Panorama of sustainability studies

A comprehensive analysis of the panorama of studies reporting environmental assessment and sustainability assessment for geothermal systems

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GEOENVI

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Executive summary

This study focuses on a comprehensive analysis of a panorama of LCA studies performed on geothermal projects, mainly from Europe. In addition, an analysis of the Geothermal Sustainability Assessment Protocol (GSAP) will be challenged against the results from the survey on environmental impact issues undertaken in GEOENVI in Work Package 2 (WP2-Overall state of the art on deep geothermal environmental data). The aim is to identify if any environmental topics specifically related to the environmental assessment of geothermal projects are missing in the GSAP or could be better adjusted into the protocol. We will also highlight the great variability between LCA and the GSAP, where both tools can be used to assess environmental aspects in different ways. LCA is a performance tool on environmental impacts, but the GSAP has a much broader scope of sustainability assessment, and is more of a management tool, used to try and improve the performance of each project. This study is only focused on environmental issues.

The results of the LCA panorama analysis highlighted the variability of the LCA studies based on e.g. goal and scope, technology and methodology, as well as identifying the environmental impacts that are assessed in the LCA method. Additional impacts have been identified related to local environmental issues to fit the application to the geothermal sector, based on the results from WP2. This outcome will assist with the work of deliverable 3.2 on making harmonized LCA guidelines for the method to be more suitable for use in a geothermal environment, on a local, regional and global scale, and some of the challenges to that work have been pointed out.

The GSAP was found to comply overall very well to the overview of the environmental aspects covered in the wiki sheet database, with only three environmental aspects not specifically addressed in comparison to the WP2 database (blowout, leak due to surface operations and aquifer depletion). It was also noticed that the end of life stage has not been considered for the GSAP.

In conclusion both methods (GSAP and LCA) have their validity, but which method to use (or a combination of the two) should be based on the preferred outcome of the planned assessment.

Introduction

Public acceptability of geothermal energy is an important topic for decision makers (Chavot, et al., 2018). Access and dissemination of key environmental performance indicators for geothermal installations are important when considering such public acceptability. Environmental concerns are one of the barriers for deep geothermal market development around the globe. Geothermal should be a safe, reliable, and environmentally friendly renewable energy source. However, all manmade activities have an impact on nature: the environmental impact of the construction of infrastructure projects should be rightly considered as well as their operation phase and end of life.

Among the different tools and methodologies, Life Cycle Assessment (LCA) is a relevant approach to assess in a comprehensive manner the potential environmental impacts for a product or a system of products, in particular for energy pathways. The assessment is performed on a wide range of environmental indicators (Asdrubali, et al., 2015; Turconi, et al., 2013) and it allows identifying, over the total life cycle of systems, the contribution of any phase of the life cycle considered (i.e: the construction, the operation, the end of life) as well as any sub-system (i.e: materials, electricity consumption, chemical substances).

Several LCA studies have been performed on geothermal systems, mainly focusing on climate change concerns (Eberle, et al., 2017) and only a few have extended the assessment to include more impact categories (Tomasini-Montenegro, et al., 2017). However, an updated analysis for a large set of representative geothermal technologies is necessary to identify any oversight of environmental issues. The GEOENVI project enables such contribution as the project covers several countries with different geological characteristics and employing various geothermal technologies.

Another important tool for analysing the environmental impact related to geothermal development is the newly designed Geothermal Sustainability Assessment Protocol (GSAP, see Appendix C). The GSAP is a framework used to assess and enhance the sustainability performance of individual geothermal power projects, with the sustainability issues divided into four different sections: 1) environmental 2) social 3) economical and 4) technical. The protocol was developed by a team of Icelandic power companies and government agencies through the modification of the widely known and accepted Hydropower Sustainability Assessment Protocol (HSAP) developed by the international Hydropower Association (IHA) (Orka náttúrunnar, 2018).

The European Union project GEOENVI has the objectives to identify environmental concerns related to geothermal development, in terms of impacts and risks. This is done by developing an adapted and standardized methodology for assessing the environmental impacts to be used by the project developers, as well as assessing the environmental impacts and risks of geothermal projects in operation or in development in Europe (https://www.geoenvi.eu/).

