Symposium on District Heating and Cooling, September 7th to September 9th, 2014, Stockholm, Sweden.

Karlsdóttir M. R., Pálsson O. P., Pálsson H., Drysdale L. M. (2015). Life cycle inventory of a flash geothermal combined heat and power plant located in Iceland. Int J Life Cycle Assess 20:503–519 (DOI 10.1007/s11367-014-0842-y)

Karlsson, T., A. Ragnarsson (1995). Use of very low temperature geothermal water in radiator heating systems Proc. World Geothermal Congress '95, Florence, Italy, Vol. 3 (1995), pp. 2193-2198.

Kaya and Mertoglu (2005). Engineering Aspects of Geothermal Production Well with Down Hole Pumps. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005

Kaya E., Zarrouk S. J. & O'Sullivan J., 2011: Reinjection of geothermal fields: A review of worldwide experience. Renewable and Sustainable Energy Reviews 15: 47-68.

Kayser, M.: Energetische Nutzung hydrothermaler Erdwärmevorkommen in Deutschland – eine energiewirtschaftliche Analyse, Doctoral dissertation, Faculty for Civil Engineering and Applied Geosciences, Tech. Univ. Berlin (Germany), 1999.

Khodayar M., Bjornsson S., Gudnason E. A., Nielsson S., Axelsson G. & Hickson C., 2018: Tectonic Control of the Reykjanes Geothermal Field in the Oblique Rift of SW Iceland: From Regional to Reservoir Scale. Open Journal of Geology 8: 333-382.

Kigen, B. (2016) PROPOSED USE OF WELLHEAD ELECTRICAL POWER IN DRILLING GEOTHERMAL WELLS AT OLKARIA, KENYA. Proceedings, 6th African Rift Geothermal Conference Addis Ababa, Ethiopia, 2nd – 4th November 2016.

Kristmannsdottir, H., & Armannsson, H. (2003). Environmental aspects of geothermal energy utilisation. Geothermics, 32, 451–461.

Kutscher, 2002. Assessment of Evaporative Cooling Enhancement Methods for Air-Cooled Geothermal Power Plants. Preprint.

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

Lacirignola, M., (2017). Life cycle assessment of enhanced geothermal systems: from specific case studies to generic parameterized models. ÉCOLE DOCTORALE Sciences et Métiers de l'Ingénieur

Laboratoire Chimie moléculaire, génie des procédés chimiques et énergétiques

Lacirignola, M., B.H. Meany, P. Padey, and I. Blanc. 2014. “A Simplified Model for the Estimation of Life-Cycle Greenhouse Gas Emissions of Enhanced Geothermal Systems.” Geothermal Energy 2 (1). doi:10.1186/s40517-014-0008-y.

Lacirignola, Martino, and Isabelle Blanc. 2013. “Environmental Analysis of Practical Design Options for Enhanced Geothermal Systems (EGS) through Life-Cycle Assessment.” Renewable Energy 50 (February): 901–14. doi:10.1016/j.renene.2012.08.005.

Ladner and Häring, 2009. Hydrauloic characteristics of the Basel 1 Enhanced Geothermal system hydraulic reservoir characterisation Prior to stimulation, 33,0-4

Lattanzi P., Beutel M. W., Costagliola P., Fagotti C. & Rimondi V., 2019: Tracing the impact of geothermal plants in the Monte Amiata area, Tuscany, Italy: evidence from Hg contents in stream sediments and tree barks. European Geothermal Congress 2019. Den Haag, Netherlands

Lemale J., 2012. La géothermie. Dunod, 2ème édition.

Legarth, B., and Saadat, A. 2005. Energy Consumption for Geothermal Wells. Proceedings World Geothermal Congress 2005 Antalya, Turkey, 24-29 April 2005

Legator M. S., Singleton C. R., Morris D. L., Philips D. L. (2010). Health Effects from Chronic Low-Level Exposure to Hydrogen Sulfide. Archives of Environmental Health: An International Journal Volume 56, 2001 - Issue 2 Pages 123-131.

