UNIVERSITÀ
DI SIENA
1240

Dipartimento di biotecnologie, chimica e farmacia

PhD Program in Chemical and Pharmaceutical Sciences
Cycle XXXIII

Dottorato di ricerca in Chimica e Tecnologie Farmaceutiche
Ciclo XXXIII

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Atmospheric emissions profiles of geothermal energy production to minimise the environmental footprint: an innovative methodological investigation based on LCA approach

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Academic year 2020/2021

I express my heartfelt thanks to Prof. Riccardo Basosi for inspiring this research and for the excellent advice received during our acquaintance, even beyond the academic world.

I also whish thanks the research group at the University of Siena, where I conducted my studies, for significant contribution received to my education.

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INTRODUCTION

Climate change involves global warming induced by human greenhouse gas pollution as well as the subsequent widespread changes in climate patterns. There have been past cycles of climate change, but humans increased much the magnitude of that effect from the middle of the 20th Century (Stocker et al., 2013).

No research body with national and international status denies that human actions have caused climate change. Greenhouse gases (GHGs), of which about 90% carbon dioxide (CO_2) and methane (CH_4) are the primary factors, the primary cause of these emissions is fossil fuel combustion for energy consumption, with additional inputs from forestry, deforestation, and the industry's process (US EPA, Overview of Greenhouse Gases).

Rising temperatures in most parts of the globe restrict ocean productivity and destroy fish stocks. Environmental impacts include the extinction or relocation of many species, especially in coral reefs, mountain ranges, and the Arctic, as their ecosystems shift. Even if attempts to reduce future warming are successful, such consequences, including increasing sea levels, increasing ocean temperatures, and acidification at sea by high CO_2 levels, will continue for centuries.

Many of these effects also exist at the present warming stage, which is approximately 1.1 °C. The IPCC has provided numerous reports projecting impacts increasing as warming progresses to 1,5 °C (and beyond). Under the Paris Convention (European Commission, 2015), 190 nations agreed to maintain warming "well under 2.0 °C ". However, global warming will hit about 2.8 °C by the end of the Century, resulting in a warming of about 3.0 °C under existing policies. To limit warming to 1.5°C, it would require emissions to be halved by 2030 to reach near-zero by 2050 (IPCC, 2018; NOAA, 2020; Tschakert, 2015).

Mitigation initiatives include research, production, and implementation of low-carbon energy technologies, increased energy management, fossil-fuel emission mitigation policies, forestation, and forest protection. Most companies and governments work to respond to current and future global warming by strengthening the coastline's protection, strengthening disaster management, and growing more resistant crops.

The general policy used to limit global warming effects talks about the decarbonisation of energy sources. Since energy production, meant as electricity and heat production, is responsible for a large part of GHGs emissions, processes based on more sustainable energy source is the baseline to try to control the effect of GHGs. A low carbon economy or decarbonised economy is an economy based on energy sources with a minimum GHGs emissions level (European Commission, 2013; IPCC, 2014; Overland et al., 2019).

Recent technologies and policy developments would allow renewable energy and energy efficiency practices to play a significant role in fossil fuel displacement, thus meeting global energy demand while reducing carbon dioxide emissions. Technologies exploiting renewable energy are increasingly being implemented and, combined with performance gains, can produce much more significant reductions in emissions than could be accomplished if actions are undertaken independently (Armstrong et al., 2016; Müller et al., 2011).

Renewable energy sources exploited nowadays are many, and the most known and familiar are hydroelectric, wind, and solar (REN21, 2016). All these energy sources are linked to the energy generated by the sun. Hydroelectric is based on the potential energy acquired by water basins when rain occurs on mountains: it exploits the water cycle induced by solar energy. In the same way, wind energy is the manifestation of a gradient of temperatures between two areas due to heating produced by sun irradiation, and, of course, solar energy is the direct exploitation of solar radiation. Therefore, environmental conditions determine the effective production from these sources.

In this context, geothermal energy production is one of the most attractive renewable sources in the low carbon economy panorama (Fridleifsson et al., 2008). It has long been known and exploited (Scali et al., 2013), but many experts assert it is not enough, considering its potential. It is linked with the Earth's geological nature; it is the manifestation of the geothermal gradient generated by radioactive decay and continual heat loss derived from Earth’s formation. The best know expressions of this are the hot springs, phenomena involving spills of hot water from the Earth’s surface.

The widespread perception considering the lack of these natural manifestations is that geothermal resource is identified with high-grade hydrothermal systems, that are too few and too limited to be a significant part of a long-term national energy plan (DiPippo, 2015; Shortall

& Kharrazi, 2017). However, it should be considered that Earth has an internal heat content of 10^{31} joules (3·1015 TWh), approximately 100 billion times the 2010 worldwide annual energy consumption. Therefore, the potential energy that can be exploited is vast (Tester et al., 2006).

Unfortunately, extraction of this kind of energy is sometimes challenging, and a few are places in the world where it is possible to use this energy easily. The most notorious case is the Icelandic one. Indeed, in this region, a larger portion of energy requests is by far covered by geothermal energy exploitation. However, the most influential site from a historical and technological perspective is located in Italy, namely in Tuscany, where the first industrial development of this resource began (Parri et al., 2016). Nowadays, the electricity production from deep geothermal in Tuscany is still relevant since 900 MWe of power are installed, which can cover energy demand for almost 1/3 of Tuscany.

Besides, this energy source has properties that make it unique compared to other renewables, and with some similarities with fossils fuels energy production systems for some aspects. Geothermal energy does not depend on environmental conditions; indeed, a geothermal power plant can produce energy 365 days a year, 24 hours a day. This property is very positive because it is essential to balance the electric grid compensating for fluctuation determined by traditional renewables such as the above mentioned solar, wind, and hydro. On the other hand, this kind of power plant also has a drawback: the energy produced with this technology is not sustainable and renewable "as it is". If the power plants are not operated correctly, the resource can be spent making it non-renewable (Dobson et al., 2020; Tezel et al., 2016). Indeed, the amount of geothermal fluid that is possible to extract from the geothermal source is not infinite, and the reservoir can be exhausted, likely a crude oil source. The geothermal field needs to be exploited prudently to avoid this phenomenon occurring, implementing correct technological solutions proved to be helpful in this sense (Allegrini et al., 1992; DiPippo, 2015; Minissale, 1991).

Another point which makes the diffusion of geothermal energy exploitation very limited is connected to the various geological structure of the earth. Usually, the places where natural manifestations are present are the one where it is possible to develop this technology simply, and so only in Iceland, Italy (Larderello), New Zeeland, Indonesia, and in other few places relevant installations are present. Despite that, much more are the regions where the geothermal gradient is enough to reach significant temperatures not so deep below the surface. Besides, new drilling technologies and new resource engineering approaches can also bring geothermal accessibility in regions where it is now impossible ("The Future of Geothermal Energy," 2006; Thorbjörnsson et al., 2016).

There is a need for a scientific and rigorous approach to assess and evaluate the aspects connected to renewability and sustainability of the resource exploitation, definitively, to assess the environmental performance of the system. In this context, the Life Cycle Assessment methodology can play a crucial role (EPA, 2008; The International Standards Organisation, 2006). The possibility to analyse the whole life cycle of a power plant deeply is valuable since it can highlight critical processes along the whole supply chain.

The research activities described in the thesis have been carried out thanks to the collaboration and supervision of COSVIG (Consortium for the Development of Geothermal Areas). Part of the research described here was also performed in Belgium, where I was hosted as a PhD visiting student at VITO NV, a research centre focused on innovation for environmental sustainability purposes.

Part of the research described here was also performed in the framework of the Horizon 2020 research and innovation program under grant agreement No [818242 — GEOENVI].

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STRUCTURE AND CONTENT OF THE THESIS

The research described in this thesis can be summarised in 3 main tasks:

1) Environmental data collection and analysis
2) Life Cycle Impact Assessment and results interpretation
3) Methodological advances

In section 1, a preliminary analysis of the research objective is performed. Thanks to an extensive research and the interaction with the power plant's operator, a typical geothermal power plant operation is modelled and described. Then, all the power plants currently installed and operating in Italy are analysed extensively, starting from the geothermal resource itself, to the environmental performances connected with this industrial activity, till the final use of the energy produced.

In chapter 1.1, the atmospheric emissions of all the Italian geothermal power plants are collected, carefully analysed, and statistically described. The interaction with ARPAT (Regional Agency for Environmental Protection) allowed examining the environmental sampling procedure for the evaluation of atmospheric emissions and regulatory issues. The collected data were also used to build an online database publicly accessible.

Then, in task 2, the Italian power plants' environmental performances are assessed through the development of a LCA study based on the environmental data collected during the first phase. An in-depth analysis of the case studies and a methodological revision is performed to identify all the potential sources of errors or and possible improvements. The main goal is to obtain rigorous methodological modelling suitable for all geothermal installations to obtain reliable results regarding their environmental performance.

In chapter 2.1, direct environmental emissions are evaluated, and thanks to the large amount of data previously collected, statistically robust results are obtained. This analysis also highlights the environmental implications linked to heavy metals' direct emissions because of their sizeable toxicity effects. It discusses the actual limitations of the Life Cycle Assessment calculation methods in detecting such emissions to evaluate their environmental burden properly. Chapter 2.2 is devoted to this topic describing different calculation methods for toxicity evaluation.

Thanks to this very complete and detailed picture of the geothermal field, in chapter 2.3, LCA is applied to a specific case study representing the state-of-the-art of the geothermal flash technology power plant for which a very detailed data inventory is built.

To bring more relevance and significance to the LCA methodology's potentiality, making use of python libraries is it possible to perform advanced statistical analysis and develop simplified models that can increase the potentiality and the meaningfulness of the LCA. In chapter 3.1, an example of this approach is described using the Italian electricity mix composition and a prospective analysis of future energy mix scenarios. Then a more complex and robust approach is described in chapter 3.2, where LCA simplified models for two case studies are presented. The Bagnore 3 and 4 geothermal system in Italy and Balmatt geothermal plant in Belgium are chosen to evaluate the ability of the method to build reliable and robust models because they employ two different conversion technologies and use destinations.

1 ENVIRONMENTAL DATA COLLECTION AND ANALYSIS

1.1 Data analysis of atmospheric emission from geothermal power plants in Italy

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Data in Brief
Volume 25, August 2019, 104339

https://doi.org/10.1016/j.dib.2019.104339

Abstract

Electric production from geothermal energy is still little exploited compared to its large potential and to the World renewable energy production from other sources. Some countries have exploited this energy source in order to enhance their transition to renewables. Today the largest geothermal energy producers in the World are New Zealand, U.S.A, Mexico, Philippines, Italy, Iceland, and, more recently, Turkey (Geothermal, 2012).

Differently from other renewable sources, geothermal energy produces impacts on the environment that are very site-specific because of the nature of the resource and its geological characteristics Bravi et al.,2010; Parisi et al.,2013. In the same way, the atmospheric emissions associated to the activity of geothermal power plants for electric or heat production (mainly CO_2, H_2S, NH_3, Hg, CH_4) are also site-specific. In fact, due to technological and geographical differences among the geothermal installations operating all over the World, it is quite impossible to identify and attribute typical emission patterns, to perform forecasts valid for multiple sites or to collect universal data. Furthermore, it is virtually impossible the comparison among technologies located in different regions or countries. Definitively, inventories of primary data, as accurate and complete as possible, are essential to correctly evaluate the peculiarities of geo-thermoelectric energy production Parisi et al.,2018.

Data reported here try to fill the gap in respect to the Italian situation. To this end, a complete survey of the atmospheric emissions from all the geothermal power plants in operation in the Tuscany Region is performed. In addition to data reporting, also some statistical analysis is performed to process data and to operate a further level of simplification which averages the emissions on the basis of geothermal sub-areas.

The data collected is related to the research article "Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants" Parisi et al.,2019.

Specifications Table

Subject area	***Atmospheric emissions***
More specific subject area	*Atmospheric emissions from geothermal power plants based on flash and dry steam technology*
Type of data	*Tables and figures*
How data was acquired	*Environmental sampling at power plant and analytical determination through different standardised methods*
Data format	*Raw and processed*
Experimental factors	*Emissions data are collected and tabulated according to a common scheme to allow an easier analysis of the information*
Experimental features	*Samplings are performed by means of standardised methods, as well as chemical determination of the pollutants*
Data source location	*Tuscany Region (Italy): geothermal areas in the provinces of Grosseto, Pisa and Siena*
Data accessibility	*Data are partially reported here and partially accessible in Mendeley data in order to keep it updated and provide larger details (*https://doi.org/10.17632/gvpy69796n.1*)*
Related research article	Parisi et al. "Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants", Journal of Cleaner production, 234, 881–894 (2019)

1.1.1 Data

Data reported here concern the atmospheric environmental emissions generated by the activity of all the geothermal power plants in operation nowadays in Italy, more precisely in the Tuscany Region [2], [3], [4], [5]. The on-site sapling activity is performed by the Regional Agency for Environment Protection of Tuscany (ARPAT). A sketch of the most important sampling points identified by ARPAT is showed in Fig. 1. Since sampling activities are not performed at regular time intervals, in Table 1 there is reported the actual state of samplings. Actually, the information described in this paper are only referred to data reported in Table 1.

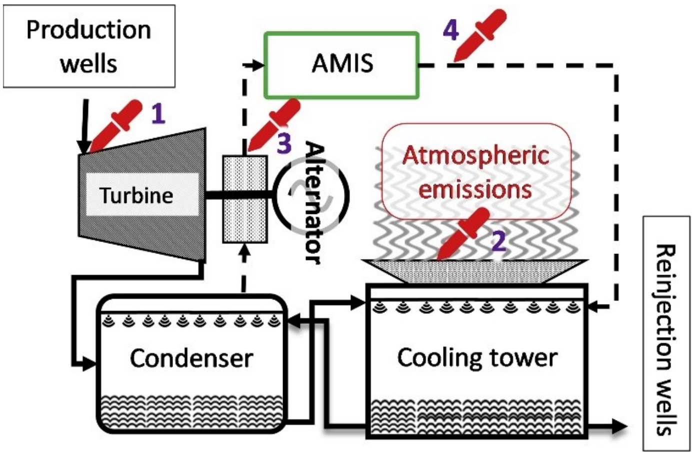

Figure 1 Sketch of the geothermal power plant configuration; the red pipettes show the most important sampling points identified by ARPAT.

Table 1The table shows the temporal distribution of sampling campaigns detailed in the ARPAT reports. F: most of the pollutants are determined; P: only few of the pollutants are determined.

	2002	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*	*2016*
Bagnore 3	F		F	F	F		F	F		F	F	F	F	F	F
Bagnore 4														F	F
Carboli 1		F							F			P	F		
Carboli 2															
Cornia 2			F									F	F		
Monteverdi 1		F					F					P			
Monteverdi 2															
Nuova Lago				F							P				
Nuova Lagoni Rossi												F			
Nuova Monterotondo									F						F
Nuova San Martino			F			F		F				P		F	
Nuova Sasso									F			P			F
Nuova Serrazzano		P												F	
Selva 1		P											F		
Farinello				F						P	F	F		F	
Nuova Castelnuovo		P			F						F		F		
Nuova Gabbro								F			F				
Nuova Larderello 3							F				F		F	F	
Nuova Molinetto			F			F						F			
Sesta 1			F						F						
Vallesecolo				F						F	F	F	F	F	
Piancastagnaio 3	P		P	F	F	F	F	F					F		P
Piancastagnaio 4	P						P			P			F		P
Piancastagnaio 5	P					F		F		F		P	F	P	
Chiusdino 1										F	F		F		P
Nuova Radicondoli								F			P		F		
Pianacce								P		P					
Rancia 1									F				F		
Rancia 2						F			F				F		
Travale			F	F	F							P			

Due to the large amount of data, a database containing all the sampling values has been generated and is hosted on Mendeley Data [6] The latter will be updated as soon as new emissions information will be available. In addition to raw data, a basic statistical manipulation has also been performed in order to assess data quality (Table 3 and Fig. 2) and to elaborate average emission patterns (Table 2) [2], [3], [4], [5].

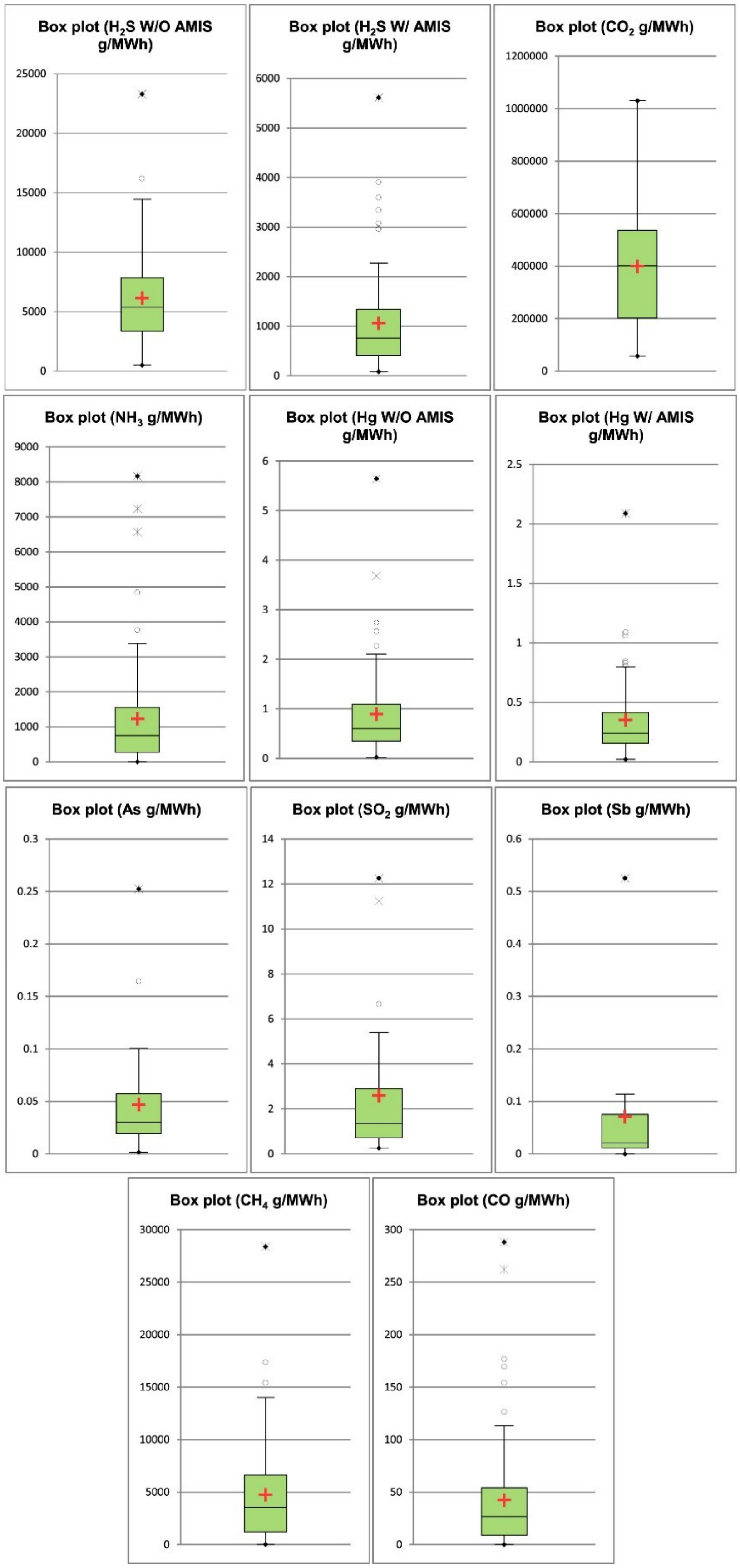

Figure 2 Box plots describing distributions of data used. Lowest and highest whiskers represent 1.5 IQR, green box is delimited by the 1st and 3rd quartile divided by the median. Circles and stars are near and far outliers respectively, while the red cross is the mean value.

Table 2 Emissions calculated for the average scenario based on data collected from all the Italian geothermal fields.

	Actual Scenario	**Scenario without AMIS**
H_2S (g/h)	1.34E+03	6.12E+03
CO_2 (g/h)	4.83E+05	4.85E+05
SO_2 (g/h)	1.99E+00	
NH_3 (g/h)	1.23E+03	3.07E+03
As (g/h)	4.00E-02	4.00E-02
Sb (g/h)	4.10E-02	4.11E-02
Hg (g/h)	3.72E-01	9.42E-01
CH_4 (g/h)	7.10E+03	7.12E+03
CO (g/h)	4.96E+01	4.98E+01
Produced Energy (MWhe)	1	1

1.1.2 Experimental design, materials, and methods

Raw data are collected from the public reports provided by the Regional Agency for Environment Protection of Tuscany (ARPAT). The public agency conducts several sampling campaigns each year to fulfil the regulation about the atmospheric emissions control of the power plants [7].

The analysis is performed in compliance with international and approved national standards. This methodological approach ensures the robustness and validation of data [8], [9], [10], [11]. Fig. 1 describes a simplified scheme of a hydrothermal flash geothermal plant operating in Tuscany: the red pipette are the sampling points identified by ARPAT [6], [12].

The sampling point n° 1 is used to record chemo-physical parameters of the entering fluids (pH, temperature, mass flow, pression, etc.) as well as the chemical composition (H_2S, CO_2, CH_4, NH_3, Hg, As, Sb). At the sampling point n°2, in the area of the evaporative tower (in this section the extracted gaseous fraction, which is conducted into the towers, is deviated to avoid doubling the emissions), the emissions of pollutants dissolved into the drift are determined (H_2S, NH_3, Hg, As, Sb), as well as chemo-physical parameters (pH, air temperature, wet bulb temperature, air mass flow, etc). Sampling points n°3 and 4° only account for the gaseous fraction of the emissions; the pollutants determined in this sampling points are H_2S, CO_2, CH_4, NH_3, SO_2 (resulting from the catalytic oxidation of H_2S) and Hg. As the abatement system (AMIS) is employed for the gaseous phase, the chemical determination is performed before and after the process to determine the abatement ratio [13].

The complete dataset of atmospheric emissions is loaded and publicly available in Mendeley Data [6]. Information stored in the repository will be continuously updated as soon as new sampling will be available, in order to expand and keep updated the environmental information disseminated by ARPAT.

Table 3 Statistical descriptors of the data used.

Statistic	*H_2S W/AMIS g/MWh*	*H_2S W/O AMIS g/MWh*	*CO_2 g/MWh*	*SO_2 g/MWh*	*NH_3 g/MWh*	*As g/MWh*	*Sb g/MWh*	*Hg W/AMIS g/MWh*	*Hg W/O AMIS g/MWh*	*CH_4 g/MWh*	*CO g/MWh*
Number of observations	463	463	463	463	463	463	463	463	463	463	463
Minimum	8.3E+01	5.0E+02	5.7E+04	2.6E-01	4.2E-01	1.7E-03	1.8E-05	2.1E-02	2.5E-02	1.6E+01	2.0E-03
Maximum	5.6E+03	2.3E+04	1.0E+06	1.2E+01	8.2E+03	2.5E-01	5.3E-01	2.1E+00	5.6E+00	2.8E+04	2.9E+02
1st Quartile	4.1E+02	3.4E+03	2.0E+05	7.0E-01	2.7E+02	1.9E-02	1.2E-02	1.6E-01	3.5E-01	1.2E+03	8.8E+00
Median	7.6E+02	5.4E+03	4.0E+05	1.4E+00	7.5E+02	3.0E-02	2.1E-02	2.4E-01	6.0E-01	3.5E+03	2.7E+01
3rd Quartile	1.3E+03	7.9E+03	5.4E+05	2.9E+00	1.6E+03	5.7E-02	7.5E-02	4.1E-01	1.1E+00	6.6E+03	5.4E+01
Mean	1.1E+03	6.1E+03	4.0E+05	2.6E+00	1.2E+03	4.7E-02	7.1E-02	3.5E-01	8.9E-01	4.8E+03	4.3E+01
Variance (n-1)	9.7E+05	1.8E+07	4.9E+10	9.1E+00	2.3E+06	2.1E-03	1.7E-02	1.1E-01	7.9E-01	2.2E+07	2.7E+03
Standard deviation (n-1)	9.8E+02	4.2E+03	2.2E+05	3.0E+00	1.5E+03	4.6E-02	1.3E-01	3.2E-01	8.9E-01	4.7E+03	5.2E+01
Skewness (Pearson)	2.2E+00	1.2E+00	5.7E-01	2.0E+00	2.6E+00	2.5E+00	3.1E+00	2.5E+00	2.6E+00	2.0E+00	2.6E+00
Kurtosis (Pearson)	6.0E+00	2.1E+00	−1.4E-01	3.5E+00	7.8E+00	8.0E+00	8.3E+00	9.4E+00	9.7E+00	6.1E+00	8.1E+00
Harmonic mean	5.2E+02	3.2E+03	2.7E+05	1.0E+00	3.2E+01	1.9E-02	2.0E-04	1.5E-01	3.5E-01	7.3E+02	1.1E-01

1.1.3 Data processing

Basic data processing is performed in order to average the emissions and obtain more general descriptions.

For each power plant the median of the samplings for each pollutant is calculated, then the g/h values are converted to g/year and weighted over the average electricity produced [1] to obtain emissions expressed as g/MWh. In case of emissions which depend on the abatement system (AMIS), the annual emission is composed by two fractions which reflect the emissions with and without the abatement system, respectively multiplied by the amount of yearly hour in which the AMIS is working or not. The sum of the two fractions (g/year) is weighted over the yearly electricity produced to obtain emissions expressed as g/MWh. This process was applied for Hg and H_2S, which are the compounds treated by the AMIS, for all the power stations. The spreadsheet loaded in Mendeley Data contains the formula used to perform the calculation. The power plants average emissions are unified by area according to geographic information reported in the data repository.

Further simplification can be performed by averaging the emissions of all the power plants as reported in Table 2. Also, two different scenarios are calculated: one representing the actual emission (actual scenario) and another which corresponds to the emissions that could be obtained if no abatement system were employed (scenario without AMIS).

1.1.3.1 Statistical description

All the collected data was statistically analysed to characterise the distribution and the errors connected to the database built. Table 3 and box plots in Fig. 2 report statistical indicators which describe the 463 observations collected at the time of the paper preparation.

The emissions obtained with the abatement system is indicated as W/AMIS, while the non-abated pollutants flow's is indicated W/O AMIS.

1.1.4 Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

1.1.5 Acknowledgments

Authors acknowledge MIUR Grant - Department of Excellence 2018-2022. NF thanks COSVIG for contributing to his PhD grant. Collaboration of ARPAT in collecting data is gratefully acknowledged.

1.1.6 Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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2 LIFE CYCLE IMPACT ASSESSMENT AND RESULTS INTERPRETATION

2.1 Life cycle assessment of atmospheric emission profiles of the Italian geothermal power plants

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Journal of Cleaner Production
Volume 234, 10 October 2019, Pages 881-894

https://doi.org/10.1016/j.jclepro.2019.06.222

Highlights

- Atmospheric direct emissions profile calculated with LCA approach.
- Sub-regional clustering of Italian geo-thermoelectric power plants.
- AMIS sharply reduces impacts on Amiata region but is less effective in other areas.
- Emissions through cooling tower represent the largest contribution to LCA score.
- Hg impacts show large uncertainty, LCIA methods need to fit better the case.

Abstract

After nearly a decade of only small development in capacity in deep geothermal sector in Europe, in recent years a resurgence of interest in geothermal power and the use of innovative technologies to increase and better exploit geo-thermoelectric generation has stolen the limelight from the scientific community. Differently from other types of energy sources, the environmental impacts determined by geothermal exploitation are extremely dependent on the geographical location. Life Cycle Assessment offers a powerful methodological approach for the investigation of the environmental footprint of power generation systems.

Focusing on an unprecedented system-modelling approach for the investigation of an environmental impacts analysis of geo-thermoelectric activity in the Tuscany Region, Italy, in this work we perform a comprehensive environmental impact assessment for the calculation of atmospheric emissions profiles connected with the operational phase of the power plants. A clustering of all the geothermal installations in operation nowadays is performed by considering geographical representativeness This allows the identification of regional geothermal subareas. Moreover, an extensive data processing analysis is implemented with the aim of reconciling the great variability found among data collected. Results demonstrate that the efforts undertaken by the operator of the geothermal power plants to limit the impact of emissions, through abatement systems like AMIS, are quite effective. Indeed, in areas where mercury and ammonia concentration in fluids constitute a problem to deal with, nowadays the emissive patterns result comparable to the other ones. Notwithstanding, mercury and ammonia emissions, mainly emitted through the cooling towers, still represent a critical problem for all the geothermal fields. On the basis of our findings, we conclude that potential chemical interactions and environmental impacts related to the variety of the compounds emitted should be object of future research and a further effort to minimise them.

Abbreviations

AMIS	Abatement System for Mercury and Hydrogen Sulphide
EGS	Enhanced Geothermal System
g/h	Grams per Hour
g/MWh	Grams per Mega Watt hour
g/y	Grams per Year
GHG	Greenhouse Gas
GWe	Giga Watt electricity
GWh/y	Giga Watt hour per year
LCA	Life Cycle Assessment
LCI	Life Cycle inventory
LCIA	Life Cycle impact Assessment
MWe	Mega Watt electricity
MWhe	Mega Watt hour electricity
NCG	Non-Condensable Gas
ORC	Organic Rankine Cycle
W/	With
W/O	Without

2.1.1 Introduction

Geothermal energy has been perceived as a convenient source for electric energy production only on a local scale so far, as just few areas in the World have enough geothermal potential to exploit it. Italy, Iceland, some U.S. States, Indonesia, Philippines, New Zealand are some of the countries that have already benefited from its exploitation. In recent years things have changed, and geothermal energy is now considered as one of the most promising renewable energy sources for producing electricity and heating. This is also proven by significant investments that are being made at international level: in fact, new technologies could allow the exploitation of reservoirs that would have been impossible to use in a cost-effective way until now (very deep drilling, binary cycle for low temperature fields, Enhanced Geothermal System). So far, environmental concerns perceived by the community have been one of the important barriers especially for deep geothermal market development. In this context, nowadays decision-makers require more reliability in the environmental performance assessment of the power plants. In fact, differently from other types of energy sources, the environmental impacts determined by geothermal exploitation are extremely dependent on the geographical location. Concerning the global panorama of the geo-thermoelectric market, traditional hydrothermal flash power plants still dominate in terms of installed capacity all over the World, because of the greater electrical producibility that such technology can generate compared to others. In fact, according to the World Geothermal Congress survey, in 2015 only 1.8 GWe of the total 12.6 GWe world installed capacity was represented by binary power plants, while innovative enhanced geothermal technologies (EGC) were just not representative. Moreover, concerning the produced electrical geothermal energy in that year, only 12% was obtained from binary power plants. (Bertani, 2016). Nevertheless, the multiple technological solutions available today have put geothermal energy into renewed attention by the scientific community. Many topics have been investigated, from countries' geothermal potential to technical innovations to the environmental impact of these power plants. This latter issue is the one that in Italy is becoming more explored and even more discussed for the social impact on the population involved (Borzoni et al., 2014; Pellizzone et al., 2019, 2017). Historically, Italy is the country that first exploited this renewable energy, in fact, it was the major geothermal producer in the World in 2005 (Bertani, 2011). Recently, many countries have invested in this energy source in Europe, sometimes overtaking Italy: for example, nowadays Turkey is the leader country for installed capacity with 1.3 GWe (EGEC, 2018). Actually, the possibility to increase the geothermal production largely depends on the perception of the community and the determination of decision-makers requiring more reliability in the environmental performance assessment of the power plants. Differently from other types of energy sources, the impacts determined by geothermal exploitation are extremely dependent on the geographical location, especially for what concerns the operative phase and the reservoir exploited which determine the peculiarity of the power plant's emission profile.

Life Cycle Assessment (LCA) is acknowledged as the most powerful methodological tool for the evaluation of the environmental performances of power generation systems (Peng et al., 2013, Turconi et al., 2013, Parisi et al. 2013, Bravi et al., 2010; Brown and Ulgiati, 2002) and for the investigation of potential impacts associated with new projects prior their construction, thus allowing definition of the best strategies for mitigation of environmental emissions or even annihilation. Indeed, there are many studies available in the scientific literature reporting detailed life cycle inventory data enabling for an accurate description of the investigated systems and allowing also for the development of sophisticated parametrised model and predictive LCAs (Pehl et al., 2017, Padey et al., 2013, 2012). In the field of geothermal energy, the scientific literature is lacking in LCA studies providing primary data. In fact, just few studies on geothermal power plants are available and the studies focused on the assessment of the environmental profile of working power plants are even fewer (Bravi and Basosi, 2014, Buonocore et al., 2015, Karlsdóttir et al., 2015, Parisi and Basosi, 2018). Most of the LCA studies on geothermal systems employ data coming from the literature or indirect and not pertinent secondary data (Marchand et al., 2015, Martínez-Corona et al., 2017). Such scarcity of specific information is also due to the fact that geothermal exploitation can be performed with different technologies (flash, dry steam, binary) and for different purposes (electricity, heat or both) (Martín-Gamboa, M et al., 2015, Ruzzenenti et al., 2014), making the collection of primary data much more difficult compared to other power generation systems. Several authors have also performed reviews (Bauer et al., 2008, Bayer et al., 2013, Menberg et al., 2016) and harmonisations (Asdrubali et al., 2015, Sullivan et al., 2012, 2010) of previous LCA studies on geothermal energy production in which they clearly underline the scarcity of accurate data and variability of information that prevent the definition of reliable eco-profiles of geothermal systems (Lacirignola et al., 2014, Lacirignola et al., 2017).

The analysis proposed in this work tries to increase the knowledge and reduce data scarcity for the geo-thermoelectric activity in Italy by analysing the emission data available for all geothermal power plants operating in the Tuscany Region in a range of 10 years of analytical determinations collected by ARPAT (Tuscany Regional Agency for Environmental Protection). Focusing on an unprecedented system-modelling approach for the investigation of an environmental impacts analysis of geo-thermoelectric activity, we perform a comprehensive assessment of atmospheric emissions profiles representative of the actual situation in all the Tuscany geothermal areas. An extensive data processing analysis is implemented with the aim of reconciling the great variability found among data collected during the whole time series. Moreover, a clustering of geothermal installations in the Tuscany Region is performed by considering geographical representativeness This allows identification of regional geothermal subareas and calculation of environmental footprints connected to the operational phase of all the power plants in operation nowadays. As pointed out by the NREL report (Eberle et al., 2017) in which a systematic review of 180 papers on LCA of geothermal power plants worldwide reveals how the field location heavily influences the greenhouse gases' (GHGs) emissions, the large variety of environmental footprint calculated for geo-thermoelectric power plants is significant. Likewise, the technology implemented for the exploitation of geothermal energy deeply characterises the eco-profiles of power plants, as showed in the same report by disaggregating the contributions to the various life cycle phases.