Work Package 2 (WP2) in GEOENVI addresses among other things, environmental impacts and risks, its perception and how the environmental footprint of deep geothermal projects in Europe is measured and controlled. Analysis of adopted solutions to reduce or circumvent the risks and impacts is also a task of WP2. The results will be published as a report with an associated multidimensional database, contributing information on environmental matters related to geothermal development, that has served as a base to help framing the work in Work Package 3 (European Commission, 2018). The main objectives of WP3 is to 1) draft harmonized guidelines to conduct environmental impact assessment integrating LCA approaches tailored to geothermal installations that will be adopted at European and possibly international level 2) T apply the harmonized guidelines on available GEOENVI LCAs case studies to test their applicability on real cases 3) To investigate with geothermal stakeholders the interest of LCAs alternative with simplified models dedicated to non LCA experts.

According to the terminology of the GEOENVI project, impact and risk are described in this way:

- **Impact:** a change in environmental condition that occurs for sure. An impact, as presented and defined through the GEOENVI project, is an unavoidable consequence of the geothermal project. Disturbance and nuisance are inconveniences caused by human activities during the industrial geothermal development. For purpose of classification, we identify disturbance and nuisance as an impact.
- **Risk**: in a given place and time, risk is the combination of the probability of occurrence of an event, the stakes and the vulnerability. A risk, as presented and defined through the GEOENVI project, is characterized by an event, that is more or less predictable, resulting from geothermal operations and generating potential consequences on human and the environment (ecosystems, atmosphere, and underground water).

Objectives of deliverable 3.1

The work on this study has been done in cooperation with all involved partners in WP3 of the GEOENVI project, especially partners involved in task 3.1 (OS, CSGI and ARMINES). The main aim of the deliverable is twofold: 1) to analyse a panorama of available LCA studies for geothermal systems. The panorama will provide a clear vision of which environmental impacts are currently handled by LCA approaches, as well as the identification of the environmental impacts that are currently not part of the LCA methodology, of the different reasons. A discussion on whether some of these environmental impacts could/should be in some way be included and adjusted into the LCA methodology. This will be based on comparison of Life Cycle Impact Assessment to the results from WP2, in order to build harmonized LCA guidelines to be more suitable for use in a geothermal environment, on a local, regional and global scale (deliverable 3.2). 2) To challenge the Geothermal Sustainability Assessment Protocol (GSAP) against the results on environmental impact aspects of WP2 in GEOENVI, to better identify if there are any environmental topics specifically related to the environmental assessment of geothermal projects missing in the GSAP or to be better adjusted into the protocol.

LCA in general

Life cycle assessment (LCA) is a methodology assessing the potential impacts related with resource use and emissions to the environment that occur during all stages of a product's life (cradle to grave). Standards (ISO 14040 and 14044) are used to describe how to conduct an LCA study. The standards cover and the rules to undertake life cycle inventory (LCI) and life cycle impact assessment (LCIA). They are not specific to geothermal installations as they only provide the main directives on how to conduct an LCA (European Commission Joint Research Centre, 2010).

The four phases of LCA are (Figure 1, (Ciroth, 2017)).

- Goal and scope definition
- Inventory Analysis
- Impact Assessment
- Interpretation