Leung D. Y. C., Caramanna G. & Maroto-Valer M. M., 2014: An overview of the current status of carbon dioxide capture and storage technologies. Renewable and Sustainable Energy Reviews 39: 426-443.

Lewis R.J., Copley G.B. (2014). Chronic low-level hydrogen sulfide exposure and potential effects on human health: a review of the epidemiological evidence. Crit Rev Toxicol. 2015 Feb;45(2):93-123. doi: 10.3109/10408444.2014.971943. Epub 2014 Nov 28.

Lim, Y.W., Grant. M., Brown, K., Siega, C., & Siega, R., 2011 “Acidising case study – Kawerau injection wells” Proc 36th Workshop on Geothermal Reservoir Engineering, Stanford University

Lobianco, L.F.; Wardani, W. Electrical Submersible Pumps for Geothermal Applications. In Proceedings of the Second European Geothermal Review—Geothermal Energy for Power Production, Mainz, Germany, 21–23 June 2010

Lund (1998). Lund, J. W.: Geothermal Direct-Use Equipment Overview. GHC Bulletin 19 (1–6) 1998

Magro G., Bellani S. & Vedova B. D., 2009: The Deep Roots of the Larderello Geothermal Field (Italy) from Heat Flux and He Anomalies. GRC Transactions 33: 405-410.

Maljković, Danica and Jón Ragnar Guðmundsson, 2017. Geothermal Energy Utilisation Potential in Croatia: Field and Study Visits’ Report.

Mamrosh, Darryl L. et al., 2014. Removal of Hydrogen Sulfide and Recovery of Carbon Dioxide from Geothermal Non-Condensable Gas Using Water.

Mamrosh, Darryl L. et al. 2012. Screening of H2S Abatement Options for Geothermal Power Noncondensable Gas at Bjarnarflag.

Manente, G., Lazzaretto, A ., Bardi, A., Paci, M., 2019. Geothermal power plant layouts with water absorption and reinjection of H2S and CO2 in fields with a high content of non-condensable gases. Geothermics. Volume 78 Pages 1-272 (March 2019)

Manzella A., Bonciani R., Allansdottir A., Botteghi S., Donato A., Giamberini S., Lenzi A., Paci M., Pellizzone A. & Scrocca D., 2018: Environmental and social aspects of geothermal energy in Italy. Geothermics 72: 232-248.

Manzella, A., Allansdottir, A., & Pellizzone, A. (Eds.). (2019). Geothermal Energy and Society. Springer.

Marchand M., Blanc I., Marquand A., Beylot A., Bezelgues-Courtade S., Traineau H. (2015). Life Cycle Assessment of High Temperature Geothermal Energy Systems. edited by Roland Horne and Toni Boyd. World Geothermal Congress 2015, Apr 2015, Melbourne, Australia. Proceedings World Geothermal Congress 2015, pp.11 - Article 02028 - ISBN 978-1-877040-02-3.

Martín-Gamboa, Mario; Iribarren, Diego; Dufour, Javier (2015): On the environmental suitability of high- and low-enthalpy geothermal systems. In Geothermics 53, pp. 27–37. DOI: 10.1016/j.geothermics.2014.03.012.

Matek B. Geothermal Energy Association (2013). Promoting Geothermal Energy: Air Emissions Comparison and Externality Analysis.

Matter, J.M., Stute, M., Snaebjörnsdóttir, S.Ó., Oelkers, E.H. Gíslason, S.R., Aradóttir, E., Sigfússon, B., Gunnarsson, I., Sigurdardóttir, H., Gunnlaugsson, E., Axelsson, G., Alfredsson, H.A., Wolff- Boenisch, D., Mesfin, K., de la Reguera Taya, D.F., Hall, J., Dideriksen, K., and Broecker, W.S., 2016: Rapid carbon mineralisation for permanent disposal of anthropogenic carbon dioxide emissions. Science, 352, 1312-1314.