This study is in no way intended to be an ecotoxicological review, as results obtained from an LCA study are not suitable to be used for that purpose. The authors' goal is to evaluate the potential atmospherics environmental impact generated by the geo-thermoelectric activity in Tuscany, employing all the available information, thus extending the analysis published by Bravi and Basosi (Bravi and Basosi, 2014) in terms of geographic dimension and data quality on the basis of the availability of larger amount of data in the historical series. To this aim, a rigorous statistical approach is adopted in order to obtain precise environmental profiles.

In addition, data presented here are a novel addition to the scientific literature of the geothermal field. The purpose is to obtain the most complete source of information about the emissions generated in atmosphere by deep geothermal exploitation of electric power generation plants in Italy, which nowadays is probably the most long-established region for geo-thermoelectric energy source in the EU. The different geochemical characteristics of the fields cause the impacts of this energy source strongly dependent on the location, in addition to the technology employed. Thus, it is hard to find estimated emissions which reflect the real emission profile and management activities of a geothermal power station. A current assessment of the concise and detailed emission profile of such productive systems is essential to ensure sustainable development of these technologies, especially considering the social aspects involved in the projects under development (Dumas and Angelino, 2016). Also, the aim of this study is to propose a protocol for the evaluation of the environmental impact related to the atmospheric emissions of geothermal exploitation that could be useful to build up a common framework for all the actors involved in the development of this energy source.

2.1.2 Materials and methods

In this work, the LCA approach is implemented according to the ISO 14040 (International Standards Organization, 2010) and ISO 14044 (The International Standards Organisation, 2006) standards, next to the more completely elaborated ILCD Handbook Guidelines (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). The methodology is composed of four phases:

- Definition of the goal and scope of the system: it includes the description of the model system and the purpose of the study, along with all the methodological key elements (functional unit, system boundaries, cut-off rules, data quality, etc) that characterise the analysis and a detailed explanation of all the assumptions made to guarantee clarity, transparency and reliability of the results;
- Life Cycle Inventory, LCI: it lists and quantifies all the input and output flows of energy and materials and releases to the environment;
- Life Cycle Impact Assessment, LCIA: impacts generated by the system are assessed through the application of an environmental impact calculation method that translate emissions, resources and energy use into a limited number of indicators;
- Life Cycle Interpretation: correlation among inventory results and impact analyses allows identification of the relevant technical information and critical points that can be employed to outline useful conclusions and recommendations to maximise the global energetic-environmental efficiency of the LCA case system in accordance with scopes and goals of the assessment.

2.1.2.1 Goal and scope definition

The objective of this study is the assessment, in a life cycle perspective, of the environmental impacts related to the exploitation of deep geothermal energy for electricity production in Italy. More specifically, the study is focused on the geothermal area located in Tuscany Region where the majority of the 916 MW Italian geo-thermoelectric plants are installed. Furthermore, the study considers all the currently operative power plants to outline sub-regional eco-profiles connected with the geo-thermoelectric activity. The findings of such an overarching study are intended to be used as a basic information for a sustainable development and exploitation of the Tuscan geothermal areas, while addressing the environmental issues concerning such kind of energy source.

2.1.2.1.1 System boundaries and functional unit

The life cycle of a geothermal power plant includes (i) the activity for the identification of the geothermal field, (ii) the drilling operations to obtain the production and injection wells, (iii) the building and commissioning of the power station and its connection to the wells through pipelines for the transportation of the geothermal fluid extracted as well as the fluid that needs to be reinjected after the utilisation and (iv) the decommissioning of all the infrastructures (power plant and wells). The outcomes of a previous study (Buonocore et al., 2015), that was focused on the whole life cycle of a power station located in Tuscany, showed that the major environmental impacts are determined by the operational phase for Flash technology, unlike other Enhanced Geothermal System (EGS) and Organic Rankine Cycle (ORC) plants installed in other countries (for example in EU Germany, Belgium, Netherlands). The analysis performed in this work implements a gate-to-gate approach focused on the atmospheric emissions generated by the exploitation of fluids and produced during the operational phase of the geo-thermoelectric industry. In Figure 1, a sketch of the system boundaries defined in this study is reported.

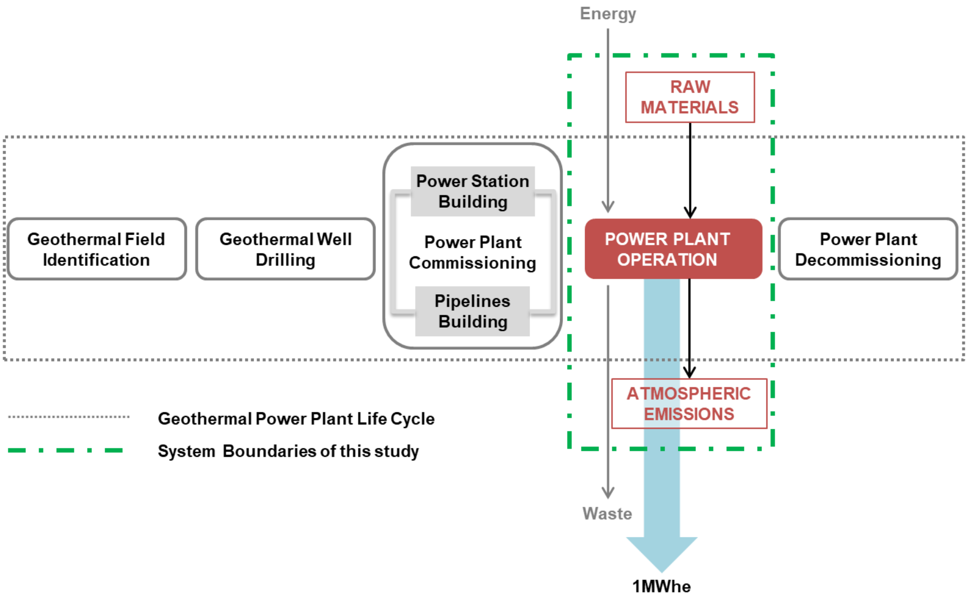

Figure 1 Geothermal life cycle and system boundaries of this study

The atmospheric emissions generated by geothermal exploitation using flash power plants can be divided into two main fractions, one gaseous and the other dissolved into the geothermal fluid. The gaseous fraction is also identified as non-condensable gases (NCGs) as they cannot be condensed at the same conditions of the geo-fluid. These gases need to be extracted in order to avoid accumulation of NCGs within the condenser and progressive loss of vacuum conditions, as this is the fundamental state to keep the power plant in operation. Gases commonly extracted from geothermal fluids are carbon dioxide (CO_2), hydrogen sulphide (H_2S), methane (CH_4), ammonia (NH_3), hydrogen (H_2), nitrogen (N_2), argon (Ar) and radon (Rn) and gaseous mercury (Hg) (Bertani e Thain, 2002; Fridriksson et al., 2016). The quantity of these gases is extremely dependent on the field exploited and it is possible to observe very large variations among the World's geothermal reservoir. Furthermore, in the geo-fluid phase other chemical species are found such as arsenic (As), antimony (Sb), boric acid (H_3BO_3), lead (Pb), selenium (Se), chromium (Cr), cadmium (Cd), nickel (Ni), copper (Cu), manganese (Mn) and vanadium (V).

The impact connected to the maintenance operations of the power plant, such as the periodic substitution of the turbine or the change of the lubrication oil, were not considered. In the same way, processes concerning the maintenance of the wells, like the activities intended to recover the flow capacity lost over the year (stimulation), were not considered. The assumption is that all the burdens connected with these activities are virtually negligible compared to the environmental impacts determined by the direct emissions of a typical condensing flash power plant, like the ones operating in Tuscany. As the main product of the considered geo-thermoelectric power plants is not heat but electricity, we choose as the functional unit 1 Megawatt/hour (MWhe) generated in the various plants by conversion of the geothermal energy.

2.1.2.1.2 Data quality and collection

Data concerning the atmospheric emissions generated by all the 34 power plants currently operating in Tuscany have been collected from the geothermal areas monitoring annual reports published by ARPAT. The timeframe considered in this study ranges from the beginning of the sampling campaign started by ARPAT in 2002 up to 2016, referring to the last report publicly available while this study was in preparation (ARPAT Tuscany Regional Agency for Environmental Protection ("in Italian"), 2018). Measurement data are based on sampling of the emission materials from the geothermal power plant's cooling towers in defined period of the year. The use of standardised methods for the analytical determination of substances (IGG-ICCOM, 2017; UNI EN, 2003; US EPA, 2017) ensure for the accuracy of the data. Moreover, in its reports, ARPAT provides emissions information concerning all the sampling points. This additional characterisation allowed us to process and interpret data with higher accuracy, in respect to the knowledge of the aggregated data. The information was then carefully analysed to identify typical patterns and to elaborate a procedure ensuring the lowest error margin possible during the data rationalisation process.

2.1.2.1.3 Geography and configuration of power plants system

Nowadays, there are 34 power plants in Tuscany in an area of about 330 Km^2 displaced among the Provinces of Grosseto, Pisa and Siena. In 2018 the geothermal electricity production was about 6500 GWh. The geothermal geographic zones in Tuscany are usually dispersed in four areas as shown in Fig.2: Larderello (South-East of Pisa Province), Lago (South of Pisa Province), Radicondoli (West of Siena Province) and the area of Mount Amiata in the southern Tuscany (East of Grosseto and South-West of Siena). The analysis of data has shown that the area of Mount Amiata presents two different geothermal fields with distinctive profiles in terms of atmospheric emissions. In fact, they are located on two sides of the mountain generating very different emission trends. Due to this, a further division of this subarea must be considered, namely Bagnore and Piancastagnaio, one on the Grosseto side and the other one on the Siena side, respectively.

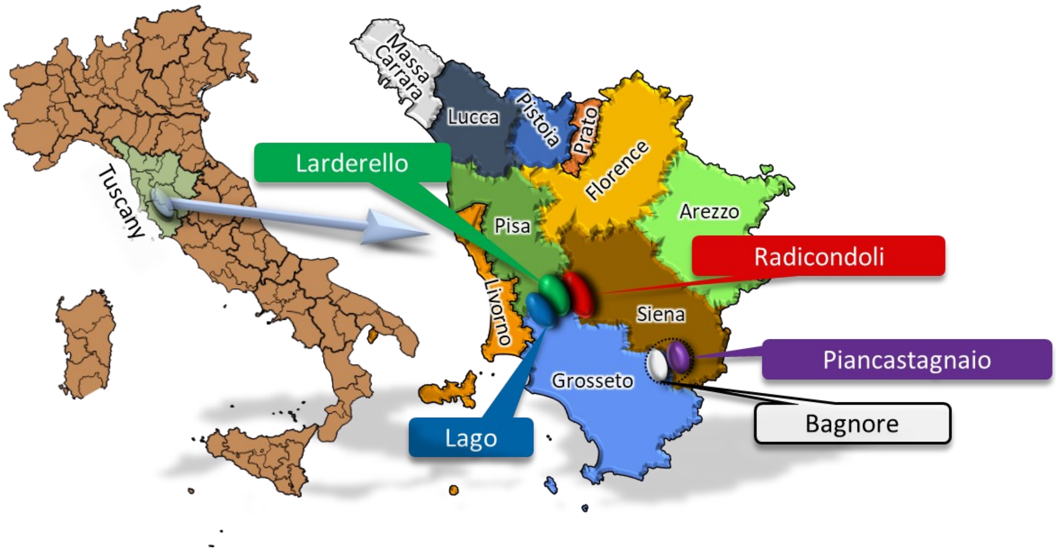

Figure 2 Map of the Italian Regions and geothermal identified subareas in Tuscany

Most of the power plants were built by ENEL and all of them are currently operated by ENEL GP (ENEL GreenPower) which developed a smart modular system to achieve the highest technical reliability. In fact, every power plant is composed by one or more standardised productive unit (of 20, 40 or 60 MWe each) which shares large part of the system component's (compressor, condenser, turbine, etc.). This approach allows the operator to use the same components for several reservoirs with different characteristics. The result is the reduction of the operating cost since the plant unavailability can be considerably reduced (DiPippo, 2015; Parri et al., 2013). From the methodological point of view, this technological configuration allowed our approach to reduce the variability of data among the geothermal areas considered, thus obtaining a more accurate analysis.

In this framework, usually one production well can serve different power stations, thanks to a very well-developed "steam network". This allows the operator to direct the flow to the power station which presents higher efficiency or redirect the steam to the active power plants during maintenance operations of some others. All the reservoirs exploited are recharged by using brine reinjection wells to maintain the renewability of the resource over the years; this is also necessary for maintaining the pressure of the reservoir within certain values to avoid dangerous geological side effects connected with the geothermal sites' exploitation (seismic activity, subsidence). The success of this managing strategy is confirmed by the fact that the area of Larderello has been exploited for electric production since 1905, and more intensively since '80s, without any significant loss (Cappetti et al., 1995; Minissale, 1991; Kaya et al, 2011). In recent years, power generation is even increased thanks to the implementation of new technological solutions allowing the exploitation of geothermal fluids that were impossible to use with previous systems because of their corrosive nature (Parri et al., 2013).

All the power plants present the same configuration if the capacity is the same. The power plant's working structure is mainly divided between the Non-Condensable Gases line (NCGs) and the fluids line, the samplings carried out by ARPAT were performed on both the lines. Figure 3 shows the basic scheme of the ENEL power plants and some of the sampling points identified by ARPAT corresponding to the data used in this work.

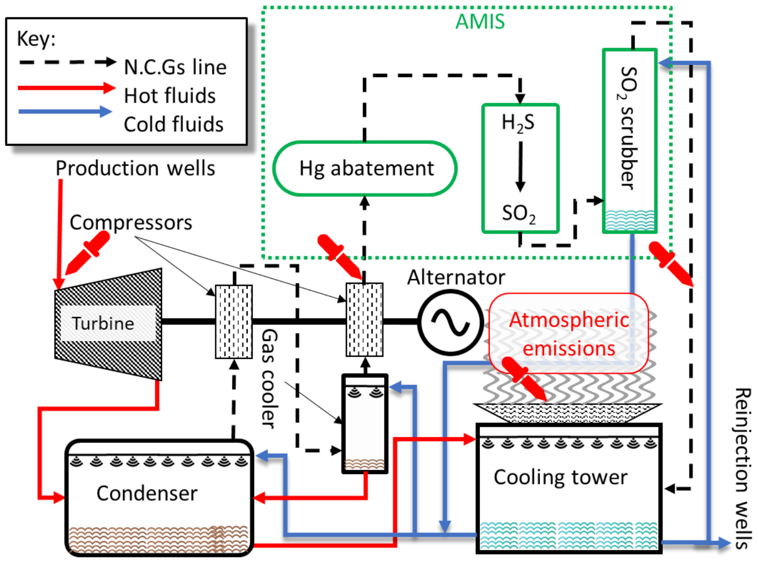

Figure 3 Basic scheme of the geothermal power plant configuration implemented by ENEL. This configuration is employed in 20 MW and 60 MW productive units in operation nowadays. The red pipettes show the most important sampling points identified by ARPAT. As the recovery of heat is not an issue of this paper, the scheme has been simplified accordingly.

The fluids coming from the production wells are directed to the turbine where they expand generating power. After this process the fluid is condensed in a direct contact condenser. In this component the already cooled geothermal fluid is used to cool down the fluid overflowing from the turbine. Then, the condensate is pumped at high pressure to the cooling tower where it is sprayed in counter flow in respect to the air flow. The cooled fluid collected here is then employed in the condenser to cool the fluid overflowing from the turbine. The NCGs must be separated from the fluid to not compromise the process as they can accumulate in the condenser obstructing the cycle. Therefore, NCGs are extracted from the condenser by using compressors directly connected to the turbine and alternator axles: gases extracted in this way are sent to the AMIS (i.e., the abatement system for mercury and hydrogen sulphide) before dispersing them into the atmosphere through the cooling towers. The AMIS is composed by three main components: an absorber made of Selenium or activated Carbon, to remove the gaseous Hg, a catalytic reactor to oxidise the H_2S to SO_2, and a scrubber where the SO_2 produced by the redox reaction is washed from the gas by using the fluids collected in the cooling tower (Baldacci et al, 2005). Since the geothermal fluid naturally contains NH_3, the basic behaviour allows an efficient washing and neutralisation of the SO_2. The treated gas is then sent to the cooling tower where it is dispersed into the atmosphere together with the drift (small drops of geothermal water).

The direct emissions from these geo-thermoelectric plants to the atmosphere take place at the cooling tower and are differentiated into two distinct sources: the NCGs line and the drift. The atmospheric emissions connected with the geo-thermoelectric activity are then directly dependent on the chemical composition of the geo-fluid of the specific site, and thus depends on the geological characteristics of the geothermal field. This is the reason why the emissions originating from different power plants - although located very close in a sub-regional area - can be very different from each other.

2.1.3 Life cycle inventory analysis

This study is focused on the potential environmental impact associated with the emission of NGCs that are found in greater concentration in the geothermal fluid (CO_2, CH_4, NH_3, H_2S) as well as gaseous Hg. In addition, also potential impacts associated to pollutants dissolved in the drift are investigated. This fraction is characterised by higher concentration of NH_3 and its salts, Hg, As, Sb, H_3BO_3, and other metals in traces (Pb, Se, Cr, Cd, Ni, Cu, Mn, V). All data regarding these chemical species were normalised with respect to the functional unit using the value of global electric production.

The need to process the original data reported by ARPAT arises from the fact that emissions detected over the years show an appreciable level of variability in their analytical determination (i.e., remarkable differences for some substances can be found in the various sampling campaigns). These differences are probably caused by technical difficulties related to some sampling procedures, such as the determination of Hg, due to the very low concentration involved and to the complex matrix present at the sampling point. Another source that determines the great variability observed could be linked to the technical characteristics of the different power stations. In fact, for different geochemical situations, the performances and characteristic emissions of the power plants appear very differentiated and largely affected by the geothermal field and, definitively, by their geographical positioning. For all these reasons, the intent of this work is to analyse the emissions of the geothermal power plants by identifying areas with common characteristics from a geographical point of view. Table 1 reports all the parameters collected and used to accomplish the analysis.

Table 1 List and description of all the parameters used to model the atmospheric emission scenarios of the geothermal power plants.

PARAMETER	SUBSTANCE	DEFINITION
Mass Flow	H_2S g/h	Power Plant Emission with AMIS
Mass Flow	H_2S g/h	Power Plant Emission without AMIS
Mass Flow	CO_2 g/h	Power Plant Emission
Mass Flow	SO_2 g/h	Power Plant Emission
Mass Flow	NH_3 g/h	Power Plant Emission with Abatement System
Mass Flow	NH_3 g/h	Power Plant Emission without Abatement System
Mass Flow	As g/h	Power Plant Emission
Mass Flow	Sb g/h	Power Plant Emission
Mass Flow	Hg g/h	Power Plant Emission with AMIS
Mass Flow	Hg g/h	Power Plant Emission without AMIS
Mass Flow	CH_4 g/h	Power Plant Emission
Mass Flow	CO g/h	Power Plant Emission
Central Parameter	MWe	Load during the sampling
Central Parameter	t/h	Supply Fluid Mass Flow during the sampling
Central Parameter	hour	Yearly Power Plant Out of Service
Central Parameter	hour	Yearly AMIS Out of Service
Electric production	MWh/y	Yearly electric production

The knowledge of all the information reported in Table 1 for each operating power plant allowed to draw a complete and detailed picture concerning the actual situation regarding the atmospheric emissions and the typical working parameters for each power plant. As mentioned above, the collection of data presented some problems regarding the expected uniformity over time. To overcome this problem, it was decided to create a typical scenario that might represent the most common emissive profile based on the consistent amount of data gathered.

This profile has been generated for each power station, then a geothermal field clustering criterion was selected (see related Data in Brief article).

This data processing allows to minimise the irregularities observed. Moreover, the impact analysis implemented in this way turns out to be not limited to a definite sampling campaign, as presented in previous studies (Bravi and Basosi, 2014; Buonocore et al., 2015), but it is representative of a typical outline accounting for all the variables involved in the geothermal energy exploitation. As for some power stations there is a lack of observed data, the scenarios are incorporated by subarea because data analysis shows good affinity among productive units in the same territory. Therefore, this process is suitable and reliable to use all the collected information. In addition, since there are several power stations installed on a relatively limited surface, it is essential to consider the whole area to obtain a correct evaluation and a good representation of the emissions profile.

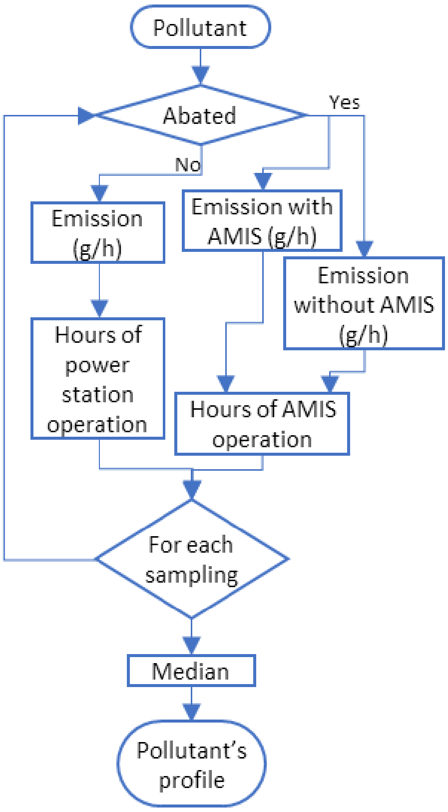

Figure 4 Logical steps followed to obtain the emission profile for each pollutant.

The profile obtained for each plant is expressed as mass flow emission for each substance, multiplied by the yearly hours of operation. For pollutants processed by the abatement system (H_2S, Hg and NH_3 in some cases) the emission value is obtained considering the number of hours in a year in which the system is out of work. Thus, the final value, expressed in yearly mass flow (g/year), is composed by two portions: one comes from the determinations with the AMIS installed, the other is composed by the determinations without the AMIS installed, each weighted by the correspondent amount of operation. The logical steps of this procedure are sketched in Figure 4. To average the values among the various samplings the median value is used in place of the average, due to the non-normal distribution of the values (Ferrara et al., 2019).

2.1.3.1 Scenario modelling

According to the clustering criterion selected to identify geothermal fields, several scenarios describing each geothermal area were created. Such sub-regional environmental scenarios are intended to give an accurate description of the actual geothermal exploitation activity in

Tuscany, by gathering information regarding both the geochemical profile of the field and the operating patterns of the power plants.

All the emissions information was collected year-by-year for each power plant and for each pollutant: those abated are treated separately in order to generate two different scenarios, one including the abatement due to the AMIS (actual scenario) and another which describes the emission like if no abatement system were in operation (W/O AMIS scenario). For each pollutant, the median value is calculated, excluding analytical determinations affected by human errors, as stated by ARPAT. This also allows to better fit the general reduction of emissions observed for some pollutants over the historical series obtained, thanks to technological improvements (Parri et al., 2013). Data concerning the amount of electricity produced every year were collected from the Market Report provided by EGEC (EGEC Geothermal, 2018). Also, in this case the median value was calculated. At this point the two scenarios were built: for the W/O AMIS scenario the emission (g/h) obtained from the previous step is multiplied by the on-order hours of the specific power station, obtaining a yearly emission value (g/y). Then this value is divided by the yearly electricity production (MWh/y), obtaining the emission value weighted by the typical electric production expressed as g/MWh for each power station. In case of the actual scenario, the number of the working hours of the abatement system is required, and it is collected from the ARPAT reports as well. The actual scenario is modelled as the scenario corresponding to the real emissions of the geothermal power plant analysed. In this case the abatement ratio caused by the AMIS is included. The resulting affected pollutants are Hg and H_2S, and in the case of Bagnore 3 and Bagnore 4¸ together with the AMIS, also the abatement due to the NH_3 treatment system is considered (Bonciani et al., 2013; Fedeli et al., 2016). The final emission value for these pollutants is then composed by two portions: one corresponding to the emission of the non-abated pollutant, multiplied by the number of hours in which the AMIS is out-of-order, while the other portion is composed by the emission value detected with the AMIS in function multiplied by the remaining hours. Finally, the emission is expressed as g/y and, following the same procedure explained above, the final value is expressed as g/MWh for each power station.

Each power station scenario is averaged accordingly to geographic and field distribution (see related Data in Brief article) in order to obtain the actual scenario and the scenario W/O AMIS for the five geothermal areas identified. Additionally, the global average scenario (average actual scenario) is computed to obtain the representation of the whole geothermal area.

Another scenario including the raw materials required during the operational phase of a geo-thermoelectric power plant has been implemented employing data published for the year 2016 (Enel Green Power, 2017). Such a scenario is useful to better judge the benefits connected with technological innovations that allow to use less chemicals to exploit the geothermal fluids. In fact, the quantity of substances employed for fluid processing clearly decreased over the years. Moreover, it is noteworthy to specify that the operator cannot employ substances that are not naturally present into the fluid, according to the regional law.

In order to compare the sub-regional emissions profiles of geo-thermoelectric activity in Tuscany, a further scenario has been built using data concerning emissions generated by the electric production from natural gas. This last process is modelled starting from the dataset present in the Ecoinvent 3.4 database (Wernet et al., 2016), referred to a conventional power plant in operation in Italy (Treyer and Paul Scherrer Institute). Such a process has been conveniently customised to match the system boundaries defined for this study. Thus, the modified dataset is composed by the energy requirement for the extraction phase, the impact generated by the gas purification processes, the energy requirement, the gas leakage along the transportation phase and the atmospheric emissions due to the combustion process in a conventional natural gas power plant.

2.1.4 Life cycle impact assessment methods

In this study the ILCD 2011 Midpoint+ normalised by EU27 2010, equal weighting, method v1.0.9, composed by sixteen impact categories, is applied to perform the analysis. As the purpose of this study is to provide eco-profiles connected with the geo-thermoelectric sector in several sub-regional areas, a midpoint (problem-oriented) approach was selected to characterise the environmental footprint on a large number of impact categories while maintaining accurate results.

Calculations were performed with the open-source software OpenLCA version 1.7 LCIA package v2.0.3 (developed by Greendelta).

The choice of the ILCD 2011 Midpoint+ method has been preferred because it allows to obtain single scores compared to other LCIA methods available in the OpenLCA software package.

Furthermore, the ILCD 2011 Midpoint+ method includes also the characterisation of the particular matter formation potential connected to NH_3 emission. Finally, as the method used is developed by the Joint Research Centre of the European Commission, its application in this study looks even more justified.

Secondary data are taken from database Ecoinvent v3.4, eventually customised when necessary. Data uncertainty analysis is performed using the Monte Carlo tool included in the OpenLCA software.

2.1.5 Results and discussion

2.1.5.1 Atmospheric emissions

Table 2 reports the emissions expressed as g/MWh of electricity produced, the data presented are obtained following the process illustrated in Figure 4 and the profiles obtained for each power station are then unified by area.

The emissions without the AMIS installed (W/O AMIS) is composed by the values detected before the AMIS was installed and, after the AMIS became operative, by the values detected at the gas extractor, where the sampling points identified by the ARPAT were located. We have included this scenario, even if it is a theoretical one and it is not representative of any actual emission of the geothermal plant, just to have an estimation, in terms of potential environmental impact, of the differences between the geothermal areas without and with technological improvements like the introduction of the AMIS system.

The actual scenario, instead, is the emission profile closer to the real situation of a geothermal area. Included in this scenario is the abatement obtained by using the AMIS and in the case of Bagnore, the ammonia abatement system is considered. Human errors in sampling activity, as registered by ARPAT, have been neglected.

2.1.5.2 Impact Assessment

The emissions data obtained after the previously described processing are employed to compute the potential environmental impact associated to each scenario and each area. Results are shown in Table 3. The W/O AMIS scenario results show the differences among the areas considered but does not represent an environmental profile, rather it gives a description of the different geochemical characteristics of the several geothermal fields. Among all, it is evident the situation of the Piancastagnaio field: the much higher emission of Hg considerably influences the human toxicity and freshwater toxicity impact categories (together with antimony for the last category). The Bagnore field, even if quite geographically close to Piancastagnaio, shows less Hg but larger NH_3 emissions, in some cases also 10 times higher in respect to other fields. The release into the atmosphere of this compound has an impact on acidification, terrestrial eutrophication and particulate matter formation categories. All the remaining areas show more aligned results, in general lower compared to Bagnore and Piancastagnaio.

Table 2 Emission values which outcome from the elaborated scenarios, expressed as g/h for each pollutant considered. The scenario without AMIS (W/O AMIS) is explanatory of the geochemical differences between the areas, it does not coincide to the emission detected in the area. The actual scenario (grey) represents the real emission currently present in each geothermal area.

Geothermal Area - Scenario	**H_2S (g/MWh)**	**CO_2 (g/MWh)**	**SO_2 (g/MWh)**	**NH_3 (g/MWh)**	**As (g/MWh)**	**Sb (g/MWh)**	**Hg (g/MWh)**	**CH_4 (g/MWh)**	**CO (g/MWh)**
Bagnore - W/O AMIS	3.62E+03	7.17E+05		1.09E+04	4.68E-02	4.62E-02	1.02E+00	1.96E+04	1.09E+02
Bagnore - actual scenario	9.24E+02	7.17E+05	1.17E+00	2.31E+03	4.66E-02	4.62E-02	2.03E-01	1.96E+04	1.09E+02
Lago - W/O AMIS	4.24E+03	2.59E+05		6.05E+02	5.98E-02	2.28E-02	4.14E-01	1.88E+03	4.32E+01
Lago - actual scenario	1.52E+03	2.59E+05	1.10E+00	6.05E+02	5.98E-02	2.28E-02	3.45E-01	1.88E+03	4.32E+01
Larderello - W/O AMIS	6.11E+03	3.43E+05		1.47E+03	5.30E-02	3.32E-02	6.97E-01	1.36E+03	1.97E+01
Larderello - actual scenario	1.62E+03	3.43E+05	7.73E-01	1.47E+03	5.30E-02	3.32E-02	4.87E-01	1.36E+03	1.97E+01
Piancastagnaio - W/O AMIS	1.02E+04	5.65E+05		1.81E+03	1.90E-02	4.58E-02	1.98E+00	7.81E+03	5.55E+01
Piancastagnaio - actual scenario	1.38E+03	5.65E+05	3.93E+00	1.81E+03	1.90E-02	4.58E-02	4.91E-01	7.81E+03	5.55E+01
Radicondoli - W/O AMIS	6.50E+03	5.32E+05		5.65E+02	2.14E-02	5.74E-02	5.94E-01	4.95E+03	2.11E+01
Radicondoli - actual scenario	1.26E+03	5.32E+05	2.99E+00	5.65E+02	2.14E-02	5.74E-02	3.32E-01	4.95E+03	2.11E+01

Table 3 Values of potential environmental impacts generated by the different geothermal areas for each scenario calculated with the ILCD Midpoint+ 2011 method. The grey rows represent the impact attributed to the actual scenario.

Impact category	Acidification	Climate change	Freshwater ecotoxicity	Human toxicity, cancer effects	Human toxicity, non-cancer effects	Particulate matter	Photochemical ozone formation	Terrestrial eutrophication
Bagnore - Scenario W/O AMIS	3.29E+01	1.21E+03	1.33E+01	7.38E-06	8.73E-04	7.27E-01	1.98E-01	1.47E+02
Bagnore - Actual scenario	6.98E+00	1.21E+03	4.03E+00	1.47E-06	1.73E-04	1.54E-01	1.98E-01	3.12E+01
Lago - Scenario W/O AMIS	1.83E+00	3.06E+02	6.05E+00	2.97E-06	3.52E-04	4.04E-02	1.90E-02	8.17E+00
Lago - Actual scenario	1.83E+00	3.06E+02	5.19E+00	2.47E-06	2.92E-04	4.04E-02	1.90E-02	8.17E+00
Larderello - Scenario W/O AMIS	4.44E+00	3.77E+02	9.34E+00	4.99E-06	5.91E-04	9.81E-02	1.37E-02	1.98E+01
Larderello - Actual scenario	4.44E+00	3.77E+02	6.88E+00	3.55E-06	4.20E-04	9.81E-02	1.37E-02	1.98E+01
Piancastagnaio - Scenario W/O AMIS	3.78E+00	7.65E+02	3.11E+01	1.43E-05	1.70E-03	8.34E-02	7.89E-02	1.69E+01
Piancastagnaio - Actual scenario	3.78E+00	7.65E+02	9.85E+00	3.54E-06	4.19E-04	8.34E-02	7.89E-02	1.69E+01
Radicondoli - Scenario W/O AMIS	3.81E+00	6.56E+02	7.62E+00	4.26E-06	5.05E-04	8.40E-02	4.99E-02	1.70E+01
Radicondoli - Actual scenario	3.81E+00	6.56E+02	4.42E+00	2.39E-06	2.82E-04	8.40E-02	4.99.E-02	1.70E+01
Unit	molc H^+ eq	kg CO_2 eq	CTUe	CTUh	CTUh	kg PM2.5 eq	kg NMVOC eq	molc N eq

The actual scenario, instead, is intended to be considered the most similar and the one which better reflects the potential environmental impact produced by the geothermal power stations considered.

The presence of the AMIS abatement system has the effect to reduce consistently the amount of Hg and H_2S released to the atmosphere, even though the LCIA method used for the analysis does not include a characterisation factor for H_2S. 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. Indeed, the bad smell produced by this compound is quite effectively reduced by the AMIS, ensuring better wellness. (Baldacci et al., 2005; International Programme on Chemical Safety (IPCS), 2003; Pertot et al., 2013)

Therefore, in this analysis, the AMIS only affects the impact categories related to Hg emission and, only for the Bagnore field, also the categories influenced by NH_3 emission.

The analysis of the impacts generated by the actual scenarios shows comparable values among all the areas thanks to the reduction of Hg, and NH_3 for Bagnore. In detail, the reduction of pollutants, and the consequent change of the indicators' values, in respect to the scenario W/O AMIS is very strong for Piancastagnaio and Bagnore fields. In fact, these territories are those where the Hg emissions are sizable due to the presence of cinnabar mines which heavily influence the chemical composition of the extracted fluids (Barazzuoli et al., 2008; Loppi and Bonini, 2000; Manzo et al., 2013). The profile of this scenario still shows the effects related to NH_3 emission for the Bagnore field: despite the presence of the abatement system devoted to NH_3 reduction, the residual value is still high compared to the other fields.

The impacts on climate change and photochemical ozone formation categories are determined by the gaseous fraction of the fluids, namely the amount of CO_2, CH_4 and CO. Even for these emissions, it is possible to observe differences among the areas: Bagnore shows the highest values followed by Piancastagnaio. For those pollutants there is no abatement system operating, therefore the values in the two scenarios are the same.