McGavran P. (2001) “Literature Review of the Health Effects Associated with the Inhalation of Hydrogen Sulfide.” Idaho Department of Environmental Quality, Boise, Idaho. June 19, 2001. p.3.

McIntush, K., D. Mamrosh, C. Beitler, and K. Kitz. October 1-4, 2017. “Integrated Hybrid Cooling, Direct-Contact Condenser, and H2S Abatement to Lower Operating Costs and Increase Injection.” Presented at the Geothermal Resources Council Annual Meeting, Salt Lake City, UT. GRC Transactions 41:2488-2507.

Mendrinos, D., Kontonleaontos, E., Karytas, C., (2006). GEOTHERMAL BINARY PLANTS: WATER OR AIR COOLED ? Centre for Renewable Energy Sources 19. 1-10.

Mergner H., Kölbel T., Schlagermann P., 2013. Geothermal Power Generation – First Operation Experiences and Performance Analysis of the Kalina Plant in Bruchsal. Conference Geothermal Power Generation.

Meunier F. (2002). Adsorptive cooling: a clean technology. Clean Prod Processes, 3:8–20.

Minichilli F., Nuvolone D., Bustaffa E., Cipriani F., Vigotti M. A., Bianchi F. (2012). State of health of populations residing in geothermal areas of Tuscany [article in Italian]. Epidemiol Prev. 2012 Sep-Oct;36(5 Suppl 1):1-104.

Minissale A., 1991: The Larderello geothermal field: a review. Earth Science Reviews 31: 133-151.

Mishra, G.S., Glassley, W., Yeh, S., (2011). Realizing the geothermal electricity potential-water use and consequences. Environ. Res. Lett. 6, 034023.

Moon, H and Zarouk, S.J, 2012. Efficiency of geothermal power plants: a worldwide review. New Zealand Geothermal Workshop 2012 Proceedings, 19 - 21 November 2012, Auckland, New Zealand

Mouchot, J., Genter, A., Cuenot, N., Scheiber, J., Seibel, O., Bosia, C., and Ravier G. (2018). First Year of Operation from EGS geothermal Plants in Alsace, France: Scaling Issues. PROCEEDINGS, 43rd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 12-14, 20181

Najafabadi, A., 2015: Geothermal power plant condensers in the world. Proceedings of the World Geothermal Congress 2015, Melbourne, Australia, 7 pp.

Nitters G, Roodhart L, Jongma H, Yeager V, Buijse M, Fulton D, Dahl J, Jantz E (2000) Structured approach to advanced candidate selection and treatment design of stimulation treatments. Paper No. SPE 63179. In: SPE Annual Technical Conference and Exhibition, Dallas, Texas, October 1–4.

Nuvolone, Daniela; Petri, Davide; Pepe, Pasquale; Voller, Fabio (2019): Health effects associated with chronic exposure to low-level hydrogen sulfide from geothermoelectric power plants. A residential cohort study in the geothermal area of Mt. Amiata in Tuscany. In The Science of the total environment 659, pp. 973–982. DOI: 10.1016/j.scitotenv.2018.12.363.

Oladottir A. A., 2012: Application of soil measurements and remote sensing for monitoring changes in geothermal surface activity in the Reykjanes filed, Iceland. 90 ECTS thesis submitted in partial fulfillment of a Magister Scientiarum degree in Geology. Faculty of Earth Sciences University of Iceland.

Oladottir A. A. & Fridriksson T., 2015: The evolution of CO2 Emissions and Heat Flow through Soil since 2004 in the Utilized Reykjanes Geothermal Area, SW Iceland: Ten Years of Observations on Changes in Geothermal Surface Activity. Proceedings World Geothermal Congress 2015. Melbourne Australia.

Óskarsson F., Ármannsson H., Ólafsson M., Sveinbjörnsdóttir A. E. and Markússon S. H., 2013. The Theistareykir geothermal field, NE Iceland: fluid chemistry and production properties. Procedia Earth and Planetray Science 7, 644-647.

Parisi, Maria Laura; Ferrara, Nicola; Torsello, Loredana; Basosi, Riccardo (2019): Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants. In Journal of Cleaner Production 234, pp. 881–894. DOI: 10.1016/j.jclepro.2019.06.222.

Paulillo, Andrea; Striolo, Aberto; Lettieri, Paola (2019): The environmental impacts and the carbon intensity of geothermal energy: A case study on the Hellisheiði plant. In Environment international 133 (Pt B), p. 105226. DOI: 10.1016/j.envint.2019.105226.

PannEnergy, 2013. Miskolci Geotermikus Projekt 2013. BET_PE_20131029.pdf

Portier S., Vuataz F.D., Nami P., Sanjuan B. & Gérard A. (2009). Chemical stimulation techniques for geothermal wells: experiments on the three-well EGS system at Soultz-sous-Forêts, France. Geothermics, 38(4), 349-359.

Pratiwi A., Ravier G., Genter A. 2018. Innovative Tool for Life-cycle CO2 Emissions Calculation of Geothermal Plants in Upper Rhine Valley. Geothermal Resources Council Annual Meeting. Reno 2018

Pratiwi, A., Ravier, G., & Genter, A. (2018). Life-cycle climate-change impact assessment of enhanced geothermal system plants in the Upper Rhine Valley. Geothermics, 75(August 2017), 26–39. https://doi.org/10.1016/j.geothermics.2018.03.012

Qi, X., Turnquist, N., Ghasripoor, F., (2012). Advanced Electric Sumersible Pump design tool for geothermal applicatons.

Rangel G., Pereira V., Ponte C., Thorhallsson S.. 2019. Reaming calcite deposits of well pv8 while discharging: a succesfull operation at Ribeira grande geothermal field, São Miguel island, Azores. European Geothermal Congress 2019.

Ravazdezh F., 2015. A study on operation and maintenance of flash steam geothermal power plants: Reykjanes power plant. UNU-GTP. Reports 2015, number 31.

Regional Agency for Environmental Protection in Tuscany (ARPAT). Monitoring data available at: http://www.arpat.toscana.it/temi-ambientali/sistemi-produttivi/impianti-di-produzione-di-energia/geotermia/monitoraggio-qualita-dellaria/ar_areegeotermiche.html.

Reinsch T, Bruhn D. The SURE consortium. Novel productivity enhancement concept for a sustainable utilisation of a geothermal resource e the SURE project. In: Proceedings, European geothermal Congress 2016, Strasbourg; 2016. p. 4.

Reinsch, T., Dobson, P., Asanuma, H., Huenges, E., Poletto, F., Sanjuan, B., (2017). Utilizing supercritical geothermal systems: a review of past ventures and ongoing research activities. Geothermal Energy Science – Society – Technology20175:16

Richter, M., 2017. Summary of geothermal drilling technologies, IEA Geothermal, August 2017.

Rodríguez, E. (2013): Review of H2S Abatement in Geothermal Plants and Laboratory Scale Design of Tray Plate Distillation Tower. MSc. Thesis. Reykjavik University, Iceland, 101 pp.

Rodríguez, E., Scott Harvey, W, Ásbjörnsson, J. E. (2015). Review of H2S Abatement Methods in Geothermal Plants.

Rodriguez, G., C. Ouyang (2013). Air Emissions Characterisation and Management for Natural Gas Hydraulic Fracturing Operations in the United States (2013). (URL: http://deepblue.lib.umich.edu/bitstream/handle/2027.42/97418/AirEmissionsHydraulicFracturing_04-23-2013.pdf?sequence=1)

Rogge, S. (2004) “Geothermische Stromerzeugung in Deutschland Oekonomie, Oekologie und Potenziale”, PhD Thesis, Berlin, 2004, Page 3.