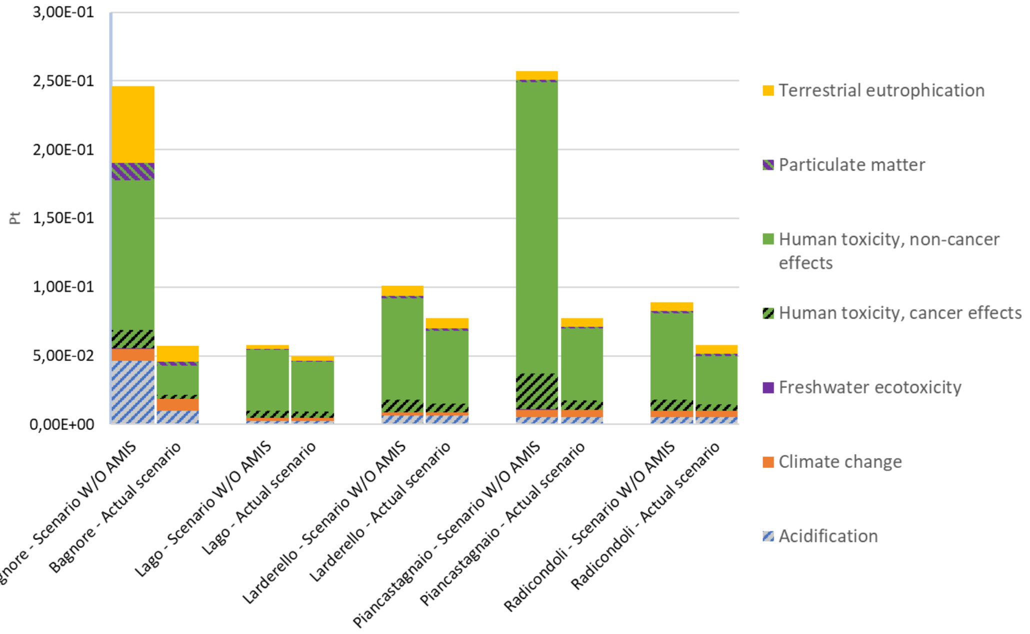

Figure 5 Single score obtained for each geothermal area, the graph is divided into column for each area, the left bar refers to the scenario without the AMIS, while the right bar corresponds to the actual scenario. Cut-off rules were defined for impact categories giving a contribution below 2% in the eco-profiles. The large reduction of potential environmental impacts between the scenarios with and without the AMIS is clearly seen.

Analysing the single score indicator results, it is possible to better visualize the differences among the areas. The graphs in Figure 5 show the effectiveness of AMIS in reducing the potential environmental impacts. In fact, for Bagnore and Piancastagnaio the reduction is 76% and 69%, respectively, while for other areas the advantage is below 50%, namely 14% for Lago, 24% for Larderello and 35% for Radicondoli. Indeed, the single score turns out to be largely composed of categories related to toxicity themes that generally are affected by a quite high uncertainty (Pizzol et al., 2011). Since these categories are based on characterization factors derived from ecotoxicological evaluations, the LCIA methods cannot model peculiar regional situations. This is even more true when the impact is generated by a heavy metal. In fact, as stated in the USETox method documentation (Fantke et al., 2015): *"It should be stressed that the characterization factors are useful for a first-tier assessment. In case a substance appears to dominantly contribute to the impact scores for toxicity, it is recommended to verify the reliability of the chemical-specific input data for this substance and to improve the data whenever possible"*. The case considered here matches this condition, as Hg heavily influences the whole impact profile and furthermore, almost totally accounts for the toxicity categories. Thus, to better understand the environmental burden caused by Hg, further investigation should be performed to properly model diffusion pathway and chemical transformations.

For a more general analysis of the geothermal power plants emissions, an average scenario among the areas was modelled. This is used to compare the geothermal exploitation with the natural gas electric production and to compare the emissions arising from different points of the plant (gas, fluids). Table 4 reports values obtained for each pollutant.

Table 4 Emissions calculated for the average scenario based on date collected from all the geothermal fields.

	Average - actual scenario (g/MWh)	**Average scenario - W/O AMIS (g/MWh)**
H_2S	1.34E+03	6.12E+03
CO_2	4.83E+05	4.83E+05
SO_2	1.99E+00	
NH_3	1.23E+03	3.07E+03
As	4.00E-02	4.00E-02
Sb	4.10E-02	4.11E-02
Hg	3.72E-01	9.42E-01
CH_4	7.10E+03	7.10E+03
CO	4.96E+01	4.96E+01

Since the AMIS can process the extracted gaseous phase of the fluid, the remaining part of pollutants dissolved in the drift is still emitted into the atmosphere through the evaporative tower. In fact, the power station abatement ratio (the efficiency of abatement in respect to the total emission, and not only in respect to the processed phase) among the areas where the Hg presence is higher (Piancastagnaio) and the others is very different (ARPAT, 2011; Barazzuoli et al., 2008; Manzo et al., 2013). Piancastagnaio shows better results because the gaseous Hg concentration is high (see Table 2), thus more substance can be absorbed by the AMIS, but the Hg concentration dissolved in the drift is quite similar for all the areas. The results of the abatement process reflect the amount of Hg emitted with the drift, since the abatement ratio over the gaseous phase is more than 95% in most cases.

Comparing the results obtained by using the emissions detected at the gas extractor after the AMIS treatment (Gas Phase) and the total emissions of the actual scenario, it is evident how the most important source of impact is determined by the drift if the AMIS system is employed, results are reported in Figure 6. The actual scenario is determined by the impact generated by the Hg dissolved in the drift, while the scenario W/O AMIS is composed by the last one in addition to the Hg emitted by the non-abated gas phase. Then, the impact generated by the processed gas is the one showed as Gas Phase.

This result is determined by the fact that no abatement system is employed for the liquid phase, so the contact between the geothermal fluid and the atmosphere in the evaporative tower generates the emission of the pollutants contained in the fluid extracted.

Other comparisons are made by evaluating the impacts generated by the geothermal electric production and those associated with electricity production from natural gas. In this case the emission information showed previously are integrated with raw materials required to treat the geofluids extracted from the wells (Gas Phase + Raw Materials).

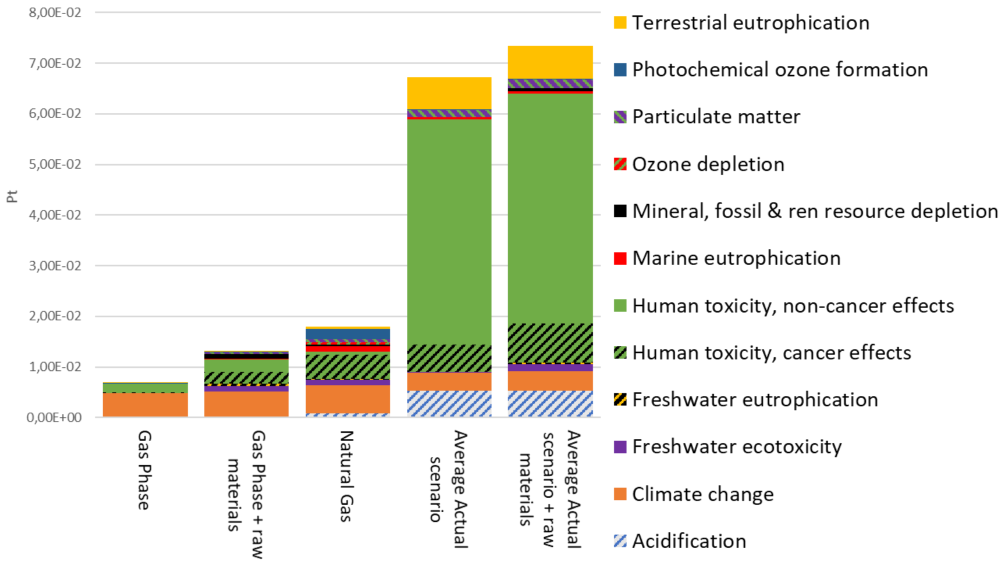

Figure 6 Single score indicators showing the differences between several scenarios of geothermal exploitation and the electric production from natural gas. Cut-off rules were defined for impact categories giving a contribution below 2% in the eco-profiles.

The substances needed are HCl used to avoid colloid formation of $CaSO_4$, and NaOH used as neutralising agent, as geothermal fluids used in some plants can contain high concentration of chlorides which might be very corrosive for the plant's elements. The NaOH is also used to control the silicate scaling formation (Brown, 2013; Parri et al., 2013). In the plants of Bagnore area, also H_2SO_4 is used to control and lower the atmospheric emission of NH_3: the acidification of the fluid maintains the NH_3 as a dissolved salt avoiding its extraction as a gas.

The analysis carried out is based on the assumption that the raw materials employed to treat the geofluids do not generate any (local?) impact, as they are injected into the reservoir. The impact related to the raw materials is considered to be only associated to the upstream production processes involved. In this case the original Ecoinvent process (Althaus et al., 2007a, 2007b; Parada, 2017) is modified to account only for the use phase.

Table 5 Percentage variation attributed to the inclusion of the raw materials use to the average scenario of geothermal exploitation.

Average Actual scenario	**Average Actual scenario + raw materials**	**Variation %**	**IMPACT CATEGORY**
5.24E-03	5.38E-03	2.65	Acidification
3.69E-03	3.81E-03	3.30	Climate change
6.66E-05	1.30E-03	94.89	Freshwater ecotoxicity
0.00E+00	4.26E-04	100.00	Freshwater eutrophication
5.43E-03	7.62E-03	28.73	Human toxicity, cancer effects
4.45E-02	4.54E-02	2.05	Human toxicity, non-cancer effects
4.46E-04	5.20E-04	14.18	Marine eutrophication
0.00E+00	5.69E-04	100.00	Mineral, fossil & ren resource depletion
0.00E+00	2.95E-05	100.00	Ozone depletion
1.44E-03	1.72E-03	16.38	Particulate matter
9.30E-05	1.96E-04	52.43	Photochemical ozone formation
6.29E-03	6.36E-03	1.03	Terrestrial eutrophication
6.72E-02	**7.34E-02**	**8.41**	**Single Score**

Table 5 shows that the greater burden is determined by the actual scenario integrated with the raw materials which increase the potential impact by 8.4% compared to the actual scenario without raw materials. Among the substances employed for fluid processing the greater impact is generated by the production process of the NaOH, while the H_2SO_4 and HCl production processes only account for less than 1% compared to the raw materials impacts. Table 5 also shows the percentage differences due to the inclusion of the raw materials on each impact category. Those presenting the higher variation are Freshwater ecotoxicity, Freshwater eutrophication, Mineral, Fossil & renewable resource depletion, Ozone depletion. Definitively, the significant amount of NaOH used to process the geothermal fluid is responsible for a sizable increase of potential environmental impact. In fact, for all the geothermal areas during the year 2016, a total of 75,388 tons of NaOH have been employed, while only 280 tons of HCl and 3,640 tons of H_2SO_4 (employed to reduce the NH_3 emission in the Bagnore field) were used.

The results presented above suggest that the only way to avoid emissions of pollutants would be the implementation of full reinjection of both fluid and gas phases. In fact, total reinjection only of the fluid would result in potential impact due to the gas (Gas Phase as in Figure 6), if the abatement system for Hg and H_2S are employed. To avoid this residual impact total reinjection should be employed (Bruscoli et al, 2015; Bonalumi et al, 2017).

2.1.5.3 Uncertainty analysis

The large amount of data collected allowed to determine the error associated to each atmospheric emission, together with the information already present in the Ecoinvent database. As the reliability of data is crucial for ensuring consistency of the study, a Monte Carlo analysis was performed in order to determine the variability and the confidence range of the scenario which represents the whole geothermal area.

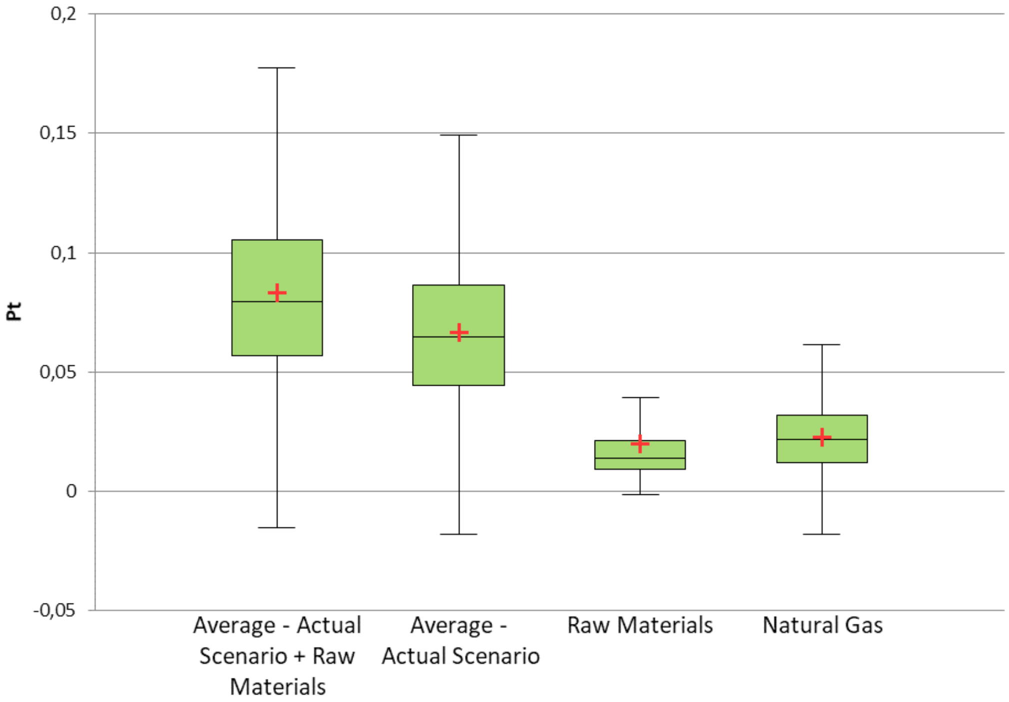

Figure 7 Box plot resulting from the Monte Carlo analysis: result is shown as single score, cross corresponds to the mean value.

The Monte Carlo simulation, performed over the main scenarios considered in this study as illustrated in Figure 7, shows that most of the uncertainty is accounted for by the atmospheric emission of the geothermal power plant, while the raw materials employed and the electric production from natural gas show much less uncertainty.

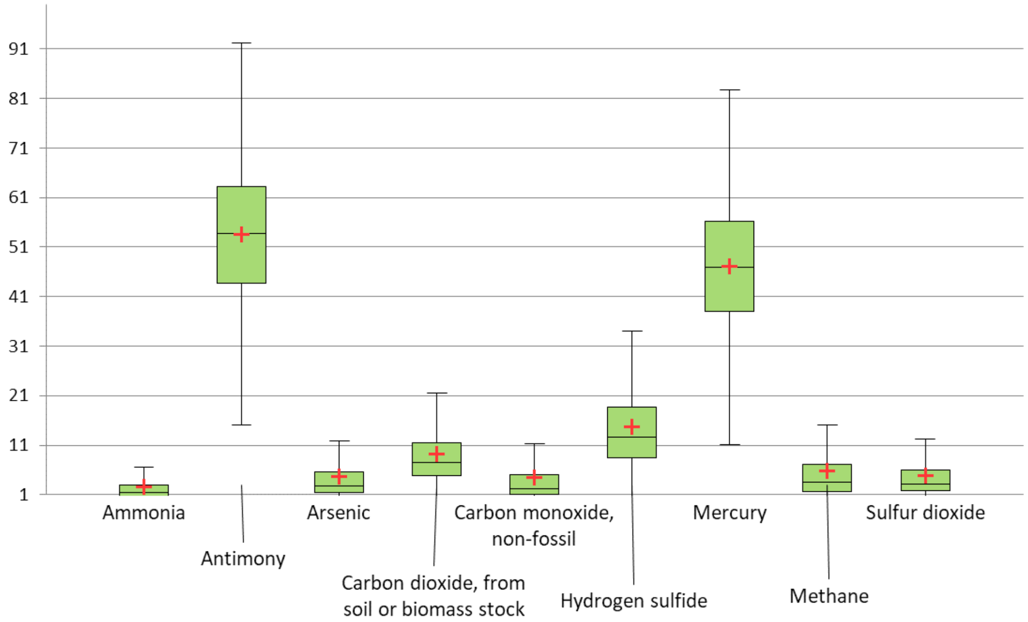

Figure 8 Box plot of the Monte Carlo analysis performed on the inventory data employing the errors calculated taking into account the variability found; results are rescaled to 0-100 range in order to compare them.

Monte Carlo simulations performed on the inventory's data show that the error associated to the measures of Hg and Sb present the largest uncertainty, compared to other pollutants (see Figure 8). As shown in Figure 9, comparing the uncertainty among impact categories expressed through normalized (unitless) values, the human toxicity- non-carcinogenic effects shows the highest uncertainty results, responsible for the large uncertainty of the geothermal scenarios. This is a direct consequence of the characterization factor attributed by the ILCD method to the gaseous emission of Hg into the atmosphere. This compound has the highest score among the pollutant atmospheric emissions with a value of $8.5x10^{-1}$ and it occupies the second position in the list of compounds included in this impact categories. The highest score is attributed to polychlorinated biphenyls with a value of 25.5. For comparison, Sb has a factor of $1.55x10^{-4}$ while the value of As is $1.6x10^{-2}$. Thus, such a high uncertainty associated with Hg is directly connected with the high uncertainty of this impact category. A different output is obtained considering the human toxicity -cancer effects category for which Hg has a characterization factor of $7.2x10^{-2}$, while As is $2.42x10^{-4}$ and Sb has no effect at all. In addition, it should also be considered that the comparison presented in Figure 9 is performed after the normalization step, which assigns to the human toxicity categories the highest ratios: $5.3x10^{-}$

^{4} and 3.6×10^{-5} for non-carcinogenic and carcinogenic effect, respectively. Thus, the margin of error related to the inventory data for Hg is further increased by the characterization and normalization factors and produces a sort of magnification of the overall uncertainty as a result.

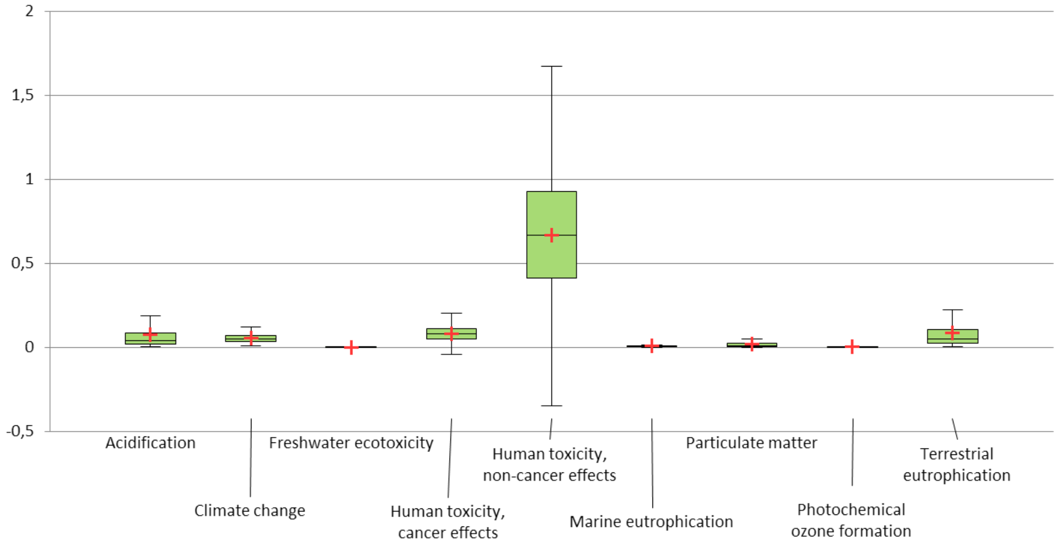

Figure 9 Box plot associated to each impact category; the statistical descriptors are calculated considering the normalised results.

The large error connected with the measure of the effect of this compound could be minimized adequately increasing the frequency of sampling and has to be better understood employing different methodological tools. Indeed, LCA analysis results should be treated with awareness of the LCIA methods limitations. A more accurate ecotoxicological analysis should be performed to connect the emission of this heavy metal to real effects on the environment and residential population’s health.

2.1.6 Conclusions

The objective of this study is the assessment of the environmental impacts associated to the atmospheric emission connected with the exploitation of deep geothermal energy for electricity production in Tuscany (Italy). To this aim, the modelling of several scenarios is proposed in order to draw geothermal fields profiles that are independent on technological differences and time. At the same time the models must be accurate, and representative of the system analysed, reflecting the geographical location and the geochemical characteristics of the reservoir exploited. Comparing our present results with previous studies which were taking into account only a single power plant to represent an entire area is evident that the environmental profile obtained with the procedure proposed in this study is much more representative of the actuality. The needs to consider all the power plants in the impact analysis is required by the fact that not all of them present the same emissions and the same operating parameters (AMIS efficiency, operational times, etc), even if they are exploiting the same field. In conclusion, a crucial point stressed by this paper that should not be neglected in further research and discussion is that the emissions profile of a geothermal area need to be representative of all the productive units working in that space.

The analysis of data shows the effectiveness of the AMIS abatement system in reducing H_2S and gaseous Hg emissions. It is noteworthy that the potential environmental pollution of geothermal areas commonly associated to the highest emission of Hg (Bagnore and Piancastagnaio) has nowadays a comparable profile to those of the "traditional" fields (Larderello, Lago, Radicondoli). Indeed, the great geochemical differences among the geothermal fields can be considered virtually eliminated. Furthermore, in some cases, the results turn out to be even better, as in the field of Bagnore the acidification of the circulating geothermal water reduces the amount of NH_3 stripped into the atmosphere. This evidence allows to confirm that, the managing strategy adopted by the operator ENEL GP through the development of a smart steam network is successful in pursuing a consistent reduction of the environmental pollution associated with flash geothermal power plants.

Nevertheless, the efforts to solve the problem of the presence of NH_3 in the drift are not so successful, as the acidification system employed just allows to limit the NH_3 stripping. Different solutions should be engineered in order to obtain a proper abatement process than just a reduction obtained thanks to the pH variation.

Therefore, NH_3 still represents a problem to deal with, overall but not only in the Bagnore field. In fact, the interaction with H_2S and other elements could generate larger production of particulate matter but, in our opinion, at the moment, there is not enough research devoted to investigating such crucial aspect.

The problem could be overcome in perspective using technologies with a total reinjection of fluids applicable also in hybrid configuration to flash power plants or typical of binary cycle installations. As already mentioned above, another scientific problem arising from the findings of this paper which deserves further attention is about the potential environmental impact caused by Hg: the high uncertainty related both to measurements and to the LCIA method itself does not yet allows to identify the real dimension of the problems related to toxicity impact categories. A step forward could be the elaboration of an optimized LCIA method able to identify and compute the potential environmental impact due to the peculiar atmospheric emissions of flash power plants and, in general, of a variety of geo-thermoelectric installations.

2.1.7 Acknowledgment

Authors acknowledge MIUR Grant - Department of Excellence 2018-2022. NF thanks COSVIG for contributing to his PhD grant.

Authors would like to thank Prof. G.P. Manfrida (University of Firenze) and D. Bonciani (COSVIG) for fruitful discussion and Professor S. A. Loiselle (University of Siena) for his valuable suggestions concerning data processing. Collaboration of ARPAT in collecting data and careful reading and revising of the manuscript by Professor Emeritus Michael Rodgers, Bowling Green State University, is gratefully acknowledged.

Author contributions: R.B. and M.L.P. designed research; N.F. and M.L.P. performed LCA analysis; all authors participated in the interpretation and discussion of results and in writing the paper.

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2.2 The toxicity of heavy metals in LCIA methods: the effects of uncertainties on characterisation factors

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Abstract

Geothermal energy is a strategic source of renewable energy that, like any energy source, generates impacts on the environment and has critical issues related to the geo-specificity of the resource. In particular, the issue of the toxicity of certain compounds and metals released into the environment during geothermal activity is at the centre of heated debates on the political level and social acceptability. The assessment of toxicity in the LCA field is a controversial and often debated issue. The objective of this work is to study the differences in calculation and results related to the choice of the environmental impact characterisation method (UseTox, CML and ReCiPe). The knowledge of the method by the operator is therefore fundamental in the interpretation of the data and the validation of the results. The USETox method is currently the most transparent in terms of how to calculate the characterization factors.

2.2.1 Introduction

Among renewable energy sources, geothermal energy is undoubtedly a special case. Since it is independent of atmospheric conditions, geothermal generation is continuous and can therefore provide a stabilising contribution to the distribution network and is capable of producing more energy than other renewable sources with the same installed power. In Italy, the geothermal industry is present exclusively in Tuscany, in the area between the provinces of Siena, Pisa and Grosseto. Currently, the installed capacity is about 915 MW with an annual geothermal production of about 6000 GWh, corresponding to more than 30% of the regional electricity demand (TERNA, 2017). The exploitation of geothermal resources generates impacts on the environment, some of which are highly site-specific, given the nature of the source, which is closely linked to the area where the geothermal source was formed. The type of technology used to exploit this resource also contributes to determining the typical impacts of geothermal areas. As is well known about the contributions deriving from the various phases of the life cycle of a geothermal system (Bayer et al, 2013; Eberle et al., 2017), atmospheric emissions from the operating phase of plants are strongly influenced by the geochemistry of the fluids used to produce electricity. The compounds most present in geothermal fluids are gases such as carbon dioxide (CO_2), methane (CH4), hydrogen sulphide (H_2S), ammonia (NH3) and mercury (Hg) in smaller quantities. There are also steam-driven solutes such as NH3, boric acid (H3BO3), Hg, arsenic (As) and antimony (Sb).

LCA studies focused on the operational phase of plants based on flash technology (by far the most widely used in the world) have highlighted a potential environmental impact similar to fossil fuel production sources such as gas and coal (Bravi and Basosi, 2014; Parisi and Basosi, 2019; Sullivan et al., 2012, 2010). In addition to greenhouse gas emissions (CO_2 and CH_4) and eutrophicating (NH_3), atmospheric emissions of Hg and As contribute significantly to the toxicity impact categories. The objective of this study is to evaluate and illustrate the large differences that the choice of an LCIA calculation method can generate in the result of the analysis. Following the work of Pizzol et al (Pizzol et al., 2011), the focus is on the human toxicity category and how much it is affected by metal emissions. In fact, due to the great uncertainty attributed to characterization factors, the final result of an LCA analysis can be very different and extremely dependent on the metal itself.

2.2.2 Case studies

In this work, an LCA gate-to-gate analysis of 3 case studies was carried out: 2 relating to electricity production from geothermal sources in Tuscany and the third relating to electricity production from natural gas, all describing the use phase only. The secondary data were taken from the Ecoinvent 3.4 database. The software used is OpenLCA 1.7.

2.2.3 Inventory

The environmental information regarding geothermal energy in Tuscany was taken from the reports published periodically by the regional environmental protection agency, which conducts annual sampling campaigns on operating plants (ARPAT, 2016). The data were collected in the 2001-2016 historical series. The statistical analysis of this information made it possible to process the average emission of the entire geothermal area of Tuscany. The average emission values of pollutants, expressed in grams per hour (g/h) for each plant, were divided by the average electricity production of each plant (EGEC Geothermal, 2018). The emission data were used to elaborate the *"Geothermal"* scenario, which represents the average emission of geothermal production in Tuscany, expressed in g/MWh. Atmospheric emissions were then integrated with the substances used to treat the geothermal fluids directed at the power plants. This information was taken from the environmental statements of the operator Enel GP (EnelGreenPower, 2017). The substances used are mainly sodium hydroxide (NaOH), which is used to lower the chloride content of fluids to make them less aggressive towards the plant's metal parts (turbines, condensers, etc.), and sulphuric acid (H_2SO_4), which is used to acidify condensates in certain fields to reduce NH3 emissions into the atmosphere. In this case, too, an average scenario is obtained for the entire Tuscan *geothermal* scenario, which presents the atmospheric emissions of the *"Geothermal"* scenario added to the flows of the upstream production processes of the products used. The scenario thus obtained has been defined as *"Geothermal + Raw materials"*.

A representative scenario of electricity production from natural gas (*Use Phase - Natural Gas*), focused only on the operational phase of the system, has been modelled from information contained in the Ecoinvent database. The result is therefore represented by the atmospheric emissions obtained during the combustion of natural gas, network losses during transport, and the impacts of the processes related to the extraction and purification of natural gas.

2.2.4 Methods

For the assessment of impacts, several LCIA methods have been chosen, among the most commonly used for LCA studies on geothermal systems, and calculations have been made for human toxicity categories only (Table 1).

In general, all three methods considered are based on the USES-LCA model (van Zelm et al., 2009) which describes the distribution of elements and substances through the various environmental compartments, the exposure of humans to certain concentrations and the effects this exposure has on human health. Although the selected methods are based on the same model, some differences in the algorithms and assumptions used, chemical-physical properties of the substances and the use of different toxicological data to calculate human health effects lead to different and hardly comparable results (EC-JRC, 2011).

Table 1: List of methods used and impact categories selected.

Method	**Version**	**Impact categories**	**Unit of measurement**
USEtox	Midpoint v2.02	Human toxicity, Cancer	CTUh
		Human toxicity, Non-Cancer	
CML-IA	Baseline v3.0	Human toxicity	Kg 1,4-DB eq
ReCiPe2016	Midpoint (H) v1.1	Human Carcinogenic toxicity	Kg 1,4-DB eq

2.2.4.1 USEtox

LCA toxicity assessment is a controversial and often debated issue that the recent UNEP-SETAC initiative has sought to address by developing the USETox model. This model was born after an in-depth study started in 2005 and directly involved developers of eco-toxicological models. The main purpose of this comparison was to identify the main differences between various impact characterisation models, both in terms of results and structure. Following the comparison, the essential elements for the model were defined and then the one that represented the best recommendation and received the widest scientific consensus was defined. The model generated through this process is USEtox, now available in version 2.1. The study was carried out through the analysis of 45 organic substances. The results highlighted deficiencies in the characterization of inorganic substances and heavy metals in particular. In fact, in the many technical documents published on the official website of the USEtox model, it is always stressed that the uncertainty of the characterization factors is very high. Besides, among the characterisation factors available, there is a class of substances for which the characterisation factor is classified as "interim", meaning that not all the minimum requirements required to calculate impacts correctly are met. These are characterisation factors that must be taken into account when performing a process sensitivity analysis, the result of this analysis will be able to tell whether it is necessary to include these flows, and if so, the result of the LCA analysis will have to be evaluated very cautiously due to the high uncertainty associated with these values (Fantke, P. et al., 2015; Rosenbaum, R., 2008). The UNEP-SETAC recommendation has been implemented by the JRC of the European Union which has integrated the standard characterisation factors of the USEtox model (recommended + interim) into the ILCD method. This method has the peculiarity of having been developed based on a calculation matrix that gives the user the possibility to vary the parameters associated to each compound to obtain different characterization factors that better reflect the characteristics of the studied process. Through this matrix, it is, therefore, possible to adapt the method to the case being studied. Both midpoint and endpoint characterization factors are available.

2.2.4.2 CML-IA

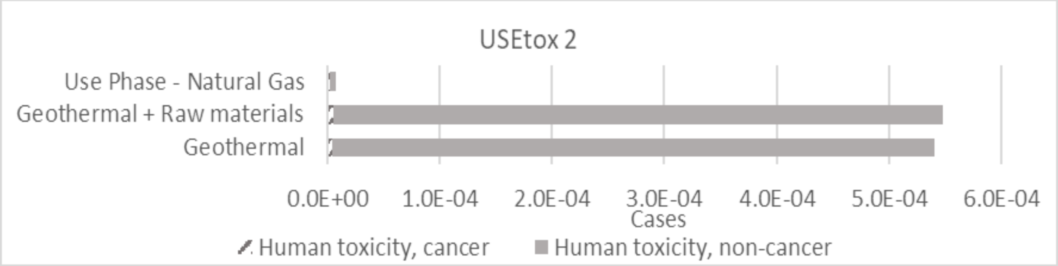
This method was developed by the Institute of Environmental Sciences of the University of Leiden and is among the most widely used in LCA. In contrast to USEtox, the impact categories defined in the baseline version cover a fairly broad spectrum of environmental issues, which is further expanded in the non-baseline version to include impact categories not very common in LCA studies. The characterisation factors come from numerous studies and scientific publications and are updated in parallel with the eco-toxicological research developed by the institute. However, the authors consider the information used and processed to obtain the characterization factors to be less accessible. The approach is midpoint, but normalization and weighing factors are available to obtain single score values (Oers, L. van, 2015).

2.2.4.3 ReCiPe2016

This method was born as harmonization of different methods. The first ReCiPe 2008 version is a combination of the Ecoindicator 99 and CML methods. The 2016 update loses this connotation and marks the development of ReCiPe as an independent method by the Dutch National Institute for Public Health and the Environment (RIVM) and Pré Consultants. It is a method that covers a very broad spectrum of environmental impact categories and, with the 2016 version, moves from a European to a global approach. It has both midpoint and endpoint characterization factors. The calculation of characterisation factors is well documented and can be downloaded from the RIVM website.

2.2.5 Results and discussions

Impacts have been calculated using only human toxicity categories. The results were analysed to identify the flows that contribute most to the final score (Figure 1).



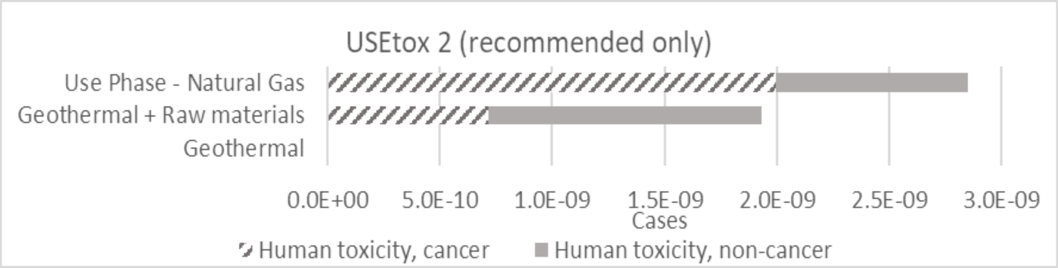


Figure 1: LCIA results with the USEtox method: in the diagram above the "recommended + interim" characterization factors are used, in the diagram below only the "recommended" factors are used.