Rosca, M., Bendea, C.C., & Vîjdea, A. (2016). Mineral and Thermal Waters of Romania.

Rutz D., Winterscheid C., Pauschinger T., Grimm S., Roth T., Doračić B., Dyer G., A. Østergaard T., Hummelshøj R. (2019). Upgrading the performance of district heating networks Technical and non-technical approaches - A Handbook.

Sammarco G. & Sammarco O., 2002: Gases released by water: impact on underground mines and on the surface. Proceedings of the International Conference Uranium Mining and Hydrology III and the International Mine Water Association Symposium. Freiberg, Germany.: 990-1000.

Sanjuan B., Millot R., Innocent C., Dezayes C., Schreiber J., Brach M., 2016. Major geochemical characteristics of geothermal brines from the Upper Rhine Graben granitic basement with constraints on temperature and circulation. Chemical Geology 428, 27-47.

Sanopoulos, D., and Karabelas, A.: H2S Abatement in Geothermal Plants: Evaluation of Process Alternatives. Energy Sources. 19 (1), (1997), 63-77.

Saouter E, Biganzoli F, Ceriani L, Versteeg D, Crenna E, Zampori L, Sala S, Pant R. (2020). Environmental Footprint: Update of Life Cycle Impact Assessment Methods – Ecotoxicity freshwater, human toxicity cancer, and non-cancer. Joint Research Centre.

Schindler M., Baumgärtner J., Gandy T., Hauffe P., Hettkamp T., Menzel H., Penzkofer P., Teza D., Tischner T. & Wahl G. (2010, April). Successful hydraulic stimulation techniques for electric power production in the Upper Rhine Graben, Central Europe. In Proceedings World geothermal congress (Vol. 2010).

Schreiber S., Lapanje A., Ramsak P., Breembroek G. et al., 2016. Operational issues in Geothermal Energy in Europe - Status and overview.DOI: 10.5281/zenodo.1249347

Schütz F., Huenges E., Spalek A., Bruhn D., Pérez P., de Gregorio M. D4.6 “Geothermal Electricity: Potential for CO2 Mitigation” GEOELEC.

Seibt P, Kabus F, Wolfgramm M, Bartels J, Seibt A. (2010). Monitoring of Hydrogeothermal plants in Germany – an Overview. Proceedings of the World Geothermal Congress 2010, Bali, Indonesia, 25 – 29 April 2010.

Selene J. Chou (2003). Concise International Chemical Assessment Document 53 “Hydrogen sulfide: human health aspects”. World Health Organisation.

Serpen, U., Türeyen, O.I., 2000. Acidizing geothermal wells. Geothermal Resources Council Transactions 24, 683–688.

Sestini, G., 1970: Superheating of geothermal steam. Geothermics, special issue, 1: 622-648.

SETIS magazine May 2015- Geothermal Energy.

Seywald M, Marschall C. Usage of radial drilling by RAG. Oil Gas European Magazine 2009;3:114e6.

Shortall, Ruth; Davidsdottir, Brynhildur; Axelsson, Guðni (2015): Development of a sustainability assessment framework for geothermal energy projects. In Energy for Sustainable Development 27, pp. 28–45. DOI: 10.1016/j.esd.2015.02.004.

Skrtic L. (2006). Hydrogen Sulfide, Oil and Gas, and People’s Health. Energy and Resources Group University of California, Berkeley.

Sigfusson, B., Uihlein, A. (2016). JRC 2015 Geothermal Energy Status Report. Technology, market and economic aspects of geothermal energy in Europe.

Sigfusson, B., Uihlein, A. (2015). JRC 2014 Geothermal Energy Status Report. Technology, market and economic aspects of geothermal energy in Europe.

Sigurardottir H., Gislason S. R., Broecker W. S., Oelkers E. H. & Gunnglaugsson E., 2010: The CO2 Fixation into Basalt at Hellisheidi Geothermal Power Plant, Iceland. Proceedings World Geothermal Congress 2010, Bali, Indonesia.

Sigurðardóttir S., Stefánsdóttir A., Gíslason P. M., Sigfússon B., Haraldsdottir H., Fanicchia F,. 2018. Deliverable D1.3 : Report on characterisation of geothermal fluid from project Development of Novel and Cost-Effective Corrosion Resistant Coatings for High Temperature Geothermal Applications (Geo-COAT)

Somma, Renato; Granieri, Domenico; Troise, Claudia; Terranova, Carlo; Natale, Giuseppe de; Pedone, Maria (2017): Modelling of hydrogen sulfide dispersion from the geothermal power plants of Tuscany (Italy). In The Science of the total environment 583, pp. 408–420. DOI: 10.1016/j.scitotenv.2017.01.084.

Stephens, F., Hil, J. and Phelps, P.J.: State-Of-The-Art Hydrogen Sulfide Control For Geothermal Energy Systems. U.S.Department of Energy, (1980).

Strawn, J.A., 1980. Results of acid treatment in hydrothermal direct heat experiment wells. Geothermal Resources Council Transactions 4, 427–430.

Suleimenov, O. M., & Krupp, R. E. (1994). Solubility of hydrogen sulfide in pure water and in NaCl solutions, from 20 to 320 C and at saturation pressures. *Geochimica et Cosmochimica Acta*, *58*(11), 2433-2444.

Sursuje, S., & Gandgil, C. (2013). Geothermal Vapour Absorption Refrigeration System. International Journal of Scientific and Engineering Research, 4(12), 162.

Sullivan, J. L., C. Clark, J. Han, and M. Wang. (2010). “Life-Cycle Analysis Results of Geothermal Systems in Comparison to Other Power Systems.” Argonne National Laboratory.

Sullivan, J. L., T. Stephens, and M. (Energy Systems) Wang. 2014. “Geothermal Power Production: Alternative Scenarios and Critical Issues.” ANL/ESD-14/2. Argonne National Laboratory (ANL). http://www.osti.gov/scitech/biblio/1132252-geothermal-power-productionalternative-scenarios-critical-issues.

Szöcs T., Kerekgyarto T., Gal N., Babinski E., Tihanyiné Szep E., Palfi E., Jerabek C., Lajtos S., Beke Z., Bertalan E., Besnyi A., Bitter Z., Konya P. & Udvardi B., 2017. Új termálvíz és gázelemzések végzése és adatok komplex értékelése.

Targioni-Tozzetti, G., 1769: Relazioni di alcuni viaggi fatti in diverse parti della Toscana. Firenze, Italy, II ed., v.3-4-7.

Teodoriu & Cheuff (2011). Teodoriu, C., Cheuff a, C.: A comprehensive review of past and present drilling methods with application to deep geothermal environment. Thirty-Sixth Workshop on Geothermal Reservoir Engineering. 2011.

Tereshchenko, Tymofii; Nord, Natasa (2015): Uncertainty of the allocation factors of heat and electricity production of combined cycle power plant. In Applied Thermal Engineering 76, pp. 410–422. DOI: 10.1016/j.applthermaleng.2014.11.019.

Treyer, K., and Bauer, C. (2012); Electricity production, geothermal (and associated LCI data). Ecoinvent v3.0 data.

Treyer K., Oshikawa H., Bauer C. & Miotti M. (2015). WP4: environment. In “Energy from the Earth. Deep Geothermal as a Resource for the Future?”, Die Deutsche Nationalbibliothek, Zurich (2015) (p. 526)

Ülkü, S. (1986) Adsorption heat pumps. Heat Recovery Syst, 277–84.