USEtox is the method that gives the highest score for scenarios related to geothermal power generation, which are almost 2 orders of magnitude higher than the value for the natural gas scenario. The big difference is to be found in the atmospheric emission of Hg, which contributes more than 99% of the total value. The calculation carried out with only the *recommended* characterization factors leads to the opposite result, i.e., it assigns the highest result to the *Use Phase - Natural Gas scenario,* while the *Geothermal* scenario, which includes only atmospheric emissions, has a zero result. This is because metals emitted into the atmosphere by geothermal power plants (As and Hg) are classified as *interim,* therefore they are excluded from the calculation. It should be noted that the USETox developers suggest applying the method by preliminarily including the characterization factors for *recommended + interim* substances so as not to exclude any impact, even if affected by uncertainty, from the analysis. The CML method presents different results (Figure 2, the diagram above). This method does not include or extrude metals (or other substances whose characterisation factor is unreliable) from the calculation, giving a potential impact related to metal emissions lower for the *Geothermal* scenario *than for the Use Phase - Natural Gas*. The last method illustrated in this comparison is the ReCiPe2016 midpoint H (Figure 2, the diagram below) according to which, similarly to that obtained with CML, the *Geothermal + raw materials scenario has the* greatest impact, while the *Geothermal scenario is* comparable to the Use Phase - *Natural Gas scenario*.

For CML and ReCiPe2016, Hg atmospheric emissions have characterization factors comparable to each other and in any case significantly lower than those proposed by USETox (reccomended+interim). This observation highlights the sensitivity of LCA (Human Toxicity category) results in the presence/absence of Hg emissions and the choice of the LCIA method. The choice of LCIA method has recently been addressed in the framework of the EC initiative on the environmental footprint of products and organisations. The conclusions reported by the EC recommended that the results of the toxicity categories should not be used when reporting the results externally, due to the difficulty of using the method and interpreting the results. As a result of these issues found during the PEF pilot phase, the USETox characterisation factors have been revised and updated by integrating the original database with data from REACH. This returns profiles that would seem to be more significant as it does not attribute such a high impact to Hg alone, as in USEtox, potentially leading to a very high error in comparison.

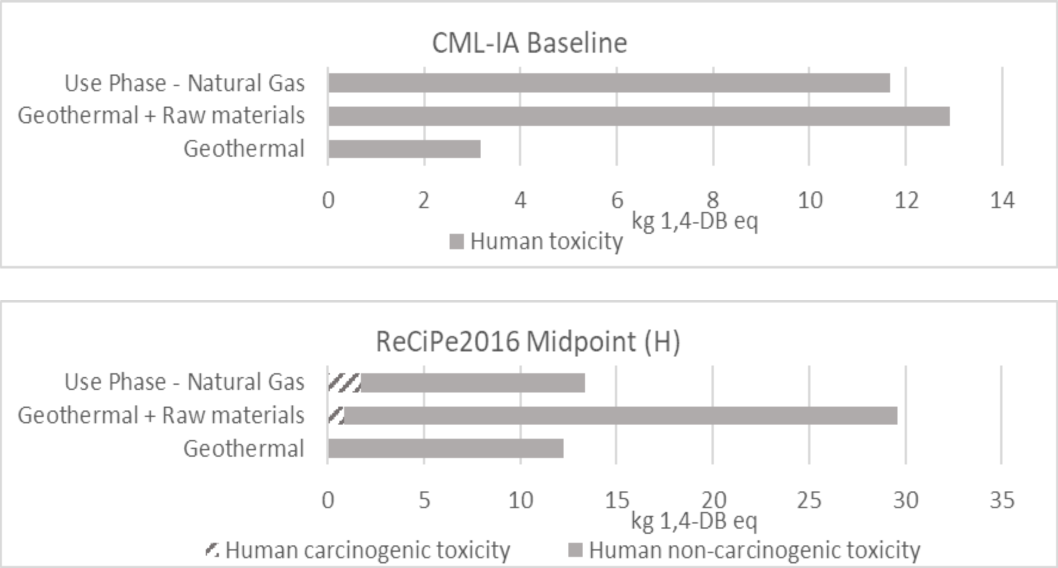


Figure 2: LCIA results obtained with the CML method (top) and ReCiPe2016 (bottom)

2.2.5.1 Characterisation factors

This section compares the characterization factors used by the different methods introduced. The values are shown in Figure 3. The differences between the characterisation factors of the various methods are evident: USEtox and CML are the methods with the greatest difference between metals, with a difference between the values for Cr VI and Hg of around 3 orders of magnitude. Between metals and the organic compound 1.4-DB, however, the difference increases up to 6 and 7 orders of magnitude for CML and USEtox respectively. Even considering metals, the "symmetricity" of the characterization factors can be seen, i.e. mercury represents the highest and lowest value among metals respectively. It is clear, therefore, that even small quantities can generate a very high difference in impact, and above all extremely dependent on the method chosen. For the ReCiPe2016, on the other hand, less marked results are obtained, in the sense that the differences between metals are around 1 order of magnitude and those between metals and organic compounds are around 5 orders of magnitude, thus making the result more comparable.

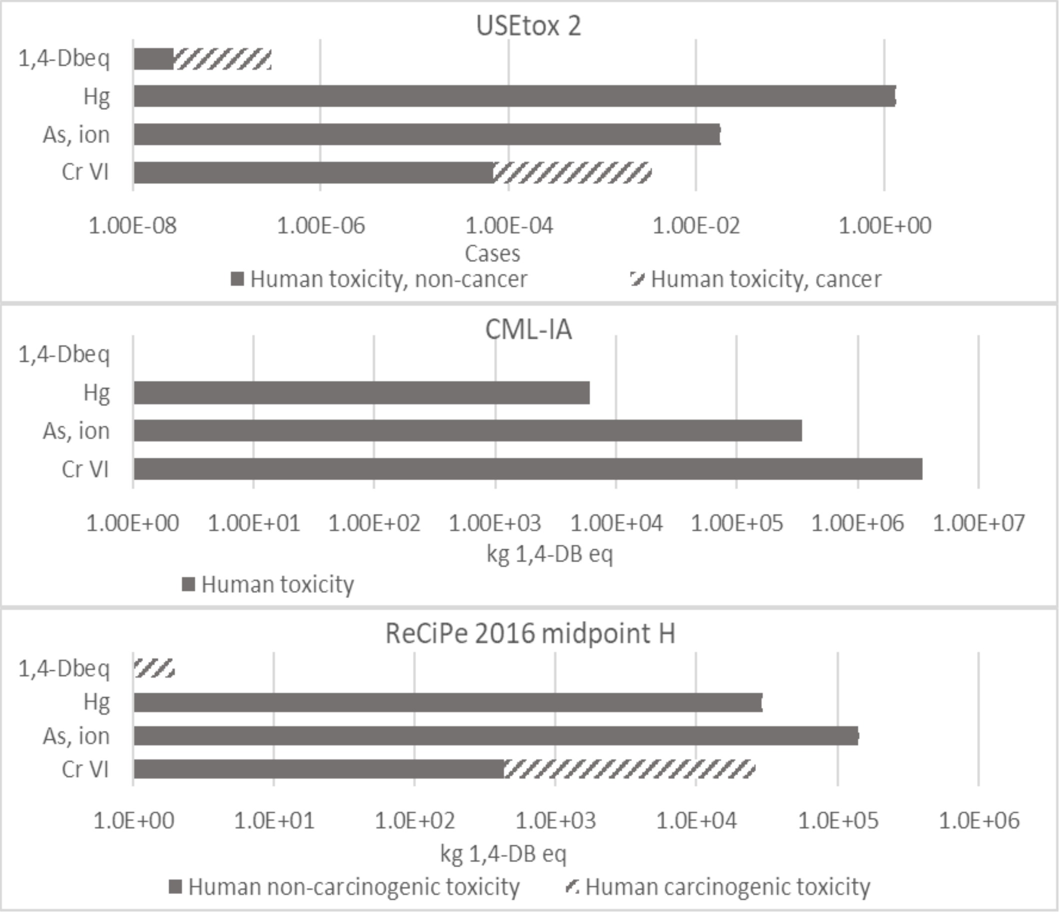


Figure 3: comparison between the characterization factors of 4 substances taken as reference for each LCIA method: Chromium (Cr VI), As, Hg and 1.4 dichloro-benzene (1.4DB). The y-axis is on a logarithmic scale with base 10.

2.2.6 Conclusions

The toxicity impact categories are among the most critical for an LCA study, both in terms of method and interpretation of the result. Also, they are the ones that are most likely to attract public attention. The result should therefore be carefully interpreted and presented as correctly as possible, without giving room for manipulation, it is understood that the toxicity impact values calculated from an LCA are just potential and do not necessarily represent a real risk. In particular, concerning metals, there are legislative emission limits which must be respected and which ensure the protection of the exposed human population. At present, in the absence of guidelines allowing a standardised LCA approach to energy systems, and in particular geothermal systems, the choice of the LCIA method is extremely important, as shown in this paper, because the results that can be obtained can lead to opposed conclusions.

The exclusion of toxicity impact categories from the LCA analysis, as recently proposed by the EC as part of the environmental footprint initiative for products and organisations, could, in our opinion, lead to conclusions that are more comparable but extremely uncertain, especially when referring to geothermal systems where metal emissions could be a determining component. The recent update of the USETox model has not yet been integrated into the software and is certainly an aspect to be verified in the future. In this context, therefore, the role of the LCA analyst becomes fundamental to safeguard the scientific validity of the methodological approach. This cannot be done without having adequate knowledge of the method used. The exposure pathways of the substances evaluated by the method, the supposed effects they generate and the extent of the damage attributed, as well as the limits and uncertainties that a particular method incorporates, must be made transparent by the method developers and part of the scientific background of the operator. It is not the method chosen that gives validity to the result of an analysis, but the accuracy and awareness with which the result obtained is discussed, analysed and contextualised by the operator.

Funding

The research conducted is part of the project No 818242-GEOENVI (https://www.geoenvi.eu/) funded by the European Community within the Horizon 2020 research and innovation programme.

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2.3 Complete data inventory of a geothermal power plant for robust cradle-to-grave Life Cycle Assessment results

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Abstract:

Technologies to produce electric energy from renewable geothermal source are gaining increasing attention due to their ability to provide a stable output suitable for baseload production. Performing life cycle assessment (LCA) of geothermal systems has become essential to evaluate their environmental performance. However, so far no documented nor reliable information has been made available for developing robust LCA studies. This work provides a comprehensive inventory of the Italian Bagnore geothermal power plants system. The inventory is based exclusively on primary data, overarching the whole life cycle stages of the system. Data quality was assessed by means of a pedigree matrix. The calculated LCA results showed, with an overall low level of uncertainty(2-3%), that the commissioning and operational phases accounted for more than 95% of the environmental profile. Direct emissions to atmosphere were shown to be the major environmental impact, particularly those released during the operational phase (84%). The environmental performances comparison with the average Italian electricity mix showed that the balance is always in favours of the geothermal energy production, except for the climate change impact category. The overall outcome confirms the importance, for flash technology employing fluid with high concentration of gas content, to use good quality primary data to obtain robust results.

2.3.1 . Introduction

The European Commission (EC) is promoting the transition of the European Union (EU) into a highly energy efficient and low-carbon economy system [1]. Energy production from renewable energy sources (RES), saving energy and natural resources, as well as reducing carbon dioxide (CO_2) emissions while managing wastes are pivotal actions to enable such a transition [2]. The EC adopted the “2030 climate and energy framework” in 2014, which has been subsequently revised in 2018 to include broader targets and policy objectives on greenhouse gasses (GHG) emission reduction for the period from 2021 to 2030. The targets for RES and energy efficiency are set to at least 40% cuts in greenhouse gas emissions (from 1990 levels), at least 32% share for renewable energy and at least 32.5% improvement in energy efficiency [3]. On November 2018, the EC presented the analytical foundation for the development of an EU Long Term Strategy for climate and energy policy and a political vision for achieving a Net Zero economy by 2050 [4]. In this context, power generation has been identified as one of the sectors with the highest potential to decarbonize. To ensure that the EU targets are met, EU legislation [5] requires that each Member State drafts a 10-year National Energy and Climate Plan (NECP), setting out how to reach its national targets. The Italian NECP [6] largely built on the 2017 Italian Energy Strategy, broadly meets the requirements set by the Regulation. The draft of the plan has been positively judged by EC as it includes an extensive list of 101 policies and measures. These ones would be enough for Italy to meet the above targets, with a particularly important contribution coming from the objective of gradually phasing out coal for electricity generation by 2025. The draft plan qualitatively mentions the interactions with air quality and air emissions policy, specifically in the context of the proposed contribution expressed as 30% share of energy from RES in gross final consumption of energy in 2030. Electric energy production from RES, particularly those not emitting into the atmosphere during the operational phase like solar, wind and hydro, will play a key role in achieving such an ambitious objective. Biomass and geothermal can also play a role in replacing fossils toward a more sustainable development, but they are not exempt from drawbacks concerning CO_2 emissions [7]. As geothermal energy has a big potential of development [8] it is becoming important to explore the state of the art of the technology in terms of a benefit/cost ratio from the environmental point of view. Among RES, geothermal energy is considered a competitive energy source because of its independence from seasonal and climatic conditions [9], ensuring reliable performances peculiar to non-renewable sources. Geothermal power plants can provide a stable production output, unaffected by the external environment, resulting in high capacity factors (ranging from 60% to 90%) and making the technology suitable for baseload production [10]. The technologies for power production from geothermal resource exploitation depend on the quality of the geothermal field, which, in general, increases with its enthalpy, typically spanning from liquid-only to steam-only (i.e., dry steam) reservoirs. Naturally occurring geothermal systems, known as hydro-thermal, are characterized by a resource fluid condition that can be considered as directly available. By contrast, enhanced geothermal systems (EGS) aim to produce hot water at locations where natural aquifers are not present by developing an "engineered reservoir". This technology has received significant attention because it allows the exploitation of geothermal energy virtually anywhere. Hydrothermal (mono, double or triple flash and dry steam) plants account for around 85% of the global geothermal power generation. In 2018 this was an estimated 90 TWh, while the cumulative capacity reached 14 GW [11]. Around 14% of the global electricity production is due to a different technology based on binary cycles [12]. This technology often exploits the total re-injection of non-condensable gases (NCGs) with some environmental advantages despite a significant decrease in efficiency and larger land occupancy [8]. In this context, the concern about the environmental performance of geothermal energy exploitation has been growing in recent years due to the expected increase of power production from geothermal sources [13].

Life Cycle Assessment (LCA) methodology is one of the most reliable and powerful tools to assess the environmental performance of power generation systems, capable of providing results that cover several environmental aspects, thus approaching the system in a more comprehensive and holistic way [14–16].

Even though LCA has been applied for quite a long time now to energy-producing systems, the field of geothermal energy exploitation still lacks primary data. Only a few studies have been aimed at determining the environmental profile of currently operating geo-thermoelectric installations in Italy [17–19] and in Iceland [20,21].

The relative complexity and high dependency on geomorphological factors of the geothermal energy source also contributes to the scarcity of specific information. Reviews performed by several authors [22–24] underlined the inaccuracy due to the lack of primary data. This trend is even more evident in harmonization [25–27], which need to deal with very large variability, making the elaboration of reliable eco-profile very difficult [28,29].

The consequence is that papers which analyse geothermal power plants mostly use secondary data, forcing the authors to rely on general literature data which are often not adequately representative of the technology and of the investigated system [30,31].

Recently, special attention has been placed on the evaluation of environmental performances of EGS [32,33]. However, at present, hydro-thermal systems dominate the current electricity generation in the geothermal sector, and the exploitation of this type of reservoir is predicted to be dominant in the future [11,34]. This picture outlines the importance of assessing the life cycle environmental impacts of conventional geothermal technologies to make sustainable choices in the context of the electric energy production sector. To avoid uncertainties, a reliable and high-quality life cycle inventory of a flash installation is needed. The only current source of data is the one provided in the study by Karlsdottir et al. [35].

The scope of the present work is to provide a high-quality, complete and documented life cycle inventory of a flash power plant, and to perform the LCA of electricity production from geothermal source with a cradle to grave approach, and to evaluate how much uncertainty of data is reflected on the final LCA results. The quality of data was assessed employing a so-called pedigree or uncertainty matrix. The Italian Bagnore power plant was selected as one of the most representative flash-based conversion system power plant. This work has been made possible by the full availability of primary data which, according to our knowledge, is unique in the literature.

The Bagnore power plant system consists of three connected units, namely: Bagnore 3, the binary group of Bagnore 3 and Bagnore 4. To correctly assess the environmental footprint of these plants, it is necessary to consider them as a whole system, namely the Bagnore system. Bagnore power plants integrate two systems for atmospheric emissions abatement, namely the AMIS (i.e. the abatement system for mercury (Hg) and hydrogen sulphide (H_2S)) and the ammonia (NH_3) abatement system. The adoption of state-of-the-art management strategies by the operator, Enel Green Power (EGP), aims at the best trade-off between production performance and environmental compliance [36].

2.3.2 Materials and Methods

2.3.2.1 Power plants description

The production of electricity from geothermal exploitation in Italy is concentrated in the Tuscany region. Currently, all the geothermal power plants have been built and operated by EGP, which manages 37 productive units allowing for a production of about 5.8 TWh/y.

The geothermal area in Tuscany is divided in four districts: Larderello, Lago and Radicondoli (halfway from the province of Siena, Grosseto and Pisa) and in the south Tuscany the area of Mount Amiata (between Grosseto and Siena) [37]. The area of Monte Amiata is composed by two productive geothermal fields, namely Bagnore and Piancastagnaio. The Bagnore field is characterized by the presence of 2 power plants, Bagnore 3 and Bagnore 4, entirely constructed and operated by EGP. Bagnore 3 is a flash plant with 20 MWe of installed power producing 170 GWh/y of electric energy. Additionally, the plant is powered by a 1 MWe Organic Rankine Cycle (ORC) unit, which provides 6.8 GWh/y of additional electric energy. Bagnore 4 is powered by two 20 MWe groups, which can input 367 GWh/y to the electric grid. Thus, the electric production from the Bagnore field is about 544 GWh/y. In addition to electric generation, also heat delivery is achieved exploiting residual heat after turbine expansion. The total heat delivered to the final users is about 32 GWh/y.

The two power plants are connected to each other to enhance the performance of the whole system. Such enhancement is reached in both power production and environmental compatibility of the geothermal power plants [38]. A shared steam network powering the two power plants, allows the optimization of the available steam flow, thus, maximizing the power output. The shared steam network also improves the environmental footprint: in case of maintenance operations to one of the three productive units, it is possible to reroute the overflowing steam towards the operating units, thus avoiding free release into atmosphere. The operator also equipped the power plants with oversized AMIS system, able to treat 150% of the entering fluid for each turbine. Such oversizing allows the system to abate the emissions also during flow rerouting for maintenance operations.

2.3.2.2 LCA methodological approach

2.3.2.2.1 Goal and functional unit

The goal of the present LCA study is to assess the potential environmental impacts that are associated with the production of electricity from the geothermal power plants of Bagnore 3 and Bagnore 4. The functional unit selected is 1 kWh of net electricity produced. This study was conducted according to the requirements of ISO 14040 standard series [39,40] and the ILCD Handbook [41], following an attributional approach. The broader scope of the study was to provide insight and reference values on the environmental performances of an operating flash-based geothermal facility relying on a very detailed LCI. The intended application was to calculate the comprehensive eco-profile of the Bagnore power plants system. Data for building the life cycle inventory was obtained directly from EGP through accurate surveys and questionnaires.

2.3.2.2.2 System boundaries

Figure 1 shows the system boundaries of the LCA study. The system modelling approach is cradle to grave and it included the following phases: commissioning, operation and maintenance (which together constitute the use phase), decommissioning and end of life (EoL). The system boundaries were set up to the point where energy, in the form of electricity and heat, is produced from the plant. The distribution of energy was not considered. The life cycle phases included in the boundaries were modelled using foreground and background processes. The distinction between foreground and background processes consists of the former being explicitly modelled for the investigated system employing data directly measured in situ and therefore highly representative of the technological and geographical[1] situation of the studied system (primary data). Background processes are all the other processes for which data were retrieved from the Ecoinvent database version 3.5 [42] (secondary data). Background processes represent an average situation with a different level of geographical and technological representativeness, ranging from national to worldwide averages.

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[1] in this context, the differentiation performed on the geographical basis is to be considered a simplification of the underlying geological setting.

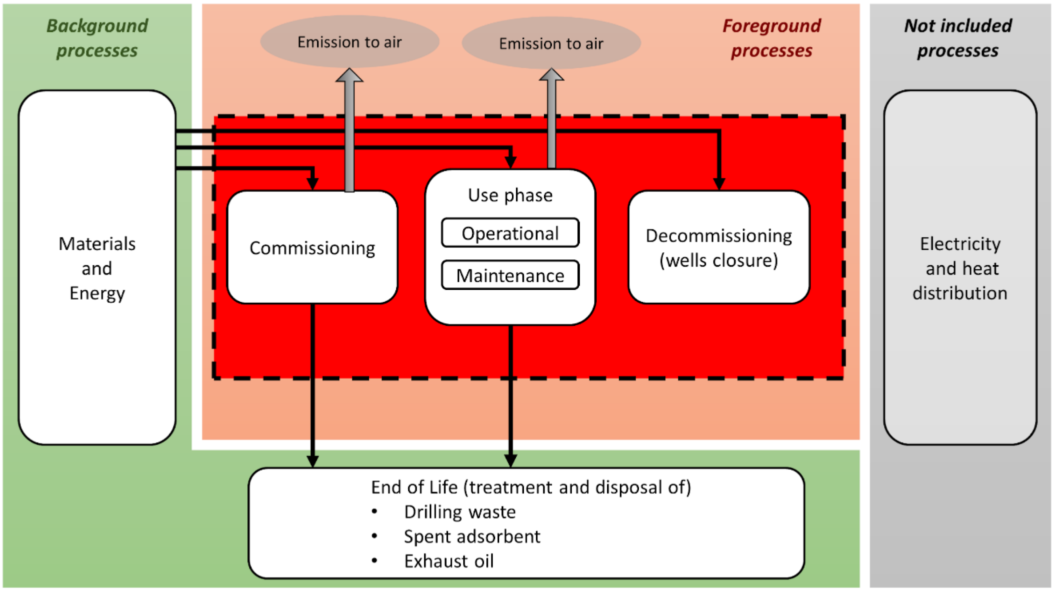

Figure 1. *Graphical representation of the system boundaries considered in this study. A distinction is made between background processes that use secondary data (Ecoinvent database v3.5) and foreground processes that use primary data representative of the Bagnore power plant system. Electricity and heat distribution infrastructure and processes are not included in this study.*

The geothermal power plant system was modelled in more detail as follow:

- The commissioning phase included the drilling of production and injection wells and the well-pad construction; the construction of pipelines; the power plants building; all the equipment needed for the power generation plant and the heating station, including the cooling towers, the ORC unit and the production of the working fluid used by the ORC system; the construction of AMIS was also included in the commissioning stage; on the contrary, the exploration and wells' testing stages were excluded from the analysis due to lack of data.
- The operational phase included the production of sulfuric acid (H_2SO_4) used in the fluid treatment for the oxidation of (NH_3); working fluid losses during normal operation of the ORC system were inventoried as direct emissions to air; the operational phase accounted for direct emissions of NCGs, Arsenic (As) and Hg to air. Maintenance activities included in the system were: AMIS maintenance, which involved the substitution of selenium based sorbent; the evaporative tower maintenance, which involved substitution of plastic parts (drift eliminator, fan); equipment maintenance, which includes lubricant oil refilling, substitution of metals components of various technical parts (i.e. turbine, compressors). More details are given in the Supporting Information in the "Inventory" sheet.
- When the geothermal power plant runs out of its lifetime, a decommissioning phase was assumed, which included exclusively the closing of the wells with cement. The activities of dismantling and recycling of machinery and equipment were excluded from the decommissioning stage because they can be employed in other plants operated by EGP.

- Finally, the EoL phase included the treatment and disposal of drilling mud and of the spent sorbent from AMIS maintenance, as well as the treatment of exhaust oil from equipment maintenance activity.

2.3.2.2.3 LCA key modelling parameters

This section reports the key modelling parameters of the geothermal plant, as well as the secondary data selection. The inventory of the Bagnore system is discussed in Section 3.1, where a general comparison in terms of data quality and coverage with the currently available LCI for Hellisheiði [35] is performed.

Table 1. *Bagnore power plant system LCA key modelling parameters.*

Geothermal source type			**Hydrothermal**
Energy generation technology			Flash
Final energy use			Electricity production
Average Reservoir Depth (shallow|deep) (m)			700 | 3000
Field Average Temperature (°C)			300 - 350
Parameter		***Unit***	***Value***
Installed power			
	Electric	MW_{e}	61
	Thermal	MW_{th}	21.1
District Heating SUPPLY|RETURN temperature		°C	100 | 60
Net energy output (annual)			
	Electric	GWh_{e}/y	544
	Thermal	GWh_{th}/y	32
Predicted lifetime		Years	40
Total Energy Produced			
	Electric	GWh_{e}	21760
	Thermal	GWh_{t}	1280
Production and injection wells		Number	8 production / 6 injection
Total length drilled		Meters	31823
Pipelines length		Meters	10400

Load factor	%	99

Site specific data have always been used when possible, whereas background data were retrieved from the Ecoinvent database [42], with a preference for specific Italian dataset when available (i.e. for the electricity mix). When not available, average European or global dataset were selected.

2.3.2.3 Data representativeness and quality

The quality of collected data was assessed by means of the Ecoinvent data quality system [43]. Five indicators (i.e. Reliability, Completeness, Temporal correlation, Geographical correlation, Further technological correlation) were assessed using a score from the best quality (score 1 that correspond to a verified measured data) to worst (score 5 corresponding to not qualified/or estimate data). The complete description of indicators and scores is reported in Table 2.

Table 2. *Data quality indicators and score description on scores*[1]*.*

Indicators	**SCORES**				
	1	**2**	**3**	**4**	**5**
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert)	Non-qualified estimates
Completeness	Representative data from all sites relevant for the market considered, over and adequate period to even out normal fluctuations	Representative data from > 50% of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Representative data from only some sites (<< 50%) relevant for the market considered or > 50% of sites but from shorter periods	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Representativeness unknown or data from a small number of sites and from shorter periods
Temporal correlation	Less than 3 years of difference to the time period of the data set	Less than 6 years of difference to the time period of the data set	Less than 10 years of difference to the time period of the data set	Less than 15 years of difference to the time period of the data set	Age of data unknown or more than 15 years of difference to the time period of the data set
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)

Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials	Data on related processes on laboratory scale or from different technology

[1] Each cell in the matrix indicates a quality characteristic of inventory data. After the analyst has selected, for each item of the inventory, an appropriate cell during the Monte Carlo procedure, the software keeps track of such choice indicating the position (1 to 5) of the selected quality characteristics in each R, C, T, G, F line of the matrix itself (see Table 9).

After a score was assigned to each data indicator for all material and energy inputs included in the inventory, the Ecoinvent data quality system calculates a corresponding numerical value of uncertainty, assigning a specific geometric standard deviation to a log-normal distribution (see the Supporting Information for standard deviation values). The propagation of uncertainty throughout the model was then calculated by means of Monte Carlo analysis (i.e. 10000 runs), obtaining a final standard deviation on the results in each impact category.

2.3.2.3.1 Important assumptions

Transport of assembled machinery to the geothermal plant site was excluded because of the limited distance between the plant and the production site (i.e., 150 km). However, the transport of the semi-products and raw material was included using the background processes in the Ecoinvent database.

For small steel parts, an aggregated mass value was provided by EGP. This quantity is supposed to cover all the steel used for general parts in the commissioning phase. Thus, it was equally divided among the six components: AMIS, gas intercooler, gas compressor, condenser, evaporative tower and turbine.

During the maintenance of the power plant, a 10% of the steel content of the steam turbine rotor was assumed to be substituted with new steel every four years.

Drilling wastes spent mineral oil and sorbent were considered to be sent to landfill. According to the information supplied, no additional treatment processes were considered.

Data on direct emissions from the power plant’s stack was taken from Ferrara et al. [44]. These emissions were modelled as output flows “emission to air, low population density”.

2.3.2.3.2 Allocation procedure

The Bagnore 3 and 4 power plant is a multifunctional system since it produces both electricity and thermal energy. In this study an exergy-based allocation procedure was chosen to deal with such multifunctionality as a proper allocation method according to the ILCD Handbook [41]. The exergy allocation method accounts for the quality (i.e. exergy content, ability to do work) of the two energy products (i.e., electricity and heat) generated by the power plant. Thus, 95% of total impacts were allocated to the electricity produced. The complete procedure to calculate allocation coefficients for electricity and heat is reported in detail in the Supporting Information in the sheet “Allocation”.

2.3.2.3.3 Life cycle impact assessment method

The ILCD 2011 Midpoint+ method v1.0.9 was adopted for translating into environmental impacts the emissions and resources use, quantified during the inventory phase. The impact categories Acidification potential (AC), Climate change (CC), Freshwater ecotoxicity (EC), Freshwater eutrophication (FEP), Human toxicity, cancer effects (HTc), Human toxicity, non-cancer effects (HTnc), Ionizing radiation Human Health effect (IR_{HH}), Land use (LU), Marine eutrophication (MEP), Mineral, fossil & ren resource depletion (MFRD), Ozone depletion (ODP), Particulate matter (PM), Photochemical ozone formation (POF), Terrestrial eutrophication (TE), Water resource depletion (WRD) were included in the analysis. The Ionizing radiation E (interim) impact category was excluded due to its not complete development [45]. The normalization step was performed by applying the reference values of the “EU27 2010, equal weighting” set. According to the latest development in European guidelines of the ILCD method [45], the discussion related to toxicity categories was excluded from the analysis. All the calculations and modelling were performed using the open-source software OpenLCA version 1.10 and LCIA package v2.0.4 [46].

2.3.3 Life cycle inventory analysis

One main objective of this research is to present the most detailed and accurate life cycle inventory based on primary data for a state-of-the-art flash geothermal power plant. The collection of information was performed with the intent of obtaining the highest level of detail in terms of LCA requirements [41]. The inventory of materials and energy input and output flows was collected for each of the separated components and based only on primary data. To our knowledge, the data inventory built in the present work represents the first of a kind

LCI available in the state-of-the-art literature for geothermal power plants based on flash technology. The resulting inventory is presented in its extended version in the Supporting Information (sheet "Inventory").

Currently, the most referred LCI available in the literature concerning flash technology is the one published by Karlsdottir et al. [35]. As much as this inventory is quite comprehensive and detailed and it has been often employed for geothermal system modelling in LCA studies ([24] and references therein), it fails in not providing primary data and overarching all the life cycle stages of the energy generation system. The present work aims at providing an improved inventory for the flash technology, which could potentially be used in conjunction with the work by Karlsdottir et al. [20,35] for geothermal system modelling in future LCA studies of geothermal power plants.

Table 3. *Main differences between the currently available life cycle inventories for flash technology.*

Parameter	**Karlsdóttir et al. (2015)**	**This work**
Data accuracy	Not all the data presents the highest level of accuracy. Sometimes secondary data are employed, or data come from extrapolation of secondary data.	Most of the data comes from primary sources, or data are directly extrapolated by the operator Company.
Data coverage	Most of the Life Cycle Stages are analysed and reported, but ● No data coverage for regular maintenance activities. ● Direct emissions to air are only partially accounted	All of the Life Cycle Stages are fully analysed and reported.
System boundaries	EoL processes are not included	EoL processes are included; only heating station building, electric supply machinery and distribution infrastructure are not included in the system boundaries

Table 3 reports the main differences between the present work (right side) and the work by Karlsdottir et al. [35] (left side). Regarding data accuracy, the inventory presented in this work is entirely based on primary data coming from the EGP Company that has executed the activities. Only a few assumptions were made based on expert knowledge as, for instance, concerning power building material requirements. In this case, the primary data used for modelling of Bagnore 4 was also used also for Bagnore 3, as suggested by the power plant operator EGP, employing scaling factor. Even though this can be considered as an estimation, it is still based on primary data and, more importantly, on the expert judgment of the operator. As a result, when considering data quality, a large part of the indicators was scored between 1 and 3 (see Table 2).

On the other hand, Karlsdottir et al. [35] includes a higher component's specificity, for example, steel grades are provided and mass weight for smaller equipment parts. Still, these data are mainly based on secondary data and authors' assumptions. The data coverage featured in this paper is higher compared to the one in Karlsdottir et al. [35]. Specifically, the present work considers all the regular maintenance activities, for example, lubricating oil substitution and regular maintenance operation of machinery, EoL treatments of wastes and wells closure operations, previously never considered.

In this paper, the same approach used in Parisi et al. [37] was adopted. Such an approach relies on a statistical analysis of all the compounds emitted during power generation from geothermal exploitation. The only difference compared to the work of Parisi et al. [37] is represented by the emission values that have been updated with the most recent ones provided by the regional environmental agency [47].

Table 4 reports the main energy and material inputs for the commissioning phase related to the functional unit. Diesel consumption is primarily associated with the wells drilling process with a specific consumption of about 12 GJ/m. Concerning material use, Portland cement and steel represent the most used materials accounting for about 70% of the total weight of equipment used in this stage. Portland cement is employed in the casing of wells and power station buildings, whereas steel is partitioned among casing, pipelines and machinery. Depending on the application, different steel grades can be used.

Table 4. *Main material and energy inputs employed in the commissioning phase. The cut-off is set at 2% of the total mass to reduce the number of inputs reported. Complete information can be found in the Supporting Information.*

Energy input		Amount	Unit
	Diesel for drilling	9.4E-03	MJ/F.U.

Material input	Amount	Unit
Excavation	6.7E-07	m3/F.U.
Portland cement	8.1E-04	kg/F.U.
Steel	3.3E-04	kg/F.U.
Gravel	2.5E-04	kg/F.U.
Bentonite	9.4E-05	kg/F.U.
Copper	5.0E-05	kg/F.U.
Sodium hydroxide	3.5E-05	kg/F.U.
Aluminium	2.7E-05	kg/F.U.
Material output	**Amount**	**Unit**
Drilling waste to disposal (EoL)	1.0E-03	kg/F.U.

The material input for maintenance activities are reported in Table 5. The maintenance stage represents the planned activities required to keep the power plant in operation. Extraordinary maintenance activities are hence omitted. The maintenance activities that result in the highest material consumption are those related to the substitution of the spent Hg absorber (Selenium), the lubricating oil replacement as well as the steel and polyvinyl chloride (PVC) replacement for power plant machinery. In this case, a substitution of 10% of the total weight of the steam turbine rotor every four years was considered.

Table 5. *Main material and energy inputs employed in the maintenance phase. The cut-off is set 2% of the total mass to reduce the number of inputs reported. Complete information can be found in the Supporting Information.*

Material input	Amount	Unit
Lubricating oil	5.5E-06	kg/F.U.
Selenium	4.1E-06	kg/F.U.
Pentane	2.8E-06	kg/F.U.
PVC	8.3E-07	kg/F.U.
Steel	7.7E-07	kg/F.U.