Vandevier, J.; Gould, B. (2009). “Application of Electric Submersible Pumping Systems in High Temperature Geothermal Environments.”Geothermal Resource Council Transactions 33;pp. 649-652.

Vandevier, J. (2010). “Run-Time Analysis Assesses Pump Performance”. Oil and Gas Journal 108.37; pp. 76-79.

Varga A., Bozso G., Garaguly I., Raucsik B., Bencsik A., Kobor B., 2019. Cements, Waters, and Scales: An Integrated Study of the Szeged Geothermal Systems (SE Hungary) to Characterize Natural Environmental Conditions of the Thermal Aquifer. Geofluids, Article ID 4863814 | 21 pages | https://doi.org/10.1155/2019/4863814.

Veldkamp, J. G., Goldberg T. V., Bressers P. M. M. C. & Wilschut F., 2016. Corrosion in Dutch Geothermal Systems. TNO report, TNO 2015 R10160.

Verkís Consulting Engineers. 2015. Geothermal Power Plants–CO2 Emissions. Verkís Report 14298-001-1.

Verma, A. (2009). Alternate power and energy storage/reuse for drilling rigs. Thesis, Texas A&M University, USA, pp. 16-22.

Vidal J., Genter A., Chopin F. & Dalmais E. (2016, September). Natural fractures and permeability at the geothermal site Rittershoffen, France. In European Geothermal Congress (pp. 19-22).

Vidal J., Genter A., Jean Schmittbuhl J. (2016). Pre- and post-stimulation characterisation of geothermal well GRT-1, Rittershoffen, France: insights from acoustic image logs of hard fractured rock. Geophysical Journal International, Oxford University Press (OUP), 2016, 206 (2), pp.845 - 860.10.1093/gji/ggw181. hal-01710808

Wanner C., Eichinger F., Jahrfeld T., Diamond L. W., 2017. Unraveling the Formation of Large Amounts of Calcite Scaling in Geothermal Wells in the Bavarian Molasse Basin: A Reactive Transport Modeling Approach. Procedia Earth and Planetary Science, 17, 344-347.

Welter S., 2018. Technisch-ökonomische Analyse der Energiegewinnung aus Tiefegeothermie in Deutschland. Thesis. Univ. Stuttgart.

Yildirim, E. D.; Gokcen, G. (2015). Thermodynamic Performance of Single-Flash Geothermal Power Plants from the Point of View of Noncondensable Gas Removal Systems. Proceedings World Geothermal Congress, Melbourne, Australia.

Wang M. (2010). Life-cycle analysis results of geothermal systems in comparison to other power systems, ANL/ESD/10-5.

Wolfgramm M., Birner J., Lenz G., Hoffmann F., Rinke M., (2012). Erfahrungen bei der Säurestimulation geothermaler Aquifere und Anlagen. November 2012, Conference: Geothermiekongress vom 13.-16.11.12 in Karlsruhe.

World Health Organisation. (2000). Air Quality Guidelines - Second Edition, Ch. 6.6 Hydrogen sulfide.

Zampori L., Saouter E., Schau E., Cristobal J., Castellani V., Sala S. (2016). Guide for interpreting life cycle assessment result. Joint Research Centre.

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The study ‘Geothermal plants' and applications' emissions: overview and analysis’ aims at providing consistent and harmonized life cycle based assessment on the release of air pollutant emissions in the deep geothermal sector in Europe, in response to existing fragmented information and debate. The full analysis is developed at scale of clusters (representative groups of different plants), identified based on geological and technological parameters, through the application of Life Cycle Assessment methodology. Results show that most existing geothermal applications report relatively limited values of greenhouse gas emissions, as well as negligible impacts on the local areas where they are located. However, in rare cases it appears that, especially depending on geothermal fluid properties, specific impacts arise, requiring tailored mitigation measures to avoid risks on environment and human health. In conclusion, a set of recommendations is presented to support future decision-making and at addressing a fair and sustainable development of the deep geothermal sector in Europe.

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