The operational stage considers the atmospheric emissions due to geothermal fluid exploitation and the material input needed by the NH_3 abatement system. As shown in Table 6, the emission of CO_2 and methane (CH_4) dominates the environmental emission profile of the Bagnore power plant system. In contrast, the H_2SO_4 is by far the most used material during the operational phase.

Table 6. *Main material input and direct atmospheric emissions from the operational phase. The cut-off is set 2% of the total mass to reduce the number of inputs to be reported. Complete information can be found in the Supporting Information.*

Material input	**Amount**	**Unit**
H_2SO_4	3.7E-03	kg/F.U.
Atmospheric Emissions	**Amount**	**Unit**
CO_2	4.1E-01	kg/F.U.
CH_4	1.2E-02	kg/F.U.

Table 7 provides information on energy and materials inputs for the decommissioning phase. The assumption is that all the drilled wells will undergo a closure process when the plant runs out its lifetime. This approach was adopted more to test the influence of the EoL processes of wells than to representing a real option. The Bagnore power plant system is managed in a sustainable way, ensuring a constant productivity without depletion of the resource. However, since a lifetime must be set in LCA, this work has considered the unlikely option that the wells will be closed after the given lifespan to account for the EoL process.

Table 7. *Main material and energy input employed in the well closure phase. The cut-off is set 2% of the total mass to reduce the number of inputs reported. Complete information can be found in the Supporting Information.*

Energy input	**Amount**	**Unit**
Diesel	6.4E-04	MJ/F.U.
Material input	**Amount**	**Unit**
Portland	1.6E-05	kg/F.U.
Gravel	3.2E-06	kg/F.U.

2.3.4 Results

2.3.4.1 Life cycle assessment of the Bagnore power plant system

Figure 2 reports the percentage of contribution of commissioning, operational, maintenance, decommissioning and EoL phases of the Bagnore power plant system to the total impacts for all the categories included in the ILCD method. The potential impacts on the 15 categories that were considered are essentially determined by the commissioning and operational phases, which contribute for more than 90% on the total impacts in each category. More in detail, the operational phase contributes for 80 - 90% of the overall potential impacts on AC, CC, HTnc, MEP, PM, POF and TE categories and about 70% to WRD. These impacts are mainly linked with direct emissions to air of NH_3, CO_2 and CH_4. Emission of NH_3 determines the impacts on AC (i.e. 96% of total impact), MEP (84% of total impact), TE (99% of total impact) and PM (86% of total impact). In contrast, the impact on CC category is shared between CO_2 (i.e., 57% of total impact) and CH_4 (i.e., 42% of total impact) emissions. The total impact on POF is determined for a 75% by CH_4.

The commissioning phase is responsible for more than 80% of the total potential impacts on EC, FEP and MFRD. The copper requirement during the building construction process is the main contributor to such impacts. The commissioning phase contributes to about 60 to 70 % on IRHH, LU and ODP categories for which the deep well construction process shows the highest contribution.

Subsequently, decommissioning and EoL phases show a negligible contribution to all the considered impact categories.

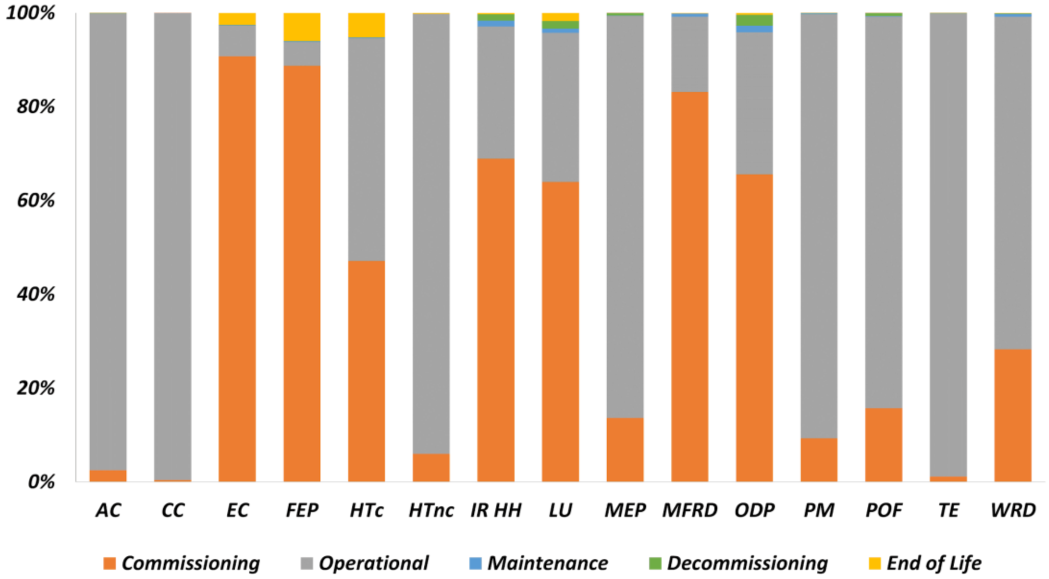

Figure 2. *Percentage of contribution of commissioning, operation, maintenance, decommissioning and EoL phases to the total impact in all the assessed impact categories.*

The characterized results of each impact category were divided by a selected reference value in order to better understand the magnitude of the results of impact category indicators and bring all the results on the same normalized scale (see the Supporting Information for normalization values). After the normalization step, CC, TE and AC categories, in this order, had the highest impacts among all the selected impact categories (Figure 3). The impacts from geothermal electricity production were compared with the impacts from the average Italian energy mix [48] to give a reference system and interpret the magnitude of geothermal eco-profile. The Ecoinvent version 3.5 employed for the analysis is based on the Italian electric energy mix by 2014. The share consisted in 60% arising from fossils (coal, gas, oil) and import (mostly nuclear). RES represents 40% of the total with 18% generated by hydro, 7% due to photovoltaics, 5% wind, 6% biofuel, 2% waste and 2% geothermal.

As shown in Figure 3, all the impacts caused by the average Italian electricity mix are higher than those of geothermal energy production with the exception of climate change due to the emissions of CO_2 and CH_4 that are intrinsic to the geothermal resource exploitation activities.

The impacts on CC, TE and AC categories for geothermal electricity production are determined almost exclusively by emissions to air during the operational phase (i.e., NH_3, CO_2 and CH_4). As shown in Figure 3, all the impacts caused by the average operational phase are mainly related to the geothermal fluid composition, thus can be considered site-dependent.

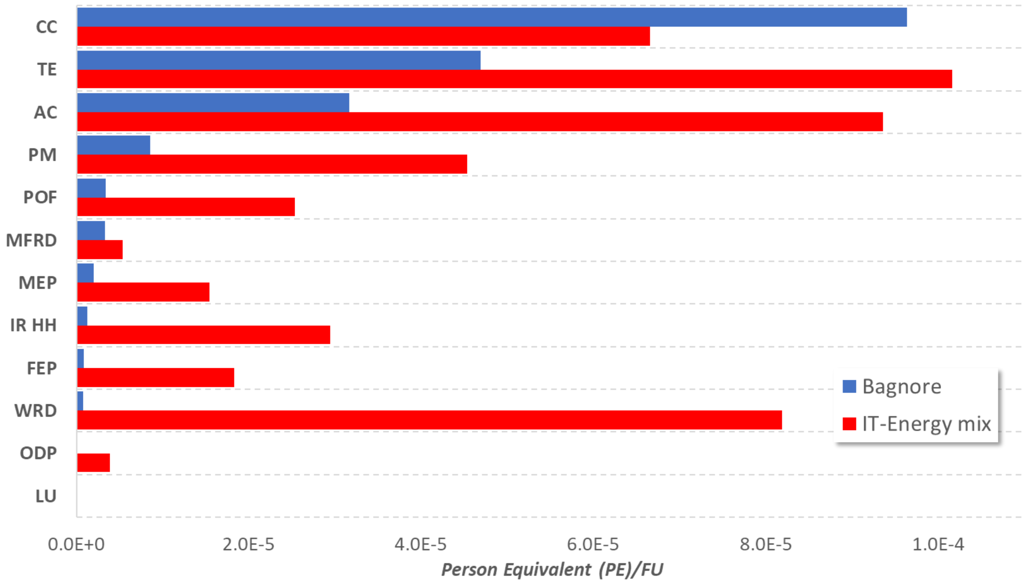

Figure 3. *Normalized results for the production of 1 kWh of electric energy from the Bagnore power plant system (blue) and from the average Italian electricity mix (red). CC, TEP, AC and PM have been identified as the categories with the highest impact.*

Table 8. *Contribution of LC phases to the most impacting categories AC, CC, PM and TE. Impacts are reported as person equivalent (PE) per functional unit (FU). Complete information can be found in the Supporting Information.*

	Unit	AC	CC	PM	TE
Commissioning	PE/FU	8.0E-07	4.3E-07	8.0E-07	5.4E-07
Operational	PE/FU	3.1E-05	9.6E-05	7.8E-06	4.6E-05

End of Life	PE/FU	1.1E-09	2.5E-09	1.4E-09	1.3E-09
Maintenance	PE/FU	7.8E-09	3.4E-09	7.0E-09	2.2E-09
Decommissioning	PE/FU	1.4E-08	9.4E-09	1.1E-08	2.3E-08
Total	PE/FU	3.2E-05	9.6E-05	8.6E-06	4.7E-05

On the contrary, the commissioning phase is common to all flash technologies and Figure 4 shows the contribution of processes within this phase. The processes considered in the commissioning phase are clustered in Drilling, Drilling waste (disposal), Equipment and Pipelines. The Drilling process includes, in addition to the drilling activities themselves, the construction of the well pads. In contrast, equipment includes all the materials and energy needed to realise the components present in the power plants and the power plants building itself. The pipelines construction process is separated from the others because they are structures connecting wells and power plants.

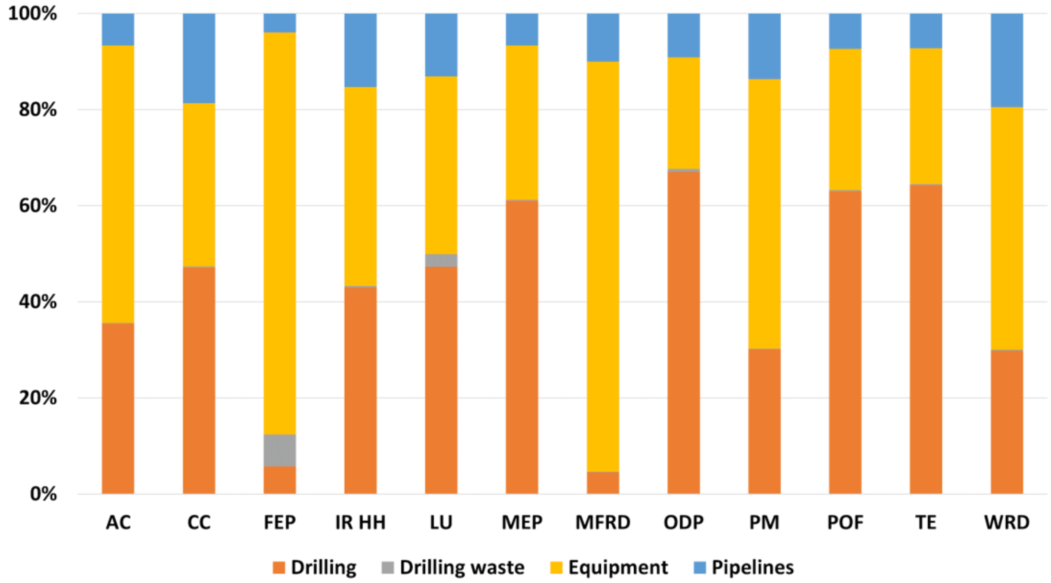

Figure 4. *Percentage of contribution of Drilling, Drilling waste disposal, Equipment and Pipelines to the commissioning phase.*

The hotspot analysis results show that the potential impacts of the commissioning phase are fairly divided among equipment and drilling processes. Building construction and the production of metals (i.e., copper) determine the impact of the equipment. Emissions from the combustion of diesel used to drive the drilling rig are the most responsible for the impact during drilling. Pipelines generally gives a contribution of around 10% of the total impacts in all categories except for CC and WRD. Drilling waste disposal has a negligible impact.

2.3.4.2 Uncertainty analysis of results

Figure 5 reports the uncertainty values (MIN, MAX and standard deviation) related to the average potential impact for the categories CC, TE, AC and PM which were previously identified as having the highest impact. The uncertainty associated with the results was calculated following the procedure described in Section 2.2.4.

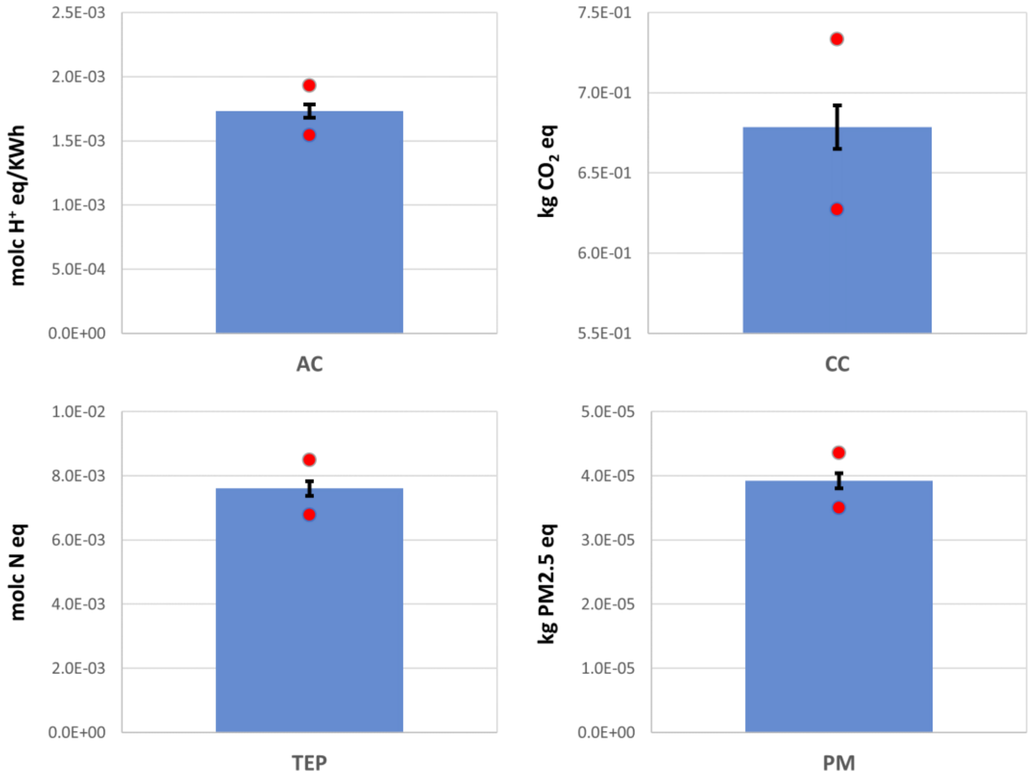

Figure 5. *Characterized impact results per kWh of electricity produced for the categories CC, TE, AC and PM. Bars represent the standard deviation around the average impact values, whereas red dots refer to MIN and MAX values.*

The calculated uncertainty of results for the identified categories is low and ranging between 2-3 %. The impact of these categories is exclusively determined by airborne emissions (primary data) during the operational phase. The good quality of data for airborne emissions (low score in all indicators, see Table 2) results in a low uncertainty of the final LCA results. In those cases where the impact is determined by other stages, with different levels of quality of primary data, the final uncertainty is generally higher and, in some cases, up to a standard deviation around the mean value of 58%.

In Table 9, the uncertainty related to the impacts for all categories is reported together with the overall score for each data quality indicator used to calculate the impacts. Generally, a low overall data quality (high scores in Table 2) corresponds to a relatively high standard deviation

(> 10%). The uncertainty of results is not exclusively related to the inventory data, but also to the secondary (background) data and their relative uncertainty as specified in the Ecoinvent database.

Table 9. *Uncertainty analysis for each impact category results and data quality indicator score. (R) Reliability; (C)Completeness; (T) Temporal correlation; (G) Geographical correlation; (F) Further technological correlation.*

Impact Category	**Impact result**	**STDV (%)**	**Overall data quality indicator**[1]				
			R	**C**	**T**	**G**	**F**
Acidification (molc H^+ eq)[2]	1.78E-03	3	1	1	2	1	1
Climate change (kg CO_2 eq)	6.82E-01	2	1	1	2	1	1
Freshwater eutrophication (kg P eq)	5.19E-06	58	1	1	4	1	1
Ionizing radiation HH (kBq ^{235}U eq)	2.96E-04	12	1	1	5	2	1
Land use (kg C deficit)	8.37E-03	18	3	4	5	3	1
Marine eutrophication (kg N eq)	6.16E-05	3	1	1	3	1	1
Mineral, fossil & ren resource depletion (kg Sb eq)	6.49E-07	20	3	2	5	2	2
Ozone depletion (kg CFC-11 eq)	4.39E-10	47	2	3	4	5	3
Particulate matter (kg PM2.5 eq)	4.35E-05	3	1	1	2	1	1
Photochemical ozone formation (kg NMVOC eq)	1.52E-04	3	1	1	3	1	1
Terrestrial eutrophication (molc N eq)[2]	7.69E-03	3	1	1	2	1	1
Water resource depletion (m^3 water eq)	5.69E-05	11	2	3	5	3	2

[1] *numbers in columns R, C, T, G, F refer to specific scores within the Ecoinvent uncertainty matrix (Table 2).*

[2] *molc unit indicates a mole of charge (molc) per unit of mass emitted.*

2.3.5 Discussion

The LCA results show that direct emissions to the atmosphere released during the commissioning and operational phases are the dominant impact for the Bagnore system. For the commissioning phase, as the emissions of CO_2 associated with the combustion of diesel used to drive the drilling rig are the principal factors responsible for the environmental impact, the eco-profile would certainly improve in the future with changing the drilling technology. Unfortunately, so far, the initiatives promoted by operators to employ an electric rig, directly powered by the medium-voltage network, aiming at a simplification of the process and a reduction of impact and costs, have been unsuccessful. The main difficulties arose with the medium-voltage network connections and for authorization procedures which look quite complex due to safety requirements.

However, the applicability of such a system looks only suitable for the consolidated stations with several wells.

The potential environmental impacts generated during the operational phase are mainly linked with airborne emissions. The comparison with the Italian energy mix allows highlighting the differences in the environmental performances, which are in favours of geothermal energy exploitation for all the environmental impact categories with the exception of climate change. This outcome is due to the significant contribution given to the average Italian electricity mix from RES like hydro, photovoltaics and wind energy, whose CO_2 emission contributions in the atmosphere during the operational phase are negligible. This confirms previous evidence that geothermal energy, although renewable, is not the cleanest one, even if it performs better than any other fossil source. This finding gives a benchmark to interpret the magnitude of the power plant eco-profile. As the emissions of NH_3, CH_4 and CO_2 during the operational phase are mainly related to the geothermal fluid composition, they can be considered site-dependent, therefore particular care should be exercised in deciding the localization of plants in the project phase. In this context, it should be mentioned that, to date, in the analysis of greenhouse gases emissions, the Intergovernmental Panel on Climate Change [49] considers the release of greenhouse gases of geothermal origin quantitatively negligible, despite the fact that this has been demonstrated not always to be true [7]. Anyway, notwithstanding the evidence that flash geothermal electricity production is contributing to CO_2 emissions more than the Italian electricity mix, some intrinsic benefits connected with geothermal development should be considered. This is particularly important in the frame of a policy sensitive to environmental and social issues: (i) geothermal energy is a renewable local based energy source and not imported; (ii) a secondary, but not negligible advantage can be found in the use of thermal fluids for civil or light industry purposes in the neighbouring area; (iii) electricity generated by geothermal contributes to the basic load and it is independent on the atmospheric conditions. However, about this latter issue we should be aware that in the future, due to discontinuity of solar and wind electricity supply, flexible power systems will be even more valuable.

The main achievement of the assessment method implemented in this work relies mainly on two aspects. Firstly, the investigated system has been selected from the latest in technological excellence in the field of flash geothermal generation in Italy. Secondly, the EGP operator granted the availability of primary data to build the LCI, as reported in the Supporting Information. This is noteworthy compared to the state-of-the-art LCA literature on geothermal systems that very often uses secondary or tertiary data.

The representativeness and quality of the inventory data, presented in section 2.3.2.3, should always be assessed to ensure robustness of LCA results. Significant elements of improvement in this work are represented by the level of detail for machinery and components, data quality and coverage, as well as the inclusion of the EoL as shown in Table 3.

The exergy-based allocation method chosen to address the multifunctionality represents another feature of this work: although not fully new, most LCA studies allocate according to mass, energy content or monetary value. Exergy reflects the difference in terms of energy quality among energy outputs and represents the most suitable method, from a thermodynamic point of view, for discerning the benefits of combined heat and power systems.

The uncertainty evaluation on LCA results performed with Monte Carlo analysis shows a non-negligible dependence on the background Ecoinvent database and the LCIA method assumptions, not on foreground data. This confirms the reliability of the LCA system modelling adopted in this work. The scientific approach employed offers a detailed insight of the research findings in agreement with the ISO 14040 and ILCD requirements. From a policy point of view, the transparency of the assessment method could support effective decision-making.

As mentioned in the Introduction, the EU has committed itself to a clean energy transition, which will contribute to fulfilling the goals of the Paris Agreement on climate change [1,5]. According to the Italian NECP targets [6], the electric generation power will be affected by an important transformation due to the goal of phasing out of coal generation plants within 2025 and necessary promotion of large contribution from RES to replace them. The maximum contribution to the growth of RES will arise particularly from the electric sector, which at 2030 will reach 187 TWh of generation from RES, equal to 16 Mtep. The strong penetration of technologies for electric energy renewable production, mainly photovoltaics and wind, will allow covering a 55.0% of the final gross electric consumptions with RES compared with the 40% of 2014. The photovoltaics and wind capacity should triple and double respectively within 2030. As much as regards other RES in the NECP, a limited growth of additional geothermal power from 813 to 950 MWe is foreseen which would represent the only maintenance of the actual 2% of the Italian electric mix. This target is considered for conventional geothermal technology, with reduced direct emission limits. It arises from the awareness that, even if geothermal energy is quite suitable for replacing fossils in electricity production, the limits due to environmental impacts still hold. The possibility of providing incentives for other technologies like that with zero emissions in plants with total reinjection of fluids is under evaluation. At the moment these technologies, like the geothermal at reduced environmental impact, are considered as innovative in the national context as wind off-shore, concentrated solar power and ocean energy.

2.3.6 Conclusions

In this paper, a cradle to grave LCA of the Italian flash technology Bagnore power plants system has been performed based on a comprehensive and accurate life cycle inventory of primary data supplied by the plant manufacturer and operator EGP. From the LCA results it can be inferred that the potential environmental impacts are determined for more than 95% by the operational (direct emissions to air of NH_3, CH_4, CO_2) and commissioning (CO_2 emissions due to diesel combustion during drilling) phases. Maintenance, decommissioning and EoL phases show a negligible contribution to all the considered impact categories. Globally, out of the sixteen impact categories selected, Climate change, Acidification, Terrestrial eutrophication and Particulate matter were the most affected. These outcomes imply that LCA results of electricity generation from flash technology employing a mid to high dissolved gas content fluid are primarily determined by emissions to air. Direct emissions into the atmosphere are the responsible for most of the environmental impact in the operational phase (84%). The comparison made with the life-cycle environmental impacts caused by the production process of the average Italian electricity mix showed that the balance is almost always in favour of the geothermal energy production, with the only exception of the climate change category. A further finding of this work is that in the commissioning phase the impact is equally divided between well drilling and equipment. It is noteworthy that the copper requirement during the building construction process is the main contributor to impacts in the commissioning phase.

Accordingly, future research might explore the possibility of replacing metals and particularly copper in building the plant.

It should be noticed that the data referring to commissioning, maintenance and EoL stages presented in this study might be used by the scientific community to evaluate potential environmental impacts of geothermal systems. On the other hand, site-specific information, such as direct environmental emissions measured during the operational phase, is exclusively valid in this specific geothermal field.

This work offers the most complete life cycle inventory for a state-of-the-art flash system conversion technology overarching the whole life cycle of the geothermal power plant. The robustness of the results obtained here, as demonstrated by the uncertainty analysis, allows one underlying the need for high quality primary data for performing reliable and consistent LCA studies. This is particularly true in the geothermal sector, where the lack of primary data and precise information about the conversion technology and the geo-specificity of the reservoir for long periods prevented the possibility to get reliable results affecting the quality of the LCA studies. In this context, the availability of primary data and the open access to technical repositories become essential to reach high standards in the LCA literature concerning geothermal systems. We believe that the accurate approach presented in this paper will aid to promote the implementation of environmental assessment studies that are essential to undertake impact minimization actions on currently operating power plants and to improve the eco-design perspective of future installations.

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3 METHODOLOGICAL ADVANCES

3.1 Performing a fast and effective Global Sensitivity Analysis using Python: a simplified example applied to the LCA of Italian electricity generation scenarios

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Abstract

In recent years, novel analytical procedures for conducting reliable LCA at a more limited computational cost have been proposed. In this paper the potential and usefulness of Global Sensitivity Analysis and "simplified models" is discussed and presented through the application to the Italian electricity mix for the assessment of the environmental profile variability related with the scenario foreseen by the Italian integrated energy and climate plan.

3.1.1 Introduction

The European Commission (EC) has started the transition of European Union (EU) into a highly energy efficient and low-carbon economic system (European Commission, 2018). The energy policy of the EC at the 2030 horizon aims at strengthening the 20-20-20 objectives and is a precondition for 2050 goals of the long-term strategy to reduce greenhouse gas emissions.

Life cycle assessment has been identified as one the most suitable methodology to evaluate potential impacts from all stages of energy production systems during their entire lifetime (Gargiulo a., et al., 2020; Hertwich Edgar G., et al., 2015; Tosti L., et al., 2020). However, performing a LCA of energy systems might have some drawbacks such as taking considerable time for its development, lack of data or scarce info, complex systems modelling, dealing with data uncertainty, etc. (Lacirignola M., et al., 2017; Weidema B.P., et al., 2013).

Given the difficulties that conducting an LCA might represent especially for non-LCA experts, the development of novel procedures to satisfy the need for a reliable LCA while keeping the effort limited is increasingly required.

A solution of growing interest is constituted by the development of “simplified model” which are equations able to give as results the impact for a determined impact category and are developed starting from a conventional LCA model defined “reference model”. The simplification is made up by limiting the amount of input data needed and eliminating the need to build an LCA model. Practically, the user just needs to substitute variables on given equation. The variables used in the simplified equation can explain most of the variance of the reference model over a defined range. This step is undertaken by performing a Global Sensitivity Analysis (GSA) and calculating the Sobol' indices (Saltelli, 2008; Sobol, I. M., 2001) from the Monte Carlo simulations. Simplified models have been already explored for wind turbines (Padey et al., 2013; Sacchi et al., 2019) and EGS plants generating electricity (Lacirignola et al., 2015).

This work aims at showing the potential and usefulness of GSA and simplified models generation applied to the Italian electricity mix to assess and evaluate its environmental profile variability in relation with the modifications planned within the EU energy transition.

3.1.2 Materials and methods

3.1.2.1 Methodological approach

The analysis is performed using a common PC running Python in Conda environment and the software are downloaded from the official repositories and installed following the documentation provided with them. The Python libraries dedicated to LCA analysis and used in the present study are Brightway [Mutel C., 2017] and lca-algebraic [lca-algebraic, 2020].

Brightway is an open-source framework designed to introduce different and alternatives capabilities for LCA analysis compared to those of commercial software such as OpenLCA, SimaPro and others. During the years, due to its open-source nature, the Brightway framework has been developed, expanded, and improved by many contributors. Moreover, Brightway framework can deal with multiple databases.

The lca-algebraic library has developed by the Centre OIE – MinesParistech for the INCER-ACV project led by the Agence de la Transition Ecologique. It is designed as a layer which works on top of Brightway2 providing additional support for parametrized inventories and obtaining ultra-fast computation of LCA results and enhanced support for Monte-Carlo based GSA. The library is used to add the functionality required to perform the computation of the Sobol index and to generate the simplified model.

The general method to generate a simplified model follows 5 steps as described in more detail in Padey at al. 2013 (Padey P., 2013):

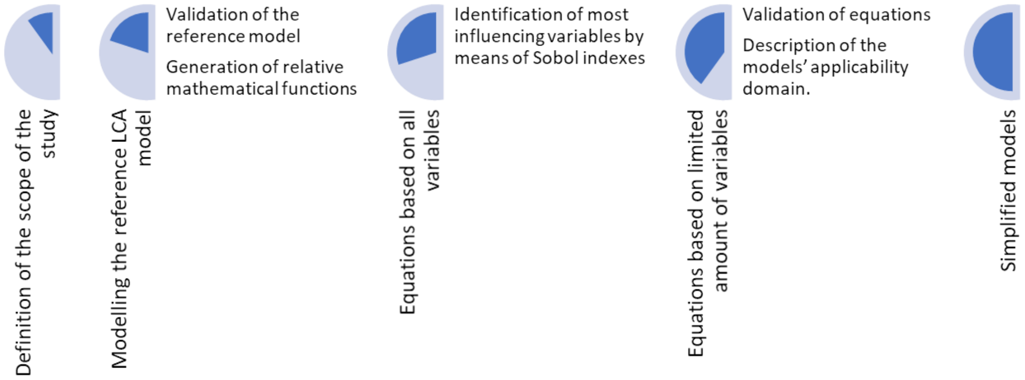


Figure 1. General procedure to generate simplified models exploiting GSA Sobol indexes

The approach followed in the present work is an adaptation of the general procedure described in Figure 1. In particular, the steps concerning the description of the scope of the study and the modelling of the reference model and parameters were performed according to the general approach. Due to simplification purposes, the validation steps against real cases were not performed and will be object of further work.

The equations were obtained including all the parameters, and the GSA of these functions was performed. The results obtained from this process allowed the identification of the most influencing parameters determining the variance and the functions based on a limited number of variables were then generated. The procedure is illustrated in Figure 1.

3.1.2.2 Case study

The case study proposed is the generation and distribution of 1kWh of electricity according to two different scenarios depending on the composition of energy sources (see Table 1): the present and future scenarios. The case study is modelled using the Ecoinvent 3.6 database cut-off and the impact evaluated by means of the ILCD 2.0 2018 method. Data regarding the composition of energy sources for the "Present" scenario are retrieved from the IEA database (IEA, 2019) while data for the future Italian electricity mix composition (2030 scenario) comes from the Italian integrated energy and climate plan (INECP, 2019).

A simplified structure of the Italian mix is modelled as reported in Table 1. Some assumptions were made to further simplify the described system and the results description, as listed in the following:

- the processes used to describe the energy sources are assumed to be constituted by only 1 technology; the choice is made based on the prevalent technology as reported by Itten R., 2014 for the actual share ("Present").
- electricity import from abroad is assumed to be constant in amount and composition applying a 2% cut-off. Distribution losses occurring till end users are assumed to be 12% constant.

Table 1. Share of the electricity energy sources used to model the system. The "Present" and "2030" scenario data are used to define parameters ranges.

Energy Source	Present	2030
bio (biomasses)	5%	4%
coal	10%	0%
gas	31%	29%
wind	5%	10%
hydro	12%	13%
geo	2%	2%
oil	3%	1%
PV	9%	18%
Distribution Losses	12%	12%
Import from Switzerland (CH)	6%	6%
Import from France (FR)	4%	4%
Import from Slovenia (SL)	2%	2%

The final model, therefore, is composed of all the background activities retrieved by the Ecoinvent database and a set of parameters which describes the model itself. Table 2 defines the fixed parameters and variables. In addition to ranges, it is also possible to define a distribution type (normal, triangular, beta, etc.) which affects the results. In this case study, a linear distribution is used for sake of simplicity, but to obtain much more reliable results, a proper distribution should be selected instead.

Table 2. Parameters definition used for model computation; here the default is the "Present" scenario

Parameter	default	min	max	distribution
PV share	0.092	0.092	0.183	linear
gas share	0.311	0.295	0.311	linear
coal share	0.099	0	0.099	linear
hydro share	0.125	0.125	0.126	linear
geo share	0.017	0.017	0.018	linear
wind share	0.051	0.051	0.103	linear
bio share	0.046	0.046	0.036	linear
oil share	0.031	0.01	0.031	linear
CH share	0.058			fixed

FR share	0.039	fixed
SI share	0.018	fixed
Distrib Network Lenght	1.10E-07	fixed
Network Losses	0.115	fixed

3.1.3 Results

Table 3 shows the results obtained from the GSA based on 25000 iterations expressed as mean value with its standard deviation (std) for each impact category.

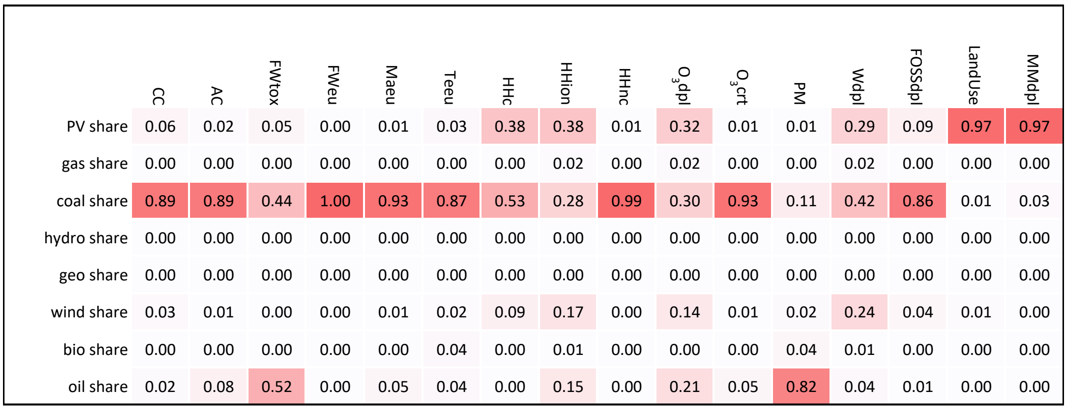
Table3. Results obtained by the Monte Carlo based GSA related to parameters variability ranges and LCA static results of the Present and 2030 scenario.

Impact Category	**mean**	**std %**	**Present**	**2030**
CC - climate change total	3.2E-01	9%	3.23E-01	1.94E-01
AC - freshwater and terrestrial acidification	1.7E-03	14%	1.91E-03	8.89E-04
FWtox - freshwater ecotoxicity	1.3E-01	5%	1.20E-01	1.00E-01
FWeu - freshwater eutrophication	9.3E-06	24%	1.07E-05	4.39E-06
MAeu - marine eutrophication	2.1E-04	16%	2.31E-04	1.02E-04
TEeu - terrestrial eutrophication	3.4E-03	11%	3.54E-03	1.88E-03
HHc - human health, carcinogenic effects	4.8E-09	2%	4.09E-09	4.15E-09
HHion - human health, ionising radiation	1.6E-02	4%	1.36E-02	1.24E-02
HHnc - human health, non-carcinogenic effects	2.8E-08	12%	2.80E-08	1.97E-08
O_3dpl - ozone layer depletion	4.9E-08	4%	4.18E-08	3.61E-08
O_3crt - photochemical ozone creation	6.9E-04	15%	7.45E-04	3.61E-04
PM - respiratory effects, inorganics	7.5E-09	8%	7.34E-09	4.67E-09
Wdpl – resources, dissipated water	2.8E-01	3%	2.20E-01	2.22E-01
FOSSdpl – resources, fossils	5.5E+00	8%	5.26E+00	3.44E+00
LandUse - resources, land use	2.2E+00	11%	1.50E+00	2.07E+00
MMdpl – resources, minerals and metals	4.1E-06	8%	2.90E-06	4.02E-06

In general, the average impact of the 2030 scenario decreases compared to the present average base scenario in each category except for land use category. The highest StD of results is observed for the FWeu impact category, followed by MAeu, O_3crt, and AC.

The GSA obtained from the lca-algebraic library allows to calculate the Sobol index of each parameter. The Sobol index is described as a Variance-based sensitivity analysis; its calculation is performed by decomposing the variance of the output model into fractions which are then attributed to a specific input parameter (first-order index) or to a combination of multiple parameters (second, third and following order index). This type of GSA is attractive because it measures the sensitivity of input parameters across the whole input space since it is a global method, it can deal with nonlinear equations and can measure the effect of interactions in non-additive systems.

Figure 2 shows the Sobol index for each impact category and parameter. In most cases, the variation of coal share in the Italian mix explains most of the variance. Few important exceptions are observed: i) the parameter “oil share” has a significant role in explaining the variance, together with coal, in the FWTox and PM category; ii) the impacts on HHc, HHion, O3dpl, O_3dpl, Wdpl can be divided among PV, coal and wind shares; iii) LandUse and MMdpl variance is explained by PV share. It is important to highlight that the Sobol index does not give information on which parameter has the largest impact on the model results. This index defines the amount of result’s variance “explained" by each parameter. For example, the variance of the CC category result is explained for 89% by the parameter “coal share”. If we look at the ranges assigned to “Coal Share” parameter, namely between 0 and 0.099 as showed in Table 2, this ratio determines most of the CC result variability.



	CC	AC	FWtox	FWeu	Maeu	Teeu	HHc	HHion	HHnc	O_3dpl	O_3crt	PM	Wdpl	FOSSdpl	LandUse	MMdpl
PV share	0.06	0.02	0.05	0.00	0.01	0.03	0.38	0.38	0.01	0.32	0.01	0.01	0.29	0.09	0.97	0.97
gas share	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.00	0.00	0.02	0.00	0.00	0.00
coal share	0.89	0.89	0.44	1.00	0.93	0.87	0.53	0.28	0.99	0.30	0.93	0.11	0.42	0.86	0.01	0.03
hydro share	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
geo share	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
wind share	0.03	0.01	0.00	0.00	0.01	0.02	0.09	0.17	0.00	0.14	0.01	0.02	0.24	0.04	0.01	0.00
bio share	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.01	0.00	0.00	0.00	0.04	0.01	0.00	0.00	0.00
oil share	0.02	0.08	0.52	0.00	0.05	0.04	0.00	0.15	0.00	0.21	0.05	0.82	0.04	0.01	0.00	0.00

Fig 2. Graph reporting the Sobol index values of the parameters for each impact category.

A similar situation is observed for the LandUse category but in this case the parameter able to explain most of the result variance is the PV share having a Sobol index of 0.97.

The information contained in Figure 2 is extremely useful when dealing with complex systems, as it gives an immediate picture of the most important parameters that influence and determine the results’ variability.

Sobol index does not give any indication about the magnitude of the variation itself. To quantify the variation of results it is necessary to apply the so called “one at the time” sensitivity analysis (OAT-SA). Figure 3 reports the variation of the LCA results obtained for the CC and LandUse impact categories that correspond to the variation of “coal share” and “PV share” parameters.

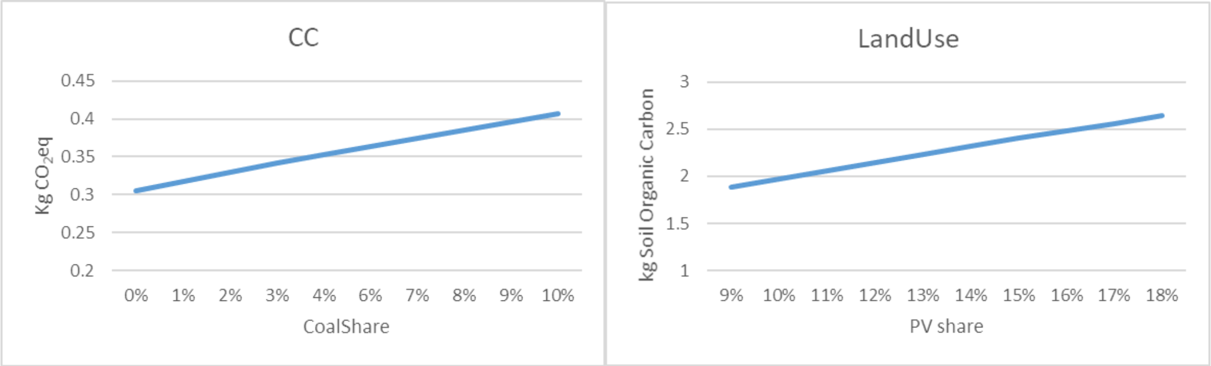


Fig 3. OAT-SA for CoalShare parameter for CC impact category (left). OAT-SA for PV share parameter for LandUse impact category (right).

Following the approach illustrated in Figure 1, and the steps described in Section 2.1 it is possible to build a set of equations whose output is the LCA result for each impact category. Each equation is composed by a constant part, which corresponds to the static part of the model, and variables which are determined by the parameters declared to be varying between the defined ranges. By using the Sobol indexes it is also possible to limit the number of variables used to build the equations to only those which determine the largest part of result's variance, namely the parameters with higher Sobol index. Therefore, a set of simplified equations can be derived for each impact categories.

Figure 4 reports two examples from the considered case study for the CC impact category. The equation a) is obtained with a 0.8 cut-off, thus only Coal Share is used in the simplified model, while equation b) present Coal Share and PV share as well, since a 0.9 cut-off is applied.

The R^2 obtained for the equations a) and b) shows an overall good fitting of 0.89 for a) and 0.95 for b). This indicates that the results for the CC category can be calculated by the simplified equations by substituting only 1 parameter and still obtaining a results which fit with the reference results (blue curve c) and d) in Figure 4) with a significant high confidence. It is important to highlight that such simplified equation must be applied only to those cases where the range of applicability is the same. The so called "range of applicability" is defined by the ranges of the defined variables as described in Table 2 and by the model characteristics.

a) $$\frac{1.21 * coal_{share} + 0.229}{coal_{share} + 0.838}$$

b) $$\frac{1.21 * coal_{share} + 0.0841 * pv_{share} + 0.217}{coal_{share} + pv_{share} + 0.7}$$

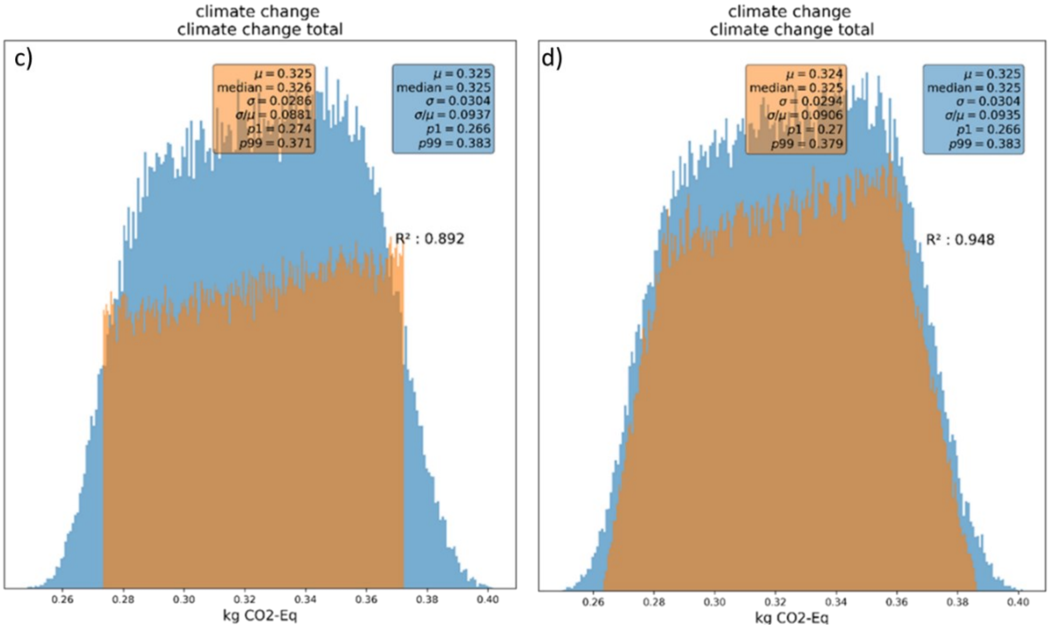


Fig 4. Simplified equations a) and b) obtained selecting different minimum explained variance cut-off (0.8 a) and 0.9 b)) and statistical distribution c) and d) of the simplified model a) and b) (orange) against the detailed one (blue) obtained with 100000 iterations

3.1.4 Conclusions

In this paper we have applied the combination of Brightway2 framework and lca – algebraic library to evaluate the environmental profile variability connected to the planned energy transition, as foreseen by the INECP. The power of the tool was demonstrated by identifying the most influencing parameters with the highest capability of describing the variance. Furthermore, we have shown how the impacts can be determined with relatively high confidence by a set of simplified equations.

Besides the numerical results of the case study used in this work as an example; the application of the tool Brightway has shown that:

- The efforts needed for Python coding is extensively paid back thanks to result’s meaningfulness.
- Complex systems that use several parameters can be simplified while maintaining a satisfying level of precision of the results.
- The development of good simplified models can reduce data gathering to only those parameters describing most of the variance.

Once that a model has been created the derived equation can be applied, to a certain extent, to all those similar systems that fall within the applicability domain of the modelled system. This option is particularly interesting for the energy sector since often, the production of energy from a given renewable source (i.e. wind, solar or biomass) is based on similar technology but different conditions (i.e. wind speed, solar radiation, biomass chemical composition).

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3.2 Parametric simplified models for the environmental evaluation of two geothermal power plants with different production technologies

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Article to be submitted

3.2.1 Introduction

Geothermal energy is a promising renewable energy source for electricity production and heating and cooling applications (IRENA, 2018). Like many of its renewable counterparts, the production of electricity and heat from the extraction of the geothermal energy implies less environmental impacts than the production from fossil fuels (Bayer et al., 2013; Marchand et al., 2015). The environmental impacts of the production of geothermal energy occur throughout the entire life cycle of the installation, and not mainly during the use phase as for fossil fuels. In addition, the environmental impacts go beyond greenhouse gas emissions (GHG) so that a holistic and multicriteria approach is essential to robustly assess the environmental impacts of the production of geothermal energy (Frick et al., 2010; Lacirignola and Blanc, 2013).

Life Cycle Assessment (LCA) is a standardised tool used to quantify various environmental impacts of a technology or product throughout its entire life cycle (ISO 14040, 2006). LCA can provide very valuable information to ease decision making processes whenever, for example, different energy-producing alternatives are compared. Despite the advantages of being standardised, holistic, multicriteria, and widely accepted, LCA suffers from a lack of guidance when applied to specific sectors and, in particular, energy pathways. When conducting an LCA, the user is faced with a lot of choices that can affect the final results. In fact, in the case of geothermal power plants, Eberle et al., (2017) showed that published life cycle GHG emissions for electricity production can vary from 20 g CO_2-eq/kWh to up to 75 g CO_2-eq/kWh for enhanced geothermal systems (EGS), between 20 and nearly 250 g CO_2-eq/kWh for hydrothermal flash plants, and between 5.7 and nearly 100 g CO_2-eq/kWh for binary hydrothermal plants. Ideally, the expert conducting an LCA should be aware of the consequences of methodological choices on the variability of environmental impact results.

The latter also depends on the life cycle data inventory built for the analysis, which generally implies an extensive and time-consuming data-gathering exercise.

Regulations increasingly recommend the use of integrated environmental impact assessment tools to support the decision-making process when comparing different energy pathways (European Commission, 2016; European Parliament, 2014; Ministère de l'Environnement, de l'Energie, et de la Mer, 2016). To support these recommendations, methodological guidelines specific to geothermal installations have been proposed to provide LCA experts with methodological indications and assistance on how to perform LCAs of geothermal installations (Blanc et al., 2020).

However, given the difficulty conducting an LCA might represent for non-LCA experts, the development of novel processes to satisfy the need for reliable and integrated decision-making tools while keeping the necessary effort limited is increasingly required.

Simplified models are an example of such tools, and within GEOENVI such simplified models have been developed for a selection of geothermal installation categories. A simplified model is meant to estimate the environmental impact of an installation from a limited number of independent input variable parameters. A simplified model is specific for an environmental impact category. It is generated following a protocol to convert a reference LCA model into a range of models relying only on a limited number of key variable parameters, which influence the environmental impact the most. This protocol uses Global Sensitivity Analysis (GSA) to identify these key variable parameters, as already explored for wind turbines (Padey et al., 2013) and EGS plants generating electricity (Lacirignola et al., 2015). The resulting simplified models are more quickly and easily applied to estimate the environmental impacts for a specific category of technological installation compared to conducting a comprehensive LCA study. However, these simplified models are specific to the category of installation they are obtained for, and their applicability domains need to be carefully reported and understood for correct use.

3.2.2 Material and methods

The objective is to develop simplified models to assess the environmental impacts of two different geothermal installations: (1) geothermal flash power plant producing electricity and a limited amount of heat, and (2) for a heat production plant including a small ORC unit producing electricity for self-consumption with very low emissions. These models are developed following a protocol initially developed for wind turbines (Padey et al., 2013) and an EGS plant generating electricity (Lacirignola et al., 2015), and generalised for a wider range of geothermal installations. The simplified models developed to correspond to seven impact categories of ILCD 2018, namely: climate change total, freshwater ecotoxicity, freshwater and terrestrial acidification, mineral and metal resource depletion, fossil resource depletion, human non-carcinogenic effects, and human carcinogenic effects. These categories are classified as high-priority categories by Blanc et al., 2020.

3.2.2.1 Description of the categories of geothermal installations

The categories of geothermal installations were chosen to represent the state-of-the-art of some of the current geothermal installations. They cover heat and electricity production, and power plant data were gathered directly from the plant operators. Rocco et al., (2020) published a report, titled 'Geothermal plants' and applications' emissions: overview and analysis', with the aim to provide a consistent and harmonised life cycle based assessment of the release of air pollutants in the deep geothermal sector in Europe for different clusters, representative groups of different geothermal installations. This implied the gathering of plant-specific data from numerous geothermal installations to derive equations for the quantification of some inventory flows, also applied in the reference LCA model presented in this report. The categorisation of the geothermal installation analysed here is consistent with the published clusters to align with these harmonisation efforts (Table 1). More details for each category are provided in the following chapters.

Table 1 – Description of the categories of geothermal installations analysed to generate the reference LCA models from which simplified models are derived. RGS stands for Representative Geothermal System.

	Flash	HeatORC
RGS	Bagnore (IT)	Balmatt (BE)
Installed capacity of the RGS	61 MWe 21.1 MWth	6.6 MWth 0.25 MWe
Geothermal source type	Vapour	Liquid
Production technology	Self-Flowing	Downhole pumps
Power/Heat generation unit	Flash steam plant	Binary / Heat exchanger

Cooling system	Wet cooling tower	Air cooling tower
Gas control system	NCG abatement system	None
Stimulation	None	Chemical
Final energy use	Electricity + Industrial heat	Heat (+ Electricity for self-consumption)
Cluster in (Rocco et al., 2020)	3P CHP	7P CHP

3.2.2.2 The methods used to generate simplified models

The generation of the simplified models relies on the five following steps.

Step 1: Definition of the scope of the study

First, the category of geothermal installation analysed should be precisely described, hence, describing the range of application of the models. The category of geothermal installation is defined with the support of a representative geothermal system (RGS). The criteria used to classify the RGSs is based on

- energy output (heat or electricity)
- type of conversion technology (dry steam, flash, binary, direct heat…)
- the level of direct emissions (low or high)
- if there is or not a Non-Condensable Gas abatement system

In addition, the chosen functional unit and the system boundaries should be stated individually for each RGS.

Step 2a: Modelling of the reference LCA model

A computational structure based on a parametrisation of the life cycle model is designed to estimate the life cycle impacts according to a set of *N* independent input variable parameters. Such detailed description is referred to as “the reference LCA model” and represents the category of geothermal installation defined in step 1. The validity range for each input variable parameter, as well as its probability distribution, results from the best technical knowledge related to the selected geothermal installation category. Once the reference LCA model is defined, a set of results, based on the variable parameters defined, are generated stochastically through Monte Carlo simulations.

Step 2b: Validation of the reference LCA model with literature

The results of Monte Carlo simulations are compared with published LCA studies as a step of validation for the reference LCA model.

Step 3: Statistical process to identify the key input variable parameters for each impact category

Key variable parameters are defined for each impact indicator. These variable parameters are those able to explain most of the variance over the range of application of the reference LCA model. This step is undertaken by performing a Global Statistical Analysis (GSA) and calculating the Sobol' indices (Saltelli, 2008). The open-source libraries Brightway2 (Mutel, 2017) and lca_algebraic v11.0 (Jolivet, 2020) are of great help to fulfil this task in the Python language. The key input variable parameters are chosen from a trade-off between selecting only a limited number (<10) of easily determined variable parameters for users, and covering a sufficient share of the variance of the considered impact indicator.

Step 4a: Generation of the simplified model per impact category

Each simplified model is generated using the selection of key variable parameters selected in step 3 as input parameters. The level of fitting of each simplified model against the reference model is assessed with the R-squared (R^2), a statistical measure that quantifies to what extent the variance of one output explains the variance of the second output (Equation (1)).

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

Where n represents the sample population, y_i the value obtained with the reference LCA model, $\widehat{y_i}$ the value obtained with the simplified model, and $\bar{y}$ the mean of all obtained values with the reference LCA model.

Step 4b: Validation of the simplified models with literature

Finally, the results of the simplified models are compared with the published literature, which might be the one already identified in Step 2. For each relevant literature case study, the values for the key variable parameters required to run the simplified models are identified.

1. The simplified model is then run with this specific set of values for the key variable parameters.
2. A final comparison is made between the literature case study and the simplified model outcome for the exact same configurations as defined by the key variable parameters.

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

An additional step might be necessary for the protocol if the results from the previous step (Step 4) are not fully satisfactory. An adjustment of the definition of the applicability domain might be required and would imply to redefine the scope of the reference LCA model with either the parametrisation scheme, the set of variable parameters or the range of validity for some variable parameters. After completing this possible adjustment, the final applicability domain of the simplified models should be summarised

3.2.3 Results and discussion

In the following paragraph, the results of the application of the described method are shown for 2 case studies. The first one represents the Flash power plant category, built starting from Bagnore as reference model; the other one refers to the category of power plants producing only heat for space heating purposes and also exploiting a small ORC for electricity self-consumption, the RGS is the Balmatt plant.

The results are reported and described following point-by-point the general protocol explained above.

3.2.3.1 Simplified models generation for the Flash category

This chapter presents the simplified models developed to assess the life cycle environmental impacts of the geothermal installations of category Flash, built on the RGS of Bagnore. The results are presented following the steps of the protocol presented in the "Protocol to generate simplified models for a category of geothermal installation".

3.2.3.1.1 Scope of the study

The geothermal system of Bagnore is a flash type geothermal power plants whose primary scope is the production of electricity. The plants also produce heat which is delivered through a heat transfer network for industrial uses. The analysed system is located in southern Tuscany, Italy, in the Monte Amiata area (Figure 1).

Figure 1 – Aerial picture of the Bagnore geothermal system

The Bagnore geothermal system is composed of two different power plants, namely Bagnore 3 and Bagnore 4, which share the production and reinjection wells. The total installed power is 61 MWe, 21 MWe for Bagnore 3 (20 MWe flash + 1 MWe Organic Rankine Cycle) and 40MWe for Bagnore 4 (2 X 20MWe flash). The annual production is about 533 GWh/y. The power plant is also designed with thermal power of 21.1 MWth, which can deliver 32 GWh/y for industrial purposes.

The geothermal source is a high enthalpy source presenting a content of non-condensable gases (NCGs) of about 7% in mass. The main NCGs component is CO_2 (6.7 % over the total geothermal flow rate). The temperature of the geothermal source at the wellhead is about 210 °C with a specific enthalpy of 2,800 J/kg.

The power plant was built by ENEL Green Power in the late ’90s and has been operating ever since by employing the latest advancements in the field of environment protection and performance optimisation. Thus, the system is an excellent candidate to represent well the category of flash power plants for electricity production. The reference LCA model developed for the Bagnore geothermal system represents the category of a geothermal flash power plant producing electricity and a limited amount of heat, exploiting a geothermal source presenting moderate to a high content of NCGs with CO_2 as the main component.

The functional unit of the reference model is the production of 1 kWh of electricity delivered to the high voltage distribution network. The model is divided into Upstream (background data) and Core module (foreground data). The activities of the upstream module are taken from the Ecoinvent database v3.6. The core module includes the construction of the infrastructures, the operation and maintenance of the installation, and end of life activities. Figure 2 gives an overview of the different life cycle stages included in the reference LCA model for the described case study.

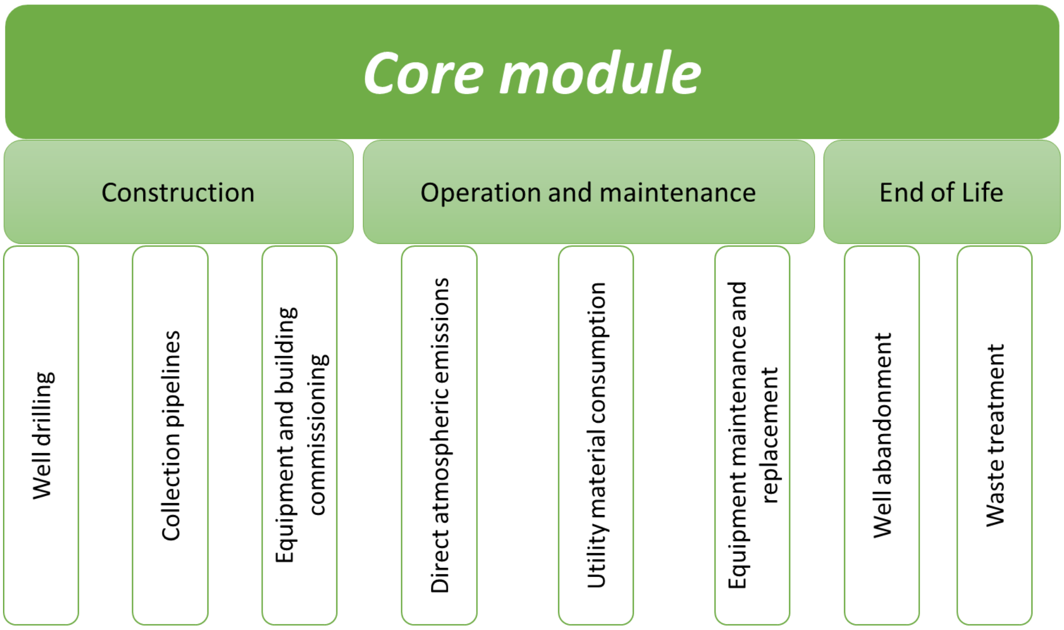


Figure 2 – Phases of the core module included in the modelling of the reference LCA model for Flash.

Following the indications reported in the guidelines (Blanc et al., 2020), the background processes are selected assigning higher priority to the proper geographic location (IT>EU>World). Market processes are preferred to include also standardised transportation distances.

3.2.3.1.2 Modelling of the reference LCA model

3.2.3.1.2.1 Construction phase

Well Drilling

The well drilling process is performed by diesel-fuelled drilling rigs, making the amount of diesel used by the drilling process an important flow. The drilling mud and cuttings produced during the well drilling represent an important inventory flows as well, due to the disposal activity related to the latter. Steel and cement are used for the casing and well’s platform construction. All these inventory flows were estimated from the equations provided in (Rocco et al., 2020) using the meters drilled (l) as an input variable parameter. These equations are listed in A1. The described drilling process is the same during maintenance activities in case make-up wells, meaning wells added to recover the productivity lost over the years, are needed.

Collection Pipelines

Geothermal flash power plants usually employ a considerable number of wells to drive the turbines compared to other geothermal technologies. As a result, the collection pipelines used to flow the geothermal fluid to the power plant consist of several thousand meters of insulated steel pipe. Therefore, this process should be considered important for LCA modelling because of the significant amount of material and energy required for earthwork.

The length of the pipelines needed is assumed to be proportional to the number of wells of the system. Equation (12) has been used to derived the pipelines' length.

$$PipelineLength\ (m) = 512 * WellsNumber + 3232 \qquad (12)$$

More pipelines can be added to the system depending on the number of make-up wells drilled.

Equipment and building commissioning

The building housing, electrical and hydraulic systems relative to internal uses (e.g. first flush diverter, electronic management system, etc) employed in the construction of a geothermal flash power plant are modelled based on primary data provided by the operator and scaled to installed power following expert's advice. The building is a hangar holding the equipment's (turbine, condenser, compressor, electric generator) and the employer's settings. The amount of energy and material is scaled on the installed capacity as shown in Equation (13).

$$Building = 1.9 \cdot 10^{-5} * ElecCapacity + 0.24 \qquad (13)$$

The equipment of the power plant is modelled as a single flash power plant with abatement system for Hydrogen Sulphide and Mercury (AMIS) with the main components being:

- Direct contact steam turbine

- Direct contact condenser
- Gas compressor for NCSs extraction
- Gas intercooler
- AMIS system (H_2S to SO_2 catalytic reactor, Hg adsorbent, SO_2 scrubber)
- Atmospheric cooling tower
- Electric generator

The inventory is constituted for the major part by steel for machinery, while the electric generator is also constituted by copper and the cooling tower by plastic. The AMIS, in addition to steel, makes use of titanium dioxide as a catalyser for the H_2S reactor and selenium used to adsorb mercury

3.2.3.1.2.2 Operation and maintenance

Direct atmospheric emissions

Flash geothermal power plants are characterised by direct atmospheric emissions connected to the operational phase due to the direct use of geothermal brine. The fluid exploited contains a typical amount of dissolved gases which are extracted from the geothermal fluid to ensure the operativity of the power plant and then emitted into the atmosphere.

Direct atmospheric emissions are strictly related to the gas fraction and composition of the geothermal source exploited. In the case of Bagnore, gas fraction in mass is 7% average, and it is constituted by 92% of CO_2

The functions used to derive the mass of gases emitted are taken from (Rocco et al., 2020) and use the amount of NCGs ($fNCGs$) present in the geothermal fluid, the relative fraction of a specific gas (f_{NCG}) and the typical flowrate ($FlowRate$) (Equation (14)).

$$M_{NCG} = fNCGs * FlowRate * f_{NCG} \tag{14}$$

Some operators also implement systems able to reduce these direct emissions. In this case study, the system employed is called AMIS, and it is designed to abate the gaseous emissions of selected compounds, H_2S and Hg. The hydrogen sulphide is oxidised through a catalytic oxidation reaction into a fixed bed reactor supporting titanium dioxide. This process produces SO_2. The gaseous mercury is adsorbed into a selenium filter. The obtained mercury selenide

(HgSe) is a very stable compound which is disposed of as hazardous waste by specialised companies. At the end of the process a washing column avoids the direct emissions of SO_2, by letting the basic pH circulating geothermal water to react with SO_2 and to dissolve it into water. The abatement of the AMIS system is implemented in the model deducing the relative amount of gases from the atmospheric emissions through the relative abatement ratio ($H_2SAbatemenRatio$ and $HgAbatementRatio$).

Utility consumption

The operational stage is also characterised by the consumption of energy from the auxiliary's equipment, such as the reinjection pumps or the evaporative towers' fans. The reference model built for this case study accounts for energy consumption only in terms of internal loss, meaning that no needs for electricity from the national network is considered. The internal loss is integrated into the calculation of electricity production.

Equipment maintenance and replacement

The maintenance activities taken into account are all the most critical planned periodic services; these include turbine refurbishment. In detail, 10% of rotor weight loss every 4 years is assumed. The steel lost is integrated by new steel. The same assumption is made for the rotor compressor. The evaporative tower maintenance is also planned every 4 years; the substitution of steel and plastic parts is accomplished.

The modelled system is equipped with 2 systems devoted to reducing direct atmospheric emissions, employing the AMIS (reduction of H_2S and Hg emissions) and though acidification of the circulating fluids (reduction of NH_3 emissions). These processes have a specific material consumption: the AMIS employs selenium sorbent to reduce the amount of Hg released to the atmosphere, and it is replaced every 4 years to maintain a good performance; the acidification of circulating fluid is accomplished by dosing H_2SO_4 to the fluid which circulate into the power plant so to keep the geofluid between a specific pH range thus avoiding stripping of NH_3.

3.2.3.1.2.3 End of life

Waste treatment

Waste treatment processes are used, according to (Blanc et al., 2020), for the waste treatment from drilling activities and disposal of selenium sorbent from the AMIS maintenance.

The disposal of drilling cuttings is modelled accordingly to the appropriate Ecoinvent v3.6 process, while the spent selenium sorbent is treated as hazardous waste and modelled by using the relative landfilling Ecoinvent activity.

Well abandonment

At the end of the service life of the system, a well abandonment program is foreseen. This program consists of the closure of all the wells drilled during the lifetime. The process is characterised by the use of diesel in engines and cement use.

3.2.3.1.2.4 Functional unit definition

Electricity production

The electricity production is the main purpose of the system and represents more than 75% of the total power output. Therefore electricity production is the functional unit of this system.

The amount of energy produced is derived from equation (15):

$$KWh_e = AVGLoad * ElecCapacity * OperatingHours * (1 - AuxNeed) \tag{15}$$

Heat production

The power plant can deliver heat, through a small heat delivery network, to closely production activities. Following the guidelines, the quantity of energy delivered to the final user is accounted for by employing system expansion and considering the avoided product approach (Blanc et al., 2020). In the model, the heat is used for industrial purpose, the right process is selected in the Ecoinvent database.

$$KW_{th} = HeatCapacity * HeatLoad * OperatingHours \tag{16}$$

3.2.3.1.2.5 Summary of variable parameters

Table 2 – Summary of all the variable parameters of the reference LCA model for Flash, together with boundaries of the uniform distribution which are used to describe a more comprehensive set of geothermal power plants. Default values represent the values for the Bagnore power plant. All the variable parameters were modelled following a uniform distribution between the minimum and maximum value which describe a more comprehensive set of geothermal power plants, therefore are not linked to the case study investigated.

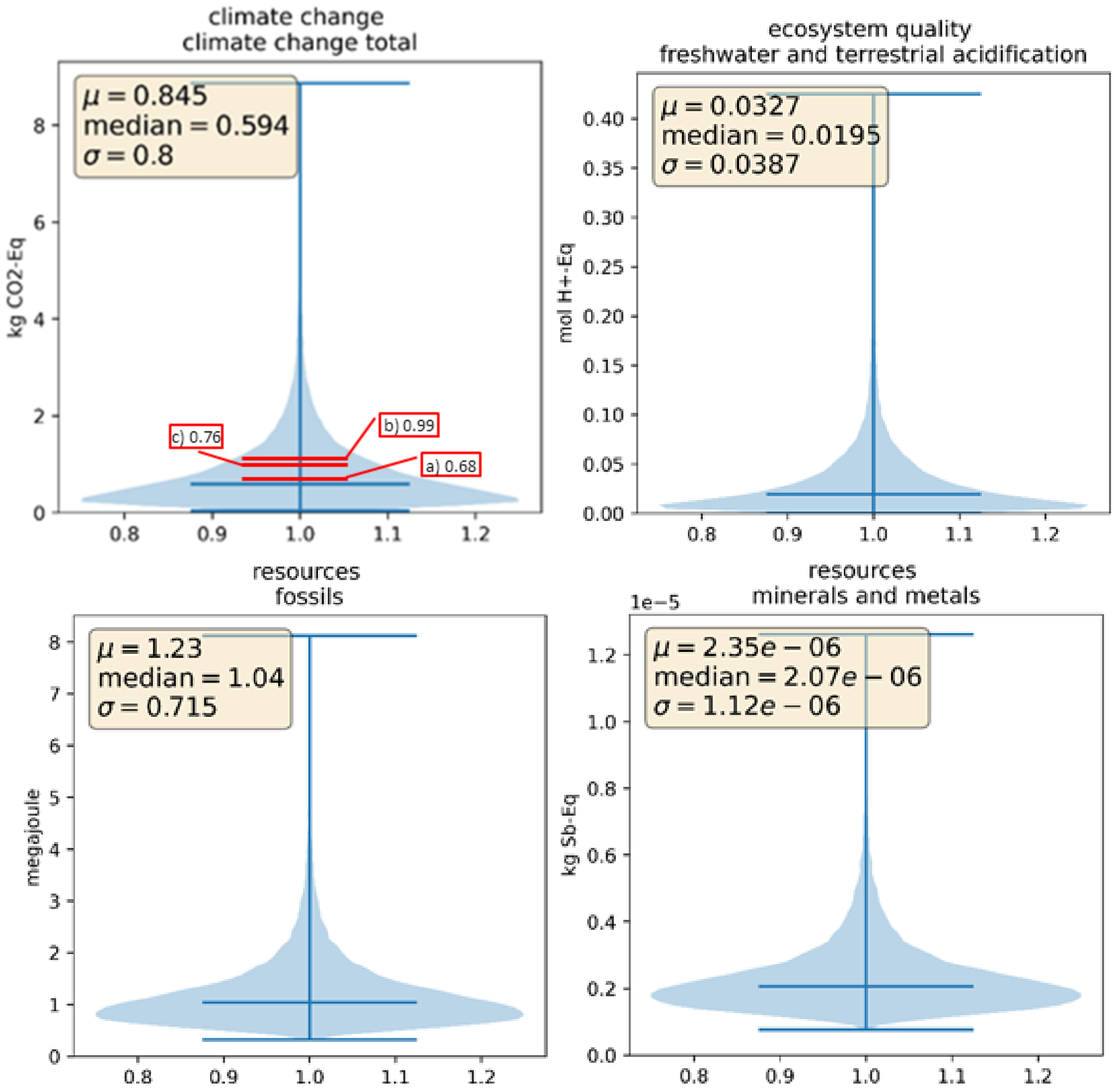
Table 2 – Summary of all the variable parameters of the reference LCA model for Flash, together with boundaries of the uniform distribution which are used to describe a wider set of geothermal power plants. Default values represent the values for the Bagnore power plant.

Label	Param	Default	min	max	unit
Average length for one well	l	2,273	586	4,727	meters
Average yearly operating hours	OperatingHours	8,670	7,600	8,760	hours
Yearly out of service hours of the AMIS abatement system	AMISOutOfServiceHours	226	17	457	hours
Abatement efficiency for Hg	HgAbatementRatio	0.98	0.7	0.99	ratio

Abatement efficiency for H2S	H2SAbatementRatio	0.99	0.7	0.99	ratio
Abatement efficiency for CO2	CO2AbatementRatio	0	0	0.25	ratio
Abatement efficiency for NH3	NH3AbatementRatio	0.9	0.75	0.95	ratio
Previsioned lifetime of the system	LifeTime	30	20	40	years
Maintenance interval time for periodic maintenance operations	MaintenancePeriod	4	2	6	years
Average load of the power plant	AVGLoad	0.99	0.8	1.1	ratio
Percentage of energy absorption from auxiliaries	AuxNeed	0.02	0.01	0.1	ratio
Ratio of make-up wells drilled yearly	MakeUpWellsRatio	0	0	0.76	items
Flow rate of the geofluid at the power plant inlet	FlowRate	400,000	110,000	1.00E+06	kg/h
Electric power installed	ElecCapacity	60,000	20,000	120,000	kWe
Heat power installed	HeatCapacity	21,100	0	21,100	kWth
Average load for heat production	HeatLoad	0.17	0	0.25	ratio
Numbers of wells drilled in the commissioning phase	WellsNumber	14	4	26	items
Mass fraction of NCGs in the geofluid	fNCG	0.07	0.006	0.12	ratio
Relative fraction of CO2 in the geofluid	fCO2	0.92	0.58	0.92	ratio
Relative fraction of CO in the geofluid	fCO	0.000368	0.0003	0.0004	ratio
Relative fraction of CH4 in the geofluid	fCH4	0.025	0.002	0.025	ratio
Relative fraction of H2S in the geofluid	fH2S	0.017868	0.0013	0.054	ratio
Relative fraction of NH3 in the geofluid	fNH3	0.028348	0.0012	0.032	ratio
Relative fraction of Hg in the geofluid	fHg	1.80E-05	9.00E-06	3.00E-05	ratio

3.2.3.1.3 Validation of the reference LCA model with literature

Results published in the literature were selected to evaluate the representativeness of the reference model's results. The applied procedure adapts the reference LCA model to the literature cases by varying the right parameters, and therefore it is possible to use data coming from several power plants on the same model. The results reported in (Bravi and Basosi, 2014; Parisi et al., 2019; Tosti et al., 2020) were used for comparison. The characterised results reported in the selected papers are integrated into the violin graph obtained from the Monte Carlo analysis of the reference model and displayed in Figure 3. Overall, the results for climate change published in the three studies and the results obtained from the reference LCA model show a good overlap.


climate change
climate change total
$\mu = 0.845$
$\text{median} = 0.594$
$\sigma = 0.8$
kg CO2-Eq
c) 0.76
b) 0.99
a) 0.68
0
2
4
6
8
0.8
0.9
1.0
1.1
1.2
ecosystem quality
freshwater and terrestrial acidification
$\mu = 0.0327$
$\text{median} = 0.0195$
$\sigma = 0.0387$
mol H+-Eq
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
resources
fossils
$\mu = 1.23$
$\text{median} = 1.04$
$\sigma = 0.715$
megajoule
0
1
2
3
4
5
6
7
8
resources
minerals and metals
1e−5
$\mu = 2.35e-06$
$\text{median} = 2.07e-06$
$\sigma = 1.12e-06$
kg Sb-Eq
0.0
0.2
0.4
0.6
0.8
1.0
1.2

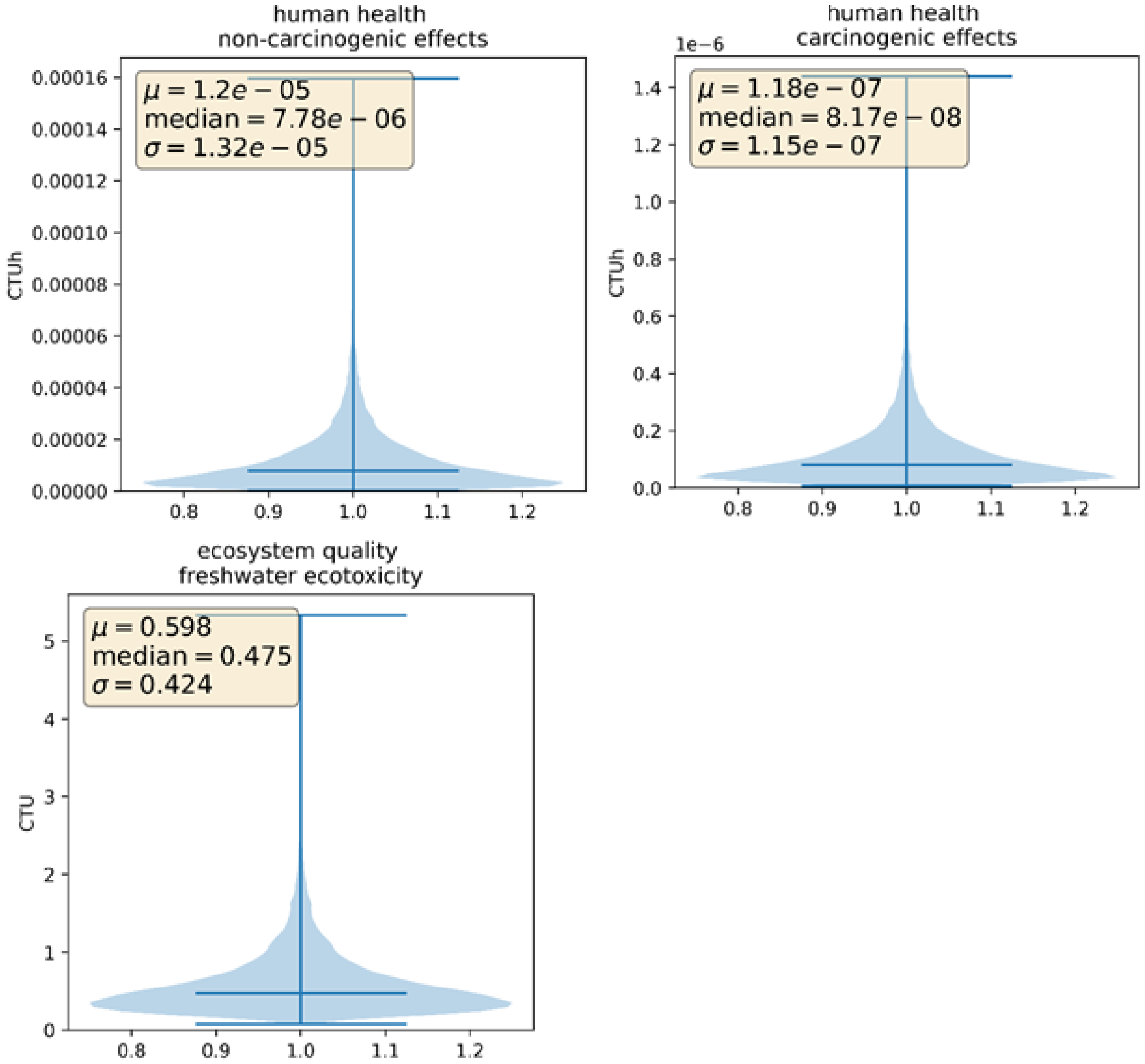


Figure 3 – Violin plot reporting the statistical distribution obtained after the Monte Carlo analysis of the reference LCA model for Flash taking into account the definition of the parameter of the reference model. Lines correspond to 95th, median and 5th percentile, while the light blue shape shows the probability density. a) stands for the results published in (Bravi and Basosi, 2014), b) (Parisi et al., 2019), and c) (Tosti et al., 2020).

3.2.3.1.4 Statistical process to identify the key input variable parameters for each impact category

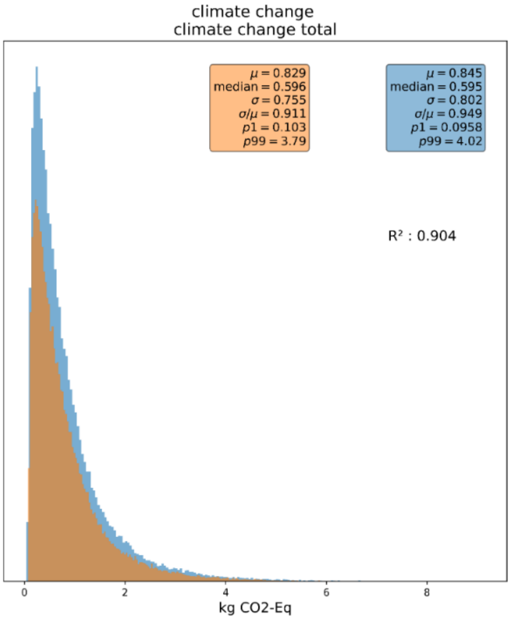
Using the first-order Sobol indices, different variable parameters were selected as key input variable parameters for the different simplified models due to their ability to explain a large portion of the reference model variance. These key variable parameters are:

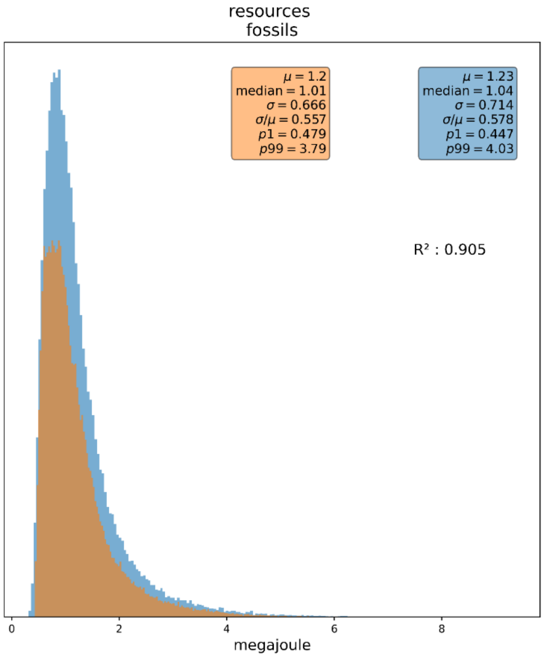
- **Elec capacity**
- **fNCG**
- **FlowRate**
- **fNH3**
- **make-up wells ratio**
- **l (average lengths of the well)**

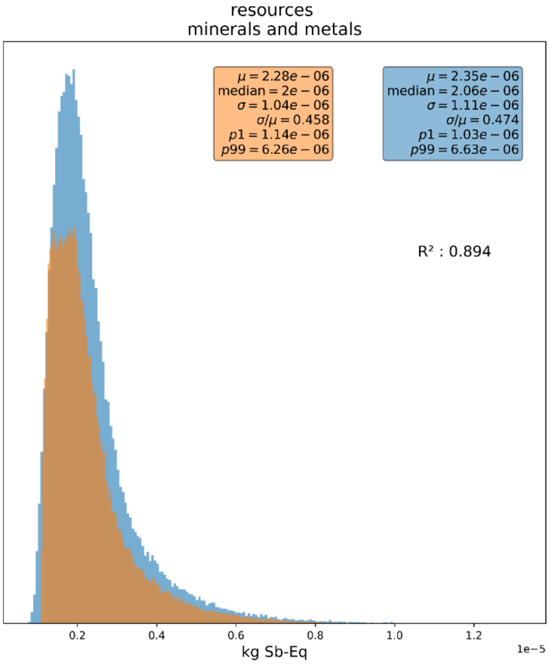
These six variable parameters explain above 80% of the total variance of all seven impact categories of interest. The choice of the key variable parameters was a trade-off between the ease with which they could be obtained, the covered variability, and the ease of application of the model. Some variable parameters refer to the geochemical properties of the geothermal field *(fNCG*, *fNH3*) while the others are more technology-related (*Elec capacity*, *Flow Rate*, *make-up wells ratio* and *l*). For the simplified model, only three to four of the six variable parameters listed above are used.

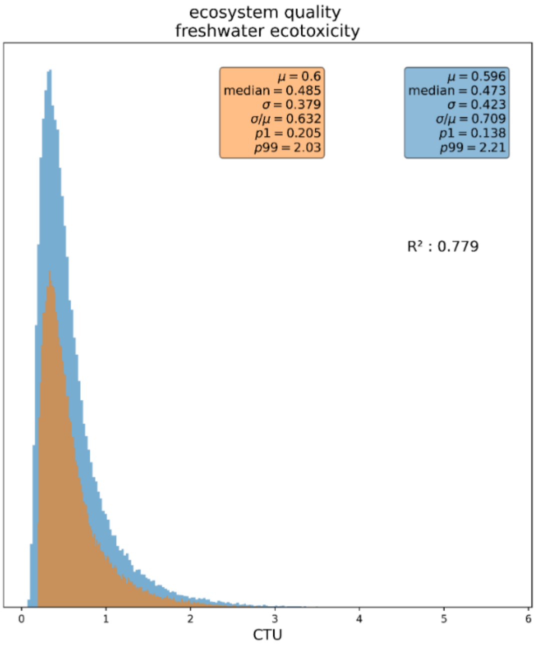
3.2.3.1.5 Generation of the simplified model per impact category

The performances of the seven simplified models are shown in Figure 4 – Performance of the reference LCA model for Flash compared to the simplified models derived for the seven ILCD 2018 impact categories of interest. Blue represents the distribution of the reference LCA model results and orange of the simplified models. The level of the fitting is evaluated by means of the R^2. The equations each model is relying on are provided in the following paragraphs.


climate change
climate change total
μ = 0.829
median = 0.596
σ = 0.755
σ/μ = 0.911
p1 = 0.103
p99 = 3.79
μ = 0.845
median = 0.595
σ = 0.802
σ/μ = 0.949
p1 = 0.0958
p99 = 4.02
R² : 0.904
0
2
4
6
8
kg CO2-Eq


resources
fossils
μ = 1.2
median = 1.01
σ = 0.666
σ/μ = 0.557
p1 = 0.479
p99 = 3.79
μ = 1.23
median = 1.04
σ = 0.714
σ/μ = 0.578
p1 = 0.447
p99 = 4.03
R² : 0.905
0
2
4
6
8
megajoule


resources
minerals and metals
μ = 2.28e − 06
median = 2e − 06
σ = 1.04e − 06
σ/μ = 0.458
p1 = 1.14e − 06
p99 = 6.26e − 06
μ = 2.35e − 06
median = 2.06e − 06
σ = 1.11e − 06
σ/μ = 0.474
p1 = 1.03e − 06
p99 = 6.63e − 06
R² : 0.894
0.2
0.4
0.6
0.8
1.0
1.2
1e−5
kg Sb-Eq


ecosystem quality
freshwater ecotoxicity
μ = 0.6
median = 0.485
σ = 0.379
σ/μ = 0.632
p1 = 0.205
p99 = 2.03
μ = 0.596
median = 0.473
σ = 0.423
σ/μ = 0.709
p1 = 0.138
p99 = 2.21
R² : 0.779
0
1
2
3
4
5
6
CTU

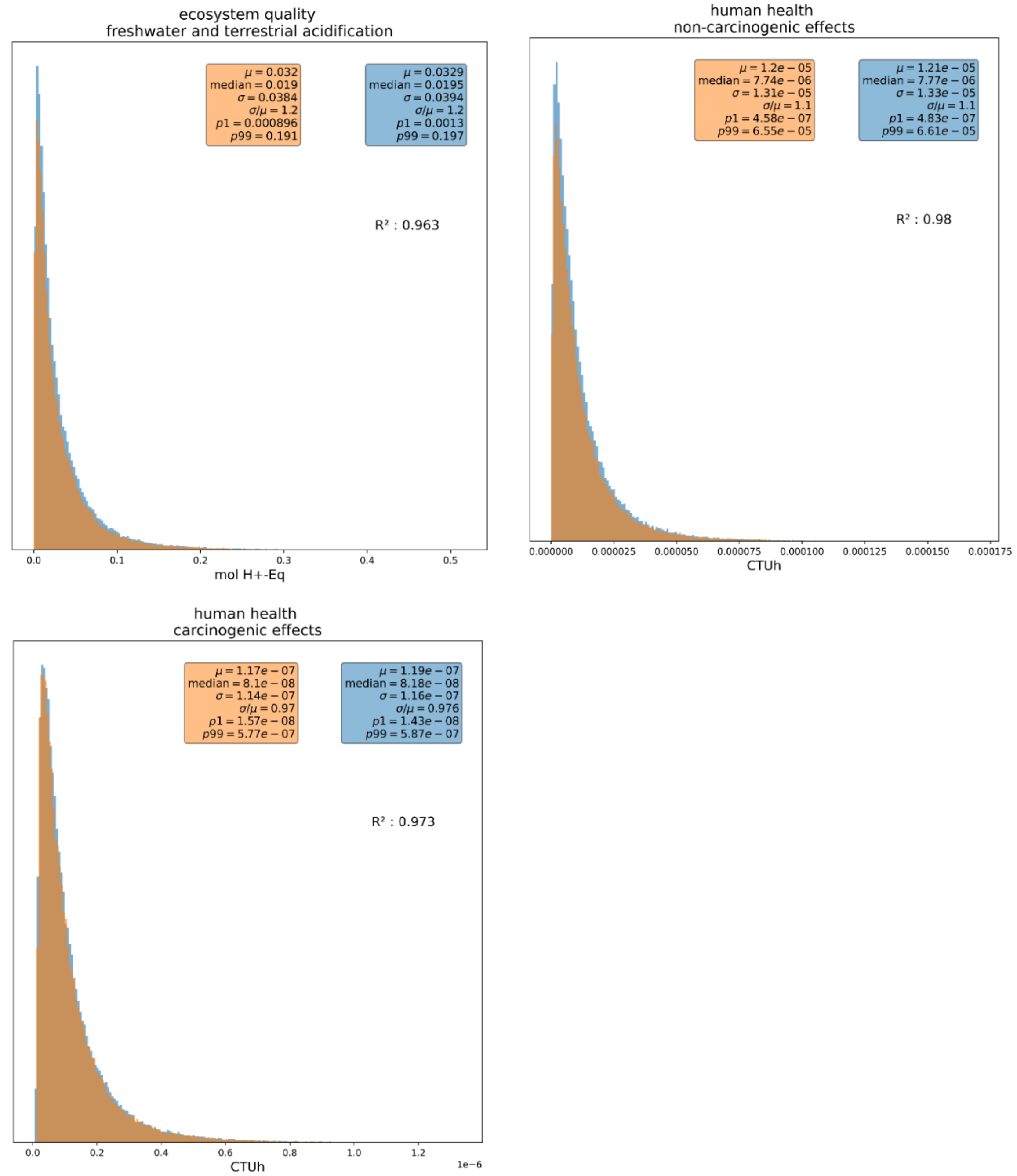


Figure 4 – Performance of the reference LCA model for Flash compared to the simplified models derived for the seven ILCD 2018 impact categories of interest. Blue represents the distribution of the reference LCA model results and orange of the simplified models.

3.2.3.1.6 Validation of the simplified models with literature

The validation of the simplified models is performed using the equation obtained for the Climate Change impact category (A2), and the works of (Tosti et al., 2020) and Buonocore et al., (2015) were selected to tests the simplified model for climate change impact category. Tosti et al., (2020) report results based on the same power plant of the reference model, while Buonocore et al., (2015) rely on a different system of dry steam type installed in Italy but currently not operating. The input variable parameters used in the simplified model for climate change and the results of the comparison are reported in Table 3.

Table 3 – Comparison of results on Climate Change (CC) impact category considering two different case studies, (Tosti et al., 2020) and (Buonocore et al., 2015)

Variable Parameter	(Tosti et al., 2020)	(Buonocore et al., 2015)
ElecCapacity (kWe)	61,000	20,000
FlowRate (kg/h)	400,000	80,000
fNCG	0.08	0.06
CC simplified model (KgCO2eq/kWe)	*0.71*	*0.51*
CC literature (KgCO2eq/kWe)	*0.63*	*0.24*

The results published in (Tosti et al., 2020) are in good agreement with the results obtained from the simplified model. The minor difference observed could be explained by the fact that a different impact assessment method is used. In detail, the ILCD 2018 reports higher characterisation factors than the ILCD 2011 Midpoint+ method v1.0.9 used by Tosti et al., (2020) for the Climate Change impact category. The same is observed when comparing to the results of (Buonocore et al., (2015). The larger difference is here related to the fact that Buonocore et al., (2015) used an older method than ILCD, namely the CML method.

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

The reference LCA model, and as a result, the simplified models developed for the seven impact categories, are designed for:

- Flash or dry steam power plant exploiting high enthalpy field
- Power plant producing only electricity or electricity and heat for industrial purposes. Heat must be less than 50% of the electricity produced
- The models are suitable for geothermal sources showing low to a high content of NGCs, the boundary of the gas composition is specified in Table 2
- Diesel power rig
- No electricity demand for auxiliaries taken from the electric network

3.2.3.1.8 Detailed results for the Flash category

Key variable parameters

Figure 5 displays the first-order Sobol indexes for the seven impact categories of interest and the 24 variable parameters included in the reference LCA model.

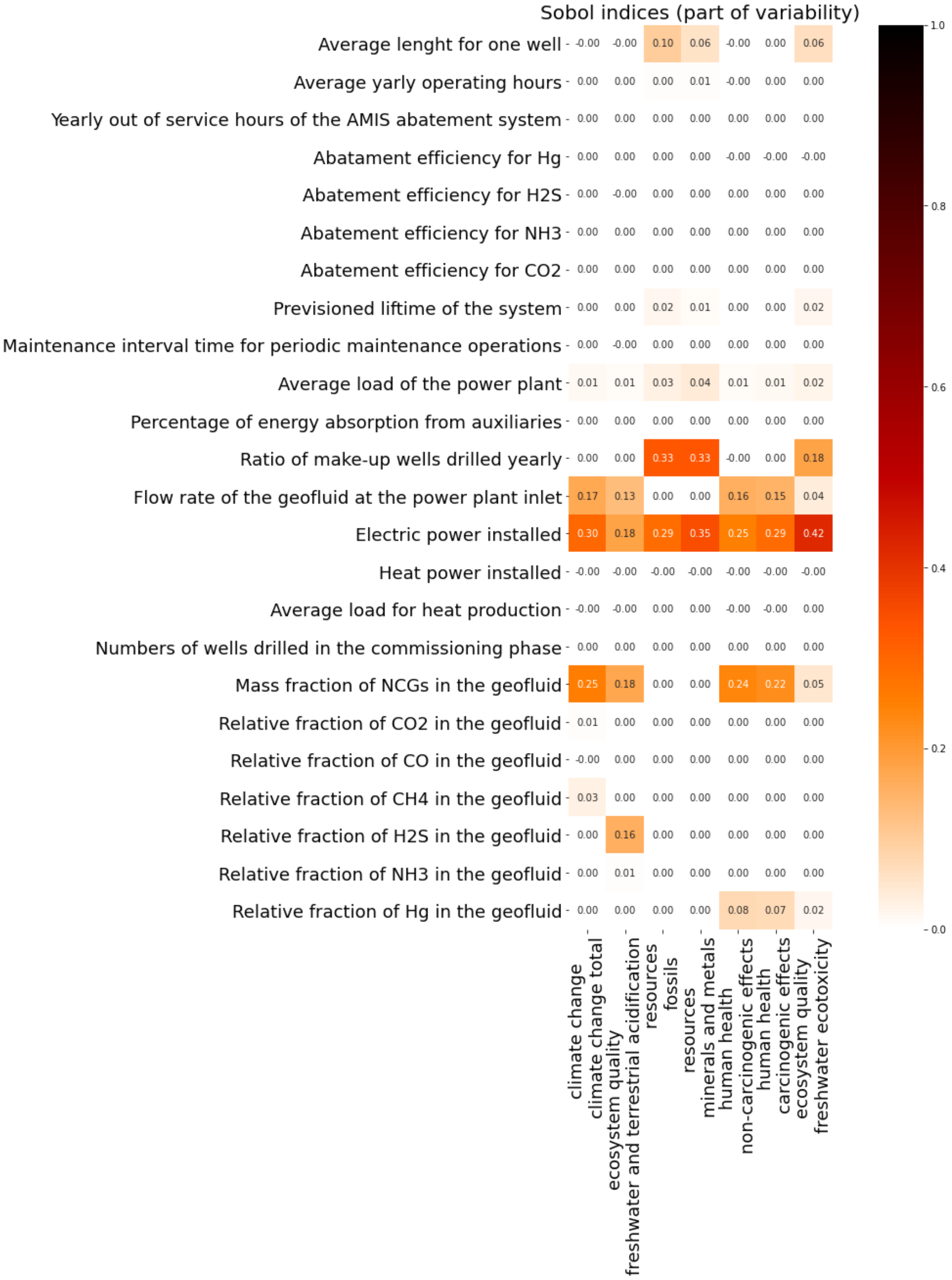


Figure 5 – First order Sobol indexes derived for the reference model for Flash

3.2.3.1.8.1 Simplified models

The equations for the simplified models for the Flash category are listed below per impact category.

Climate change, total

$$\frac{2.56 \cdot 10^{-7} \mathit{ElecCapacity}^2 + 1.18 * \mathit{FlowRate} * \mathit{fNCG} + 4.14 \cdot 10^3}{\mathit{ElecCapacity}} \tag{43}$$

Resources, fossil

$$\frac{\begin{gathered} 3.8 \cdot 10^{-6} \mathit{ElecCapacity}^2 + 0.0509 * \mathit{ElecCapacity} + \\ 4.73 * \mathit{MakeUpWellsRatio} * l + 3.54 * \mathit{MakeUpWellsRatio} * l^{1.2} + \\ 0.178 \mathit{MakeUpWellsRatio} * l^{1.23} + 4.03 \cdot 10^4 \mathit{MakeUpWellsRatio} + \\ 0.0582 * l^{1.2} + 9.29 \cdot 10^3 \end{gathered}}{\mathit{ElecCapacity}} \tag{44}$$

Resources, minerals

$$\frac{\begin{gathered} 6.4 \cdot 10^{-12} \mathit{ElecCapacity}^2 + 3.14 \cdot 10^{-7} \mathit{ElecCapacity} + \\ 7.5 \cdot 10^{-6} \mathit{MakeUpWellsRatio} * l + 3.95 \cdot 10^{-6} \mathit{MakeUpWellsRatio} * l^{1.2} + \\ 9.79 \cdot 10^{-8} \mathit{MakeUpWellsRatio} * l^{1.23} + 0.0885 \mathit{MakeUpWellsRatio} + \\ 6.7 \cdot 10^{-8} * l^{1.2} + 0.0223 \end{gathered}}{\mathit{ElecCapacity}} \tag{45}$$

Ecosystem quality – Freshwater ecotoxicity

$$\frac{\begin{gathered} 5.76 \cdot 10^{-7} \mathit{ElecCapacity}^2 + 0.0129 \mathit{ElecCapacity} + \\ 10.7 \mathit{MakeUpWellsRatio} * l + 0.342 \mathit{MakeUpWellsRatio} * l^{1.2} + \\ 1.37 \cdot 10^4 \mathit{MakeUpWellsRatio} + 0.174 * l + 1.24 \cdot 10^4 \end{gathered}}{\mathit{ElecCapacity}} \tag{46}$$

Ecosystem quality – Freshwater and terrestrial acidification

$$\frac{\mathit{FlowRate} * \mathit{fNCG} * (1.54 * \mathit{fH2S} + 0.00822)}{\mathit{ElecCapacity}} \tag{47}$$

Human health – Non-carcinogenic effects

$$\frac{0.978 * \mathit{FlowRate} * \mathit{fHg} * \mathit{fNCG}}{\mathit{ElecCapacity}} \tag{48}$$

Human health – Carcinogenic effects

$$\frac{4.14 \cdot 10^{-14} \mathit{ElecCapacity}^2 + 0.00827 * \mathit{FlowRate} * \mathit{fHg} * \mathit{fNCG} + 0.000731}{\mathit{ElecCapacity}} \tag{49}$$

3.2.3.2 Simplified models generation for the HeatORC category

This chapter presents the simplified models developed to assess the life cycle environmental impacts of the HeatORC category of geothermal installations, namely a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. The results are presented following the steps of the protocol presented in the "Protocol to generate simplified models for a category of geothermal installation".

3.2.3.2.1 Scope of the study

The category of geothermal installation analysed here is a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. The functional unit is the production of 1 kWh of heat delivered to a user. The system boundaries include both the upstream module – based on secondary data – and the core module – based on primary data and representing the construction of infrastructure, operation and maintenance phases of a geothermal energy conversion plant (system). The 2D seismic exploration campaign that took place prior to the first drilling is excluded from the study as no accurate data is available on the fuel consumption.

The geothermal heat plant of Balmatt serves as a basis for the development of the reference LCA model (Figure 6). Balmatt is a deep geothermal demonstration project in Mol, Belgium, started in 2009 by VITO. In 2015 – 2016, VITO drilled two deep geothermal wells (3,610 and 4,341 m) on its premises in Mol-Donk. The geothermal capacity installed mainly consists of thermal capacity (6.6 MW_{th}) and a smaller ORC demonstration electrical capacity (0.25 MW_e). Among others, the geothermal plant will include facilities for materials research (e.g. corrosion testing and development of coatings) and a bypass for testing heat exchanger or prototypes of innovative binary systems under real conditions. Moreover, both wells are accessible to test new stimulation and production techniques and equipment.

Figure 6 – Geothermal power plant of Balmatt (VITO)

The depth of the top of the fractured carboniferous limestone geothermal reservoir was encountered between 3,170 and 3,300 meters at the project location. An overview of the 2 operational wells (MOL-GT-01 and MOL-GT-02) and of the originally additional foreseen production well (MOL-GT-03) is given in Table 4.

Table 4 – Operational and foreseen production wells for the Balmatt power plant.

Type well	Reference	Depth	Date	Well treatment after drilling
1 production well	MOL-GT-01	3,610 m MD, 3,608 m TVD	January 2016	Chemical stimulation
1 injection well	MOL-GT-02	4,341m MD, 3,830m TVD	September 2016 Autumn 2018	Chemical stimulation
1 extra (production) well	MOL-GT-03	4,905m MD, 4,236 m TVD	July 2018	

Since the partial completion of the plant on 14th May 2019, it has operated for 16 days accumulatively, with a last joint period of 10 days. On Sunday 23rd June 2019, 2 days after terminating the longest operational period, an induced earthquake occurred close to the injection well MOL-GT-02 with a magnitude M=2.1. The Balmatt project team and partners are further investigating the data from the seismometer network to better characterise this event. During the testing phase, the production temperature observed ranged from 121 to 126 °C and the average production flowrate achieved was between 70 and 150 m^3/h provided by an Electrical Submersible Pump (ESP).

The geothermal brine is highly saline with TDS of about 165 g/L, mainly dominated by Na-(Ca)-Cl elements, with a Gas Liquid Ratio of 2.3 Nm^3/m^3. The gas consists mainly of CO_2 (~75 vol.%) and CH_4. Due to the high amount of dissolved gasses, surface installations are operated under a pressure of 40 bars to avoid degassing (NCG emissions), linked flashing and corrosion issues. Two heat exchangers with a total capacity of 6.6 MW transfer the geothermal heat to a secondary loop with fresh water. The brine is fully reinjected by the reinjection pump in the injection well MOL-GT-02.

Once in full operation, the plant will be used to supply 50 GWh/year:

- 50% for heat delivery (25,000 MWh_{th}): supply heat to an existing district heating network providing energy to VITO's research facilities, as well as facilities of SCK-CEN and Belgoprocess. There is a temperature regime of 95-70 °C.
- 50% for electricity production (10% efficiency: 2,500 MWh_e)

The amount of electricity consumed by the pumps is 3,300 MWh, so all produced electricity will be self-consumed.

3.2.3.2.2 Modelling of the reference LCA model

A reference LCA model was developed for the Balmatt geothermal plant. It aims at being representative for a heat production plant including a demonstration ORC producing electricity for self-consumption with very low emissions. The Balmatt geothermal heat plant is in many ways similar to the Rittershoffen case study but specific characteristics of geothermal plants in Belgium have been accounted for. The model follows mostly the recommendations of the guidelines for the life cycle assessment of geothermal energy systems (Blanc et al., 2020).

The chapters below describe the various life cycle stages in more detail. The reference model is based on the reference model of the Rittershoffen case study, as the plant characteristics are very similar. Therefore, the full model explanation is not repeated and only the differences with the Rittershoffen reference model are highlighted. For the default values of the variable parameters, specific data of the Balmatt plant is used. In addition, unlike the Rittershoffen reference model, the Belgian electricity grid mix is used for the Balmatt model.

3.2.3.2.2.1 Construction

Exploration

The diesel required and staff transport during exploration phase and the CO_2 released during well testing are excluded from the Balmatt reference model, as no sufficient primary data is available.

Well drilling

The construction of the drilling platform and retention basin is excluded from the Balmatt reference model, as no primary data is available.

Three wells were drilled within the Balmatt project: two production wells and one reinjection well. The drilled length is based on primary data.

Other aspects are modelled in the same way as the Rittershoffen reference model.

Geothermal power plant

In addition to the elements modelled for Rittershoffen, an ORC unit is modelled using the Ecoinvent process 'heat and power co-generation unit construction, organic Rankine cycle, 200kW electrical', corrected for the actually installed electrical power.

Piping for freshwater, filters and valves are excluded from the reference model, as no primary data is available for Balmatt. Other aspects are modelled in the same way as the Rittershoffen reference model.

3.2.3.2.2.2 Operation and maintenance

No direct emissions, scaling inhibitor, water, filters, valves and pipes for freshwater are taken into account. Unlike the Rittershoffen reference model, the Belgian electricity grid mix is used for the Balmatt model. Other aspects are modelled in the same way as the Rittershoffen reference model.

3.2.3.2.2.3 End of life

End of life is modelled in the same way as the Rittershoffen reference model, including well abandonment.

3.2.3.2.2.4 Functional unit definition

The total power capacity of the geothermal plant is 6.6 MW_{th} and 0.25 MW_e. The generated electrical power is used for self-consumption. The total thermal energy produced in kWh is calculated as in Equation (17).

$$E_{th} = P_{th} * (1 - 0{,}5) * OH \tag{17}$$

With E_{th} the thermal energy produced (in kWh), P_{th} the thermal power capacity of the geothermal plant (in kW_{th}), OH the yearly operating hours (in hours), and 0.5 is the capacity factor employed to balance the extracted heat transferred to the Organic Rankine Cycle for electricity production.

3.2.3.2.2.5 Summary of variable parameters

Table 5 lists all the variable parameters used in the reference LCA model for the HeatORC category, their default value for the Balmatt geothermal plant, as well as their boundaries. A uniform distribution is assumed for all variable parameters, as no information is available to justify applying alternative distributions.

Table 5 – Variable parameters used for the reference LCA model for HeatORC. The "Default" values represent the values of the Balmatt power plant, the Min. and Max. values are the lower and upper boundaries of the single variable parameters. OM stands for operation and maintenance.

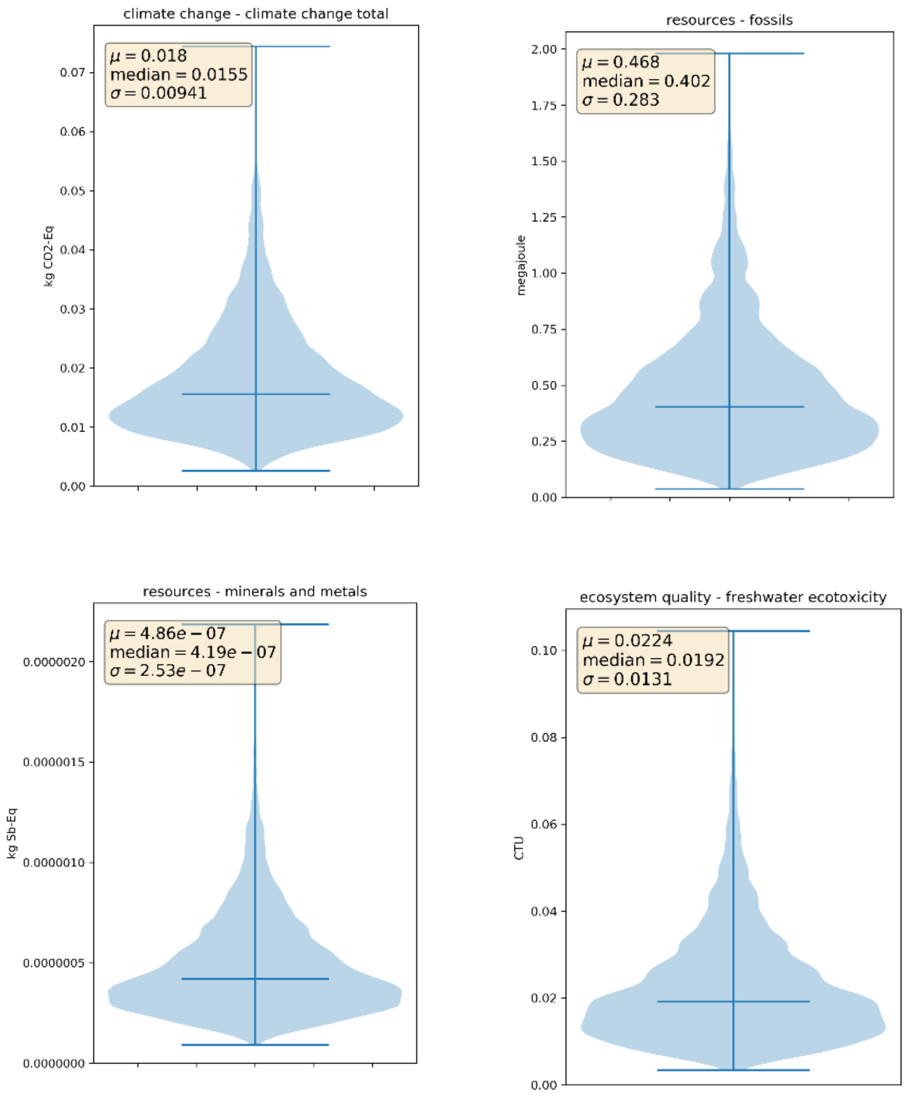
Phase	Label	Variable parameter	Default	Min.	Max.	Unit
General	Flow rate	Flow_rate_tph	108	72	144	t/h
General	Electric power	MWe	0.25	0	1	MW
General	Operating hours	Operating_hours	8,000	5,000	8,500	h
General	Lifetime	LT_years	30	20	40	y

General	Thermal power	MWth	6.6	6.6	25	MW
Power plant	Length geothermal fluid pipe	L_gw_pipe_m	200	100	300	m
Power plant	Power ESP pump	power_ESP_kW	600	200	1,200	kW
Power plant	Power reinjection pump	power_pump_kW	350	0	500	kW
Power plant	Mass Balmatt heat exchanger	M_heatexchanger_Balmatt_kg	57,679.2	23,070	92,280	kg
Power plant	Area of the power plant	A_powerplant_m2	800.05	400	1,200	m2
Stimulation	Volume stimulated fluid (chemical)	V_stimulated_m3	240	40	250	m3
Drilling	Length well	well_length	3,725	1,300	5,500	m
Drilling	Ratio meters drilled and well length	Ratio_MD_well_length	1.25	1	1.5	-
Drilling	Number injection wells	N_well_injection	1	1	2	-
Drilling	Number production wells	N_well_production	1	1	2	-
Transport	Distance for the cuttings	km_cuttings	275	50	500	km
Transport	Transport operation and maitenance	km_passenger_OM_pday	0	10	50	km

End of life	Energy for well abandonment	E_abd_diesel_MJ	570,000	38,600	750,000	MJ
End of life	Mass cement for well abandonment	M_cement_abd_kg	18,750	12,500	25,000	kg

3.2.3.2.3 Validation of the reference LCA model with literature

The results of the Monte Carlo simulations for the reference LCA model using the distributions of the variable parameters specified in Table 5 are shown in Figure 7.



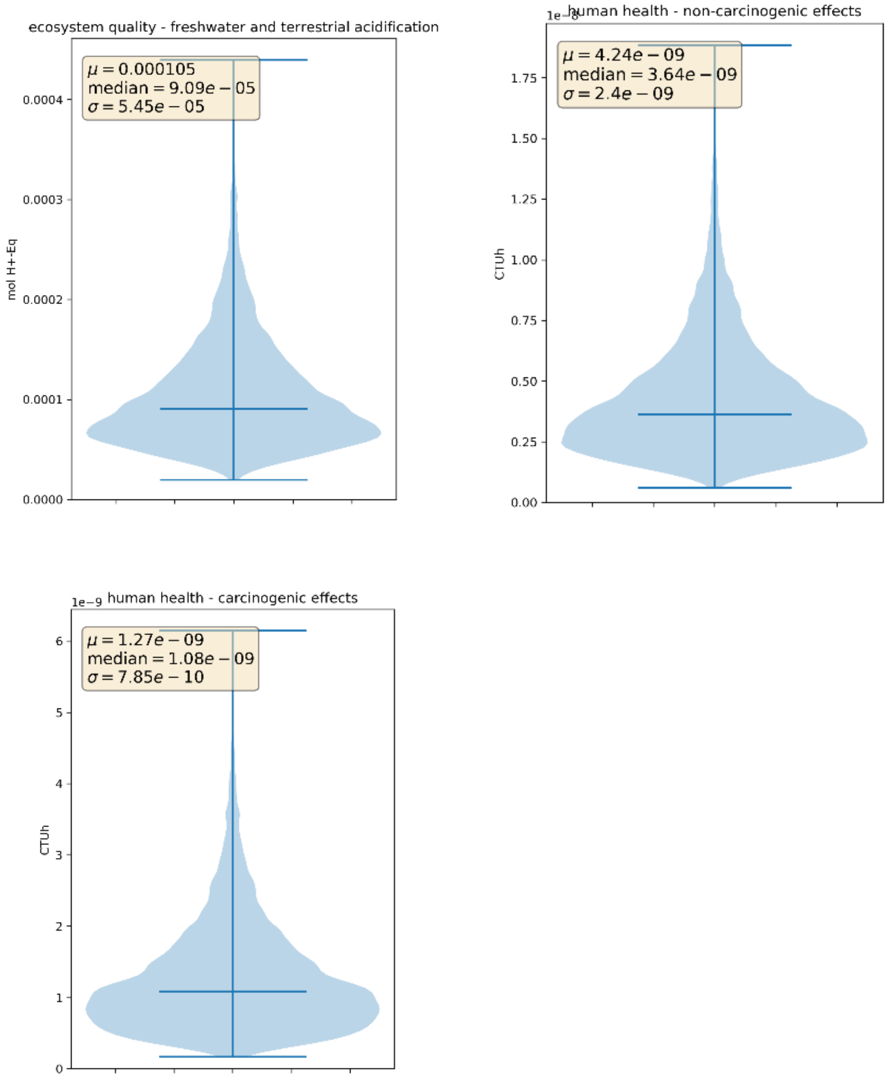


Figure 7 – Results of the Monte Carlo simulations for the reference LCA model for HeatORC for the seven ILCD 2018 impact categories of interest. In the violin plot, the horizontal lines correspond from top to bottom to the 95th percentile, the median and 5th percentile, while the light blue violin shape represents the probability density.

The impact values derived from the reference model with the default values for Balmatt are presented in Table 6.

Table 6 – Impact category results for the reference LCA model for HeatORC using the default values of Balmatt for the fixed and variable parameters

Impact category	Reference unit	Balmatt default values
climate change - total	kg CO_2-Eq	0.026854
ecosystem quality - freshwater and terrestrial acidification	mol H+-Eq	0.00014

resources - fossils	MJ	0.7864
resources – minerals and metals	kg Sb-Eq	5.8941E-07
Human health – non-carcinogenic effects	CTUh	4.9735E-09
Human health – carcinogenic effects	CTUh	1.3298E-09
Ecosystem quality – freshwater ecotoxicity	CTU	0.024626

The total climate change impact of geothermal binary power plants using EGS reported in (Frick et al., 2010) is around 0.047 kg CO_2-eq./kWh. This value falls within the 95% confidence interval shown in Figure 7, but is relatively high. This is easily explained by the many differences between the study and the Balmatt reference model: the LCA study in Frick et al. (2020) considers the production of both electrical power and thermal power (3.45 MWth and 1.75 MWe), while Balmatt primarily produces heat, with a demonstration of electrical power production using an ORC (6.6 MWth and 0.25 MWe). Due to the lower efficiency of conversion to electricity, this is associated with higher environmental impacts per functional unit. Moreover, only chemical stimulation is applied at Balmatt, consisting of 40-250 m^3 of fluid injected and 13 MJ diesel consumed by the injection pump, while the plant assessed in Frick et al. (2010) considers hydraulic stimulation, including a large volume of injected fluid (260,000 m^3) and 3,000 GJ diesel consumed by the injection pump. The larger need for diesel consumption for the hydraulic stimulation could explain the large value of the indicator climate change. There are also large methodological differences: the LCA study in Frick et al. (2010) uses an older method and characterisation factors and is based on Ecoinvent 2 background data, while the Balmatt reference model uses Ecoinvent 3. All these factors can have a significant effect on the results of the LCA.

Rocco et al. (2020) estimate the environmental impacts for geothermal heat power plants with different characteristics using the EF v3.0. impact category for average EU characteristics (Table 7). The estimates from this study lie within the boundaries of the Monte Carlo results of the reference LCA model for the impact categories climate change, freshwater and terrestrial acidification, human health non-carcinogenic effects. It does not for the impact indicators human health carcinogenic effects and freshwater ecotoxicity. It is important to note that both these indicators have a level of confidence indicating to use the indicators with caution due to the large uncertainty associated with the methods (Blanc et al., 2020).

Table 7 – Environmental impacts of geothermal heat power plants generated for the EF v3.0. impact category and reported in (Rocco et al., 2020)

Impact category	Reference unit	Min.	Max.
Climate change - total	kg CO_2-Eq	7.5E-03	1.0E-02
Ecosystem quality – freshwater and terrestrial acidification	mol H+-Eq	7.2E-05	1.1E-04
Human health – non-carcinogenic effects	CTUh	3.1E-09	3.7E-09
Human health – carcinogenic effects	CTUh	7.7E-11	9.1E-11
Ecosystem quality – freshwater ecotoxicity	CTUe	2.0	2.6

Overall, due to the specific nature of the Balmatt case, only few literature studies provide a meaningful comparison. Nevertheless, the values reported in (Frick et al., 2010; Rocco et al., 2020), are mostly within the interval reported by the reference model, except for two indicators that have a large uncertainty.

3.2.3.2.4 Statistical process to identify the key input variable parameters for each impact category

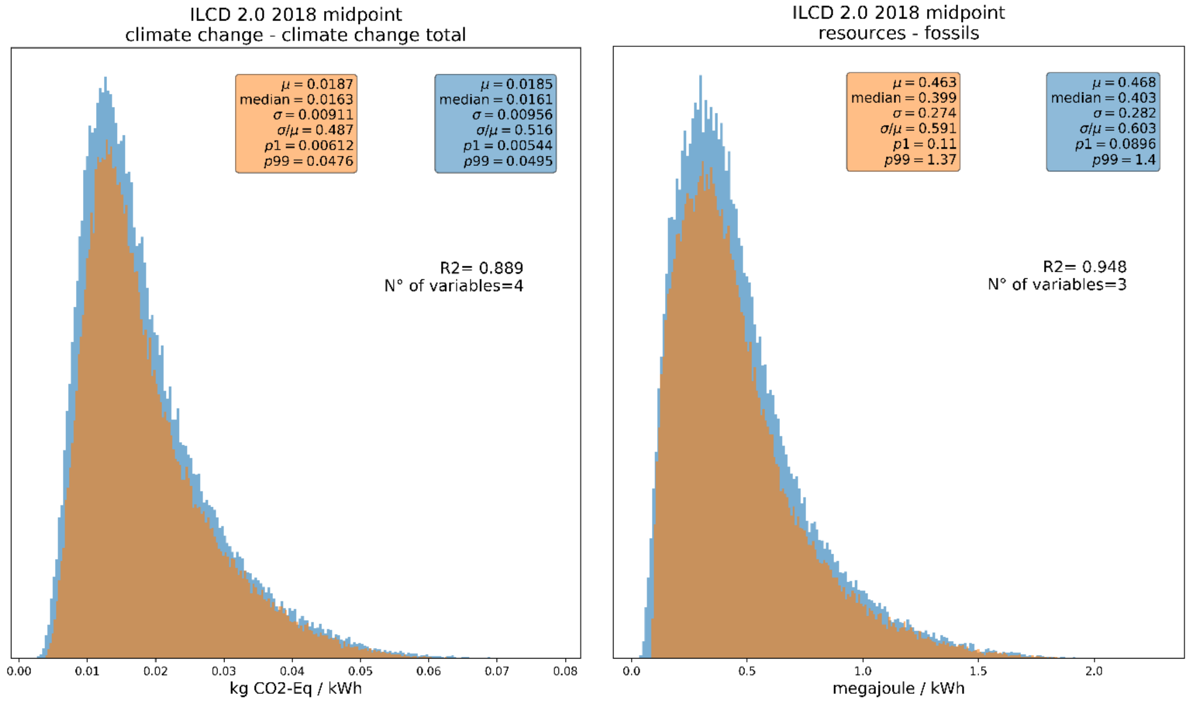
The A4 lists the first order Sobol indexes of all variable parameters. The following variable parameters explain large part of the variance:

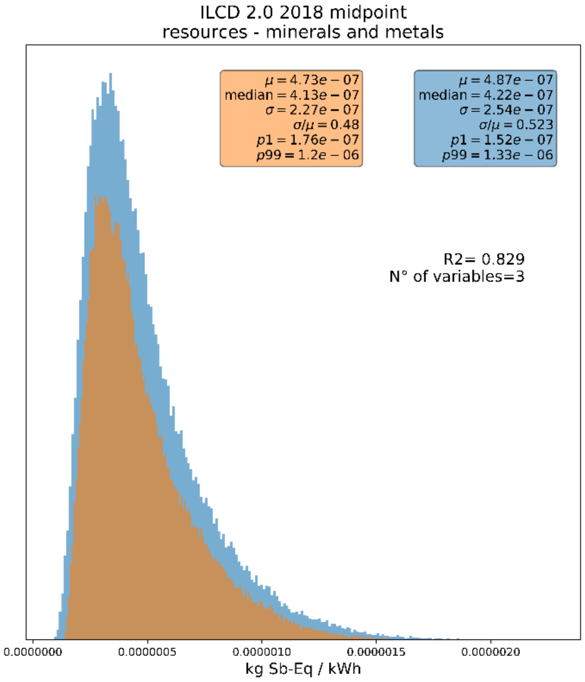
- **Installed thermal power**
- **Power of the reinjection pump**
- **Power of the production pump (ESP)**
- **Yearly operating hours of the plant**
- **Number of injection wells**

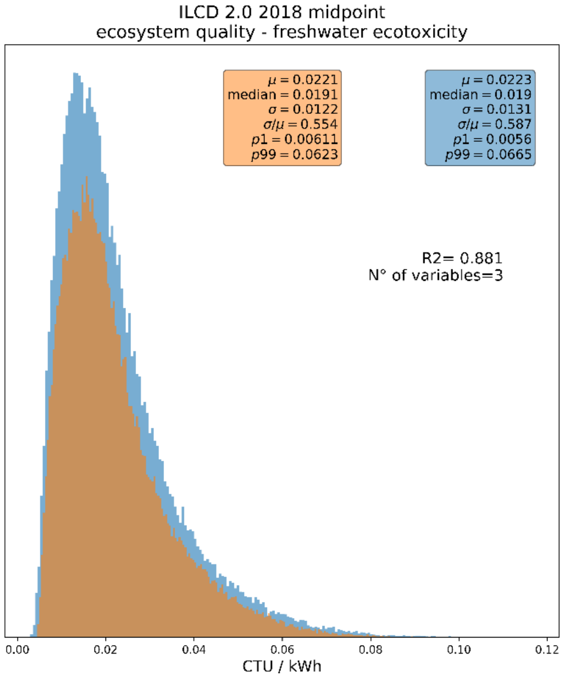
These five variable parameters are therefore selected to generate the simplified models. Per indicator, the simplified model for that indicator includes the three to four most important variable parameters of the five mentioned above.

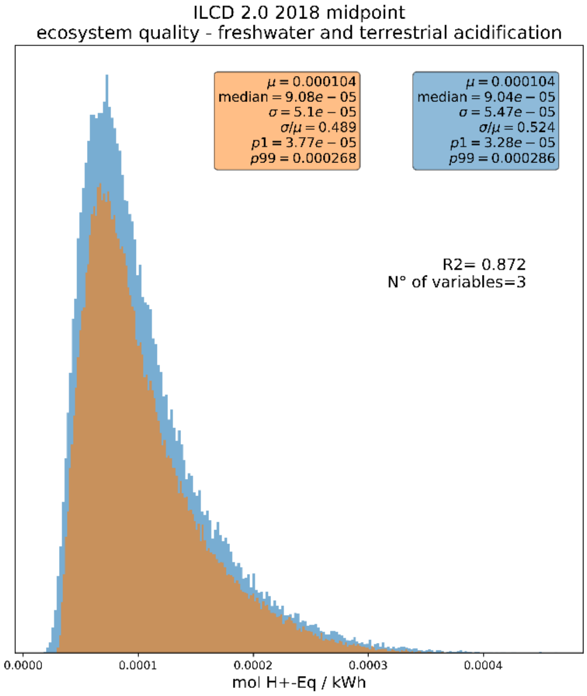
3.2.3.2.5 Generation of the simplified model per impact category

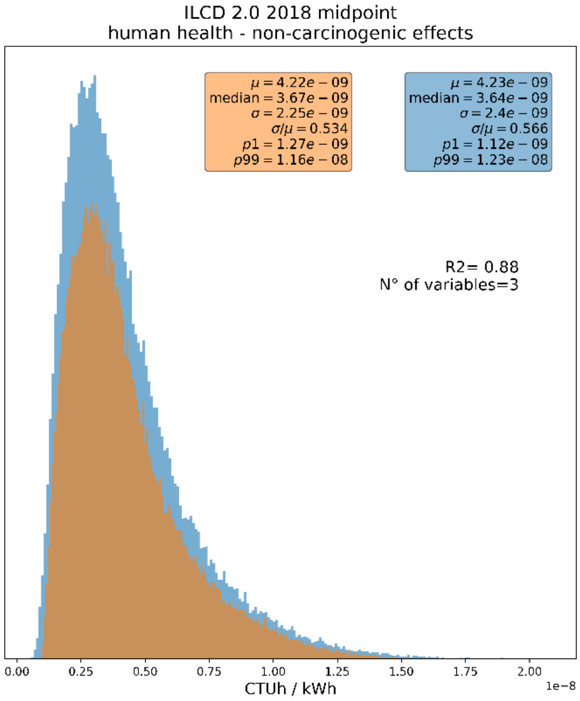
Per indicator, the simplified model for that indicator includes the three to four most important variable parameters, selected from the five most relevant ones listed above. The equations each model is relying on are provided in A4. The performance of the seven simplified models are shown in Figure 8 by displaying the overlap between the impact category distributions for the simplified and reference LCA models and calculating the level of fitting by means of the R^2. Overall, the R^2 are above 87% for all impact categories except for minerals and resources depletion category, where the R^2 is 83%.




ILCD 2.0 2018 midpoint
resources - minerals and metals


ILCD 2.0 2018 midpoint
ecosystem quality - freshwater ecotoxicity


ILCD 2.0 2018 midpoint
ecosystem quality - freshwater and terrestrial acidification


ILCD 2.0 2018 midpoint
human health - non-carcinogenic effects

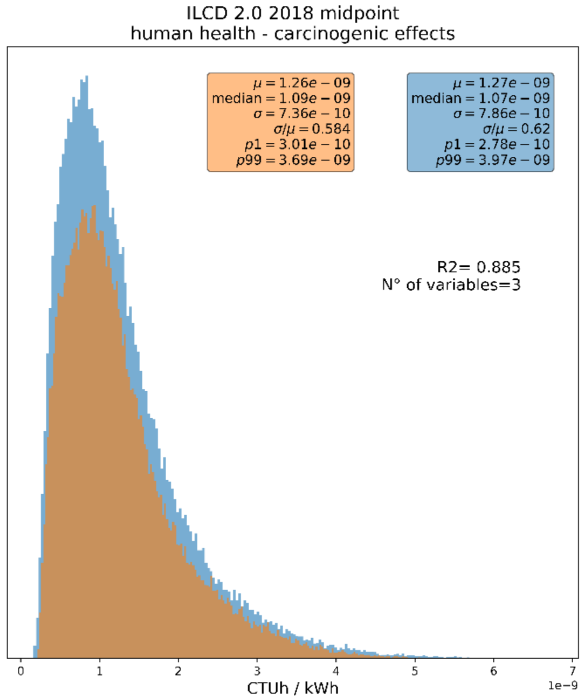


Figure 8 – Performance of the reference LCA model for HeatORC compared to the simplified models derived for the seven ILCD 2018 impact categories of interest. Blue represents the distribution of the reference LCA model results and orange of the simplified models.

3.2.3.2.6 Validation of the simplified models with literature

A final validation step consists in applying the simplified models' equations to specific configurations reported by other case studies. None of the references gathered in section 2.b reported enough information to determine the variable parameters and to apply the simplified models. Therefore, this validation is not performed right now, but further research at a later stage is recommended.

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

The reference LCA model, and as a result the simplified models developed, are designed for:

- geothermal plants for heat generation with ORC unit for possible electricity production for self-consumption;
- very low to no direct emissions;
- located in Belgium (or in another location with a similar electricity mix as in Belgium and similar geological characteristics);

- connected to the Belgian power grid (or in another location with a similar grid mix);
- the range of values for the variable parameters.

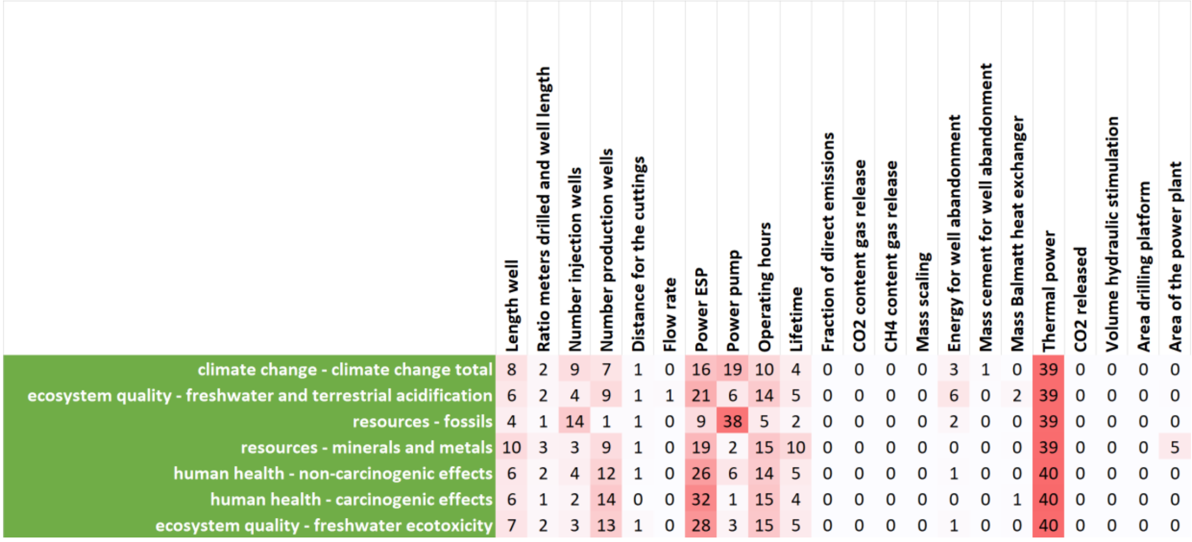
Even though the Balmatt geothermal plant is a demonstration plant that is difficult to compare to other geothermal power plants, the Balmatt reference model is based on the reference model of Rittershoffen and can therefore be applied to similar power plants, within the above-mentioned boundaries.

3.2.3.2.8 Background data for the HeatORC category

3.2.3.2.8.1 Key variable parameters

Table 8 shows the first order Sobol indexes for the seven impact categories of interest and all variable parameters included in the reference LCA model.

Table 8 – First order Sobol indexes for the seven impact categories of interest and all variable parameters included in the reference model for HeatORC. EQ stands for ecosystem quality, HH for human health, and R for resources.



	Length well	Ratio meters drilled and well length	Number injection wells	Number production wells	Distance for the cuttings	Flow rate	Power ESP	Power pump	Operating hours	Lifetime	Fraction of direct emissions	CO2 content gas release	CH4 content gas release	Mass scaling	Energy for well abandonment	Mass cement for well abandonment	Mass Balmatt heat exchanger	Thermal power	CO2 released	Volume hydraulic stimulation	Area drilling platform	Area of the power plant
climate change - climate change total	8	2	9	7	1	0	16	19	10	4	0	0	0	0	3	1	0	39	0	0	0	0
ecosystem quality - freshwater and terrestrial acidification	6	2	4	9	1	1	21	6	14	5	0	0	0	0	6	0	2	39	0	0	0	0
resources - fossils	4	1	14	1	1	0	9	38	5	2	0	0	0	0	2	0	0	39	0	0	0	0
resources - minerals and metals	10	3	3	9	1	0	19	2	15	10	0	0	0	0	0	0	0	39	0	0	0	5
human health - non-carcinogenic effects	6	2	4	12	1	0	26	6	14	5	0	0	0	0	1	0	0	40	0	0	0	0
human health - carcinogenic effects	6	1	2	14	0	0	32	1	15	4	0	0	0	0	0	0	1	40	0	0	0	0
ecosystem quality - freshwater ecotoxicity	7	2	3	13	1	0	28	3	15	5	0	0	0	0	1	0	0	40	0	0	0	0

3.2.3.2.8.2 Simplified models

The equations for the simplified models based on the selected variable parameters are listed below per impact category

Climate change, total

$$\frac{0.000326 * Operating_{hours} * power_{pumpkW} + 0.957 * power_{ESPkW} + 423.0}{MWth * Operating_{hours}} \tag{57}$$

Resources, fossil

$$\frac{0.0112 * N_{wellinjection} * power_{pumpkW} + 0.167 * N_{wellinjection} + 1.93}{MWth} \tag{58}$$

Resources, minerals

$$\frac{1.7 \cdot 10^{-7} * Operating_{hours} + 3.0 \cdot 10^{-5} * power_{ESPkW} + 0.0211}{MWth * Operating_{hours}} \tag{59}$$

Ecosystem quality – Freshwater ecotoxicity

$$\frac{0.014 * Operating_{hours} + 2.29 * power_{ESPkW} + 486.0}{MWth * Operating_{hours}} \tag{60}$$

Ecosystem quality – Freshwater and terrestrial acidification

$$\frac{0.000138 * Operating_{hours} + 0.00733 * power_{ESPkW} + 3.35}{MWth * Operating_{hours}} \tag{61}$$

Human health – Non-carcinogenic effects

$$\frac{6.85 \cdot 10^{-9} * Operating_{hours} + 3.98 \cdot 10^{-7} * power_{ESPkW} + 9.05 \cdot 10^{-5}}{MWth * Operating_{hours}} \tag{62}$$

Human health – Carcinogenic effects

$$\frac{3.28 \cdot 10^{-10} * Operating_{hours} + 1.46 \cdot 10^{-7} * power_{ESPkW} + 2.04 \cdot 10^{-5}}{MWth * Operating_{hours}} \tag{63}$$

3.2.4 References

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4 CONCLUSIONS

Climate change is an issue that nowadays is becoming more and more urgent, not only among policymakers and technicians but within public opinion above all. Indeed, a broader audience involvement might be desirable in this context. Thanks to that, decision-makers also set more actions easing the implementation of environmentally friendly activities. There are many processes that can be improved in terms of eco-sustainability, starting from mobility, industrial processes and breeding and agricultural activities in Western countries; these are all very impactful activities. However, decarbonization of energy production needs to be primarily accomplished to achieve concrete progress towards greener human activities, since it is an essential input of almost any supply chain.

Therefore, research in this field is crucial, and evaluating the real environmental performance of energy production systems covers a vital role: Life Cycle Assessment is a powerful tool to reach this goal. The methodology has been extensively tested and is supported by the scientific community, pledging to deliver results compliant with all the recent improvements and discoveries in the environmental assessment field. The application of the LCA methodology, in fact, has been successfully applied to many sectors, disclosing critical aspects connected with the whole value chains and making relevant information available. But likely all scientific disciplines, a key part of making valid results is the reproducibility of the result itself, and to do this many applications of the method must be performed. Unfortunately, in the field of deep geothermal energy this has not happened yet, even though it is an energy resource with great potential to carry on the green deal.

The LCA results here presented in various aspects, demonstrated that the potential environmental impacts for typical Italian flash plant are determined for more than 95% by the operational (direct emissions to air of NH_3, CH_4, CO_2) and commissioning (CO_2 emissions due to diesel combustion during drilling) phases. Maintenance, decommissioning, and End of Life phases show a negligible contribution to all the considered impact categories. Globally, the most influenced impact categories are Climate change, Acidification, Terrestrial eutrophication and Particulate matter. These outcomes imply that atmospheric emissions determine LCA results of electricity generation from flash technology exploiting a mid to high dissolved gas content geofluid for some impact categories. A further finding is that the impact is equally divided between well drilling and equipment in the commissioning phase.

The thesis also reports the highly complete life cycle inventory for a state-of-the-art flash system conversion technology overarching the geothermal power plant's whole life cycle. This result is valuable since in the geothermal panorama very few are the available information, and it is challenging to find transparent inventories giving detailed information about technical representativeness and information sources. Indeed, the possibility of using a detailed, complete and transparent inventory database for a LCA is crucial to obtain results that are meaningful and robust so that results can represent reality rigorously.

The application of LCA for the analysis of geothermal energy systems allowed to obtain environmental performance results highly representative for the site-specificity of the resource and, from a methodological pint of view, to point out which are the criticalities of the LCA method. Indeed, the result interpretation step of the LCA process is crucial. Without a proper analysis of the generated results, there is a substantial risk of undertaking a wrong evaluation of the results and communicating incorrect conclusions. This is particularly true concerning the toxicity impact categories. Since these categories are the ones that most likely can attract public attention, results should be carefully interpreted and presented as much correctly as possible. It is understood that the toxicity impact values calculated from an LCA are just potential and do not represent a real risk assessment. Concerning metals, there are legislative emission limits that must be observed, ensuring the protection of the exposed human population.

As extensively presented in the thesis, LCA can identify hot-spots along the supply chain and suggest actions to improve environmental compliance. Unfortunately, the procedure is very time consuming and requires particular technical competencies. Moreover, lots of detailed and accurate information are needed in order to obtain meaningful results. Therefore, methods feasible to reduce and simplify the procedure to obtain results are under development to be implemented for geothermal projects.

A procedure used to realize simplified LCA models is described in the thesis. The method presented can reduce the complexity against the classical approach significantly, giving up part of the information that detailed LCA can deliver. Regardless of this, such methods can be useful since not every time an in-depth analysis is required. For example, simplified models can be instrumental in performing a more straightforward environmental assessment for many systems. Simultaneously, the non-expert users can employ them to obtain LCA results reliable enough without having specific competencies.

The methodological advances presented in the thesis are just a brief perspective of what is possible to develop with the available advanced tools. It is demonstrated that it is possible to deduce effortlessly useful equations that allow producing results, from a LCA perspective, of the national electricity mix. With just a few pieces of information, the LCA results of such a complex system like the national electricity mix can be calculated for multiple impact indicators. The methods have also been applied to geothermal systems giving even better results in meaningfulness and usefulness. Many stakeholders within the decision-makers community can be potentially interested in developing such tools for specific classes of systems, allowing them to quickly assess systems' environmental performances, speeding up implementing the most appropriate policies.

In conclusion, the research described in this thesis shows the effectiveness of the LCA approach in delivering meaningful results and its potential methodological advantages for analysing energy systems. With a special focus on geothermal systems, the results presented in this work allow for highlighting different crucial issues for this energy source: if on the one hand, its exploitation can be beneficial to move in the direction of the carbon neutrality of the European energy system, geothermal energy generates potential environmental impacts that need to be analysed in a context-related perspective.

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