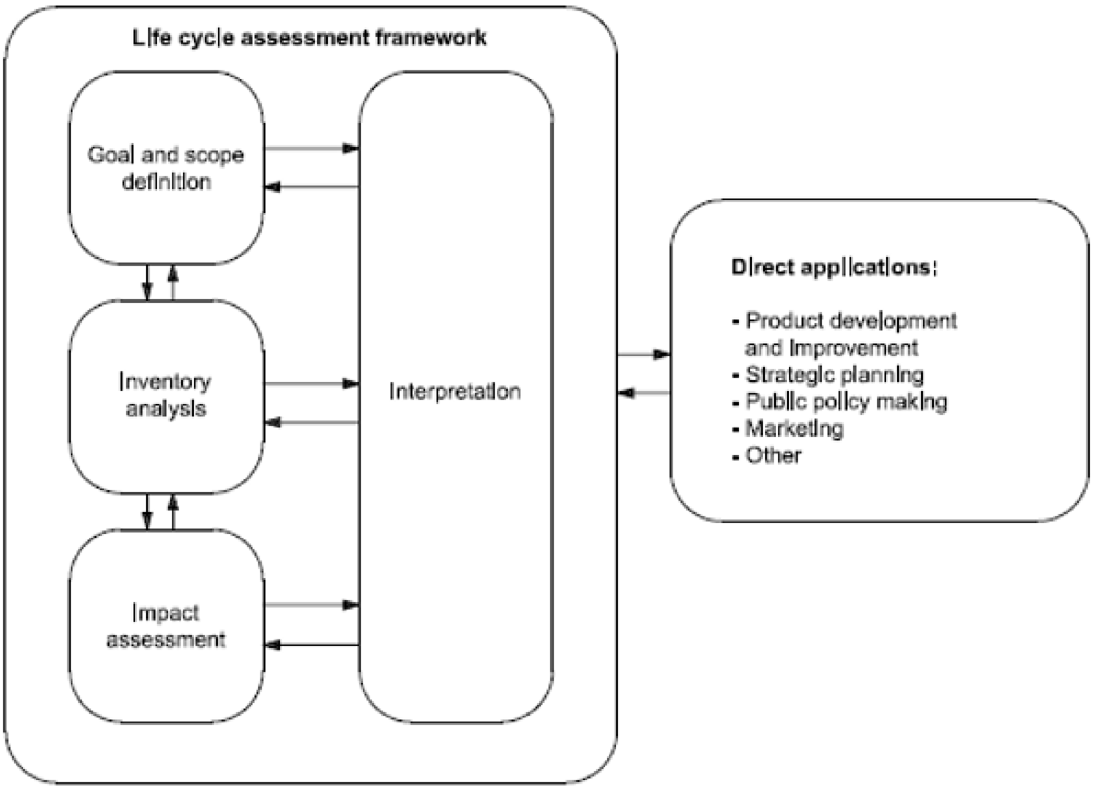


Figure 1. The four phases of LCA. *(Ciroth, 2017)*

Goal and scope

This phase of LCA aims at defining the product and its life cycle, as well as describing the system boundaries. LCA models are in general a simplification of a complex reality. This step is a challenge for the LCA modeller to develop a model so that the simplifications and distortions of the complex reality do not influence the results except to a minor extent. The 6 key aspects of the Goal definition step are (European Commission Joint Research Centre, 2010):

- Intended application(s) of the deliverables
- Limitations due to the method, assumptions, and impact coverage
- Reasons for carrying out the study and decision
- Target audience of the deliverables

- Comparative studies to be disclosed to the public
- Commissioner of the study and other influential actors

Scope definition - study object: To define the study object (if not done in the goal definition) and identify it as closely as possible. When deriving the scope from the goal, several scope items should be clearly defined, like functional units (FU) and system boundaries (European Commission Joint Research Centre, 2010).

Inventory

The inventory analysis is focused on the environmental inputs (resources) and outputs (emissions). It gives a list of all materials and energy flows for all processes that are within the product system and its interaction with environment (Curran, 2008). If necessary, the goal and scope can be adjusted.

LCA impact assessment

In the LCA impact assessment (LCIA) potential environmental impacts are calculated based on the inventory results of the life cycle. Inputs and outputs are multiplied by a specific characterisation factors and all the contributions to different impact categories are summed up to obtain a single impact value for each considered category. The indicator results of all impact categories are detailed in this step and the magnitude and importance of the impacts can further be assessed by normalization and by weighting (Curran, 2008).

Interpretation

The interpretation phase is a way to identify significant issues based on the LCI and LCIA results, determine data sensitivity and present results and recommendations.

Strengths and limitations of LCA

In general, LCA is a good overview of environmental throughout the life cycle of a project, depending on impact assessment methodology and chosen categories for the study.
Some of the limitations regarding LCA, are that the implementation is rather time-consuming, and only potential effects are addressed. Also, there are many assumptions/decisions to be made (e.g. system boundaries, allocation method), where variations in practice can result in different LCA results (Curran, 2014). Lack of comparability between studies is also well known and results can be difficult to communicate.
To overcome this potential drawback related to a lack of comparability among LCA studies related to geothermal installations, GEOENVI project is providing an analysis of the panorama of published LCA studies. The panorama will also provide a clear vision of which environmental impacts are currently handled by LCA approaches.

Geothermal Sustainability Assessment Protocol (GSAP)

Geothermal development is highly advanced and has a long and successful history in Iceland. This includes electrical power production, space heating, heating of swimming pools and green houses along with various other industrial purposes. Over 90% of space heating and 27% of electrical production in Iceland comes from geothermal resources (Johannesson, et al., 2020).

The Geothermal Sustainability Assessment Protocol (GSAP), is a modified tool based on the widely accepted Hydropower Sustainability Protocol (HSAP). Three power companies (The

National Power Company of Iceland, Reykjavik Energy, HS Orka) and two government agencies (Orkustofnun - The National Energy Authority of Iceland, Umhverfisstofnun - The Environment Agency of Iceland) formed the GSAP working group in early 2016, with the aim of developing the GSAP to measure, guide and improve the industrial performance of geothermal power projects, based on four key factors: **social, environmental, technical and economic,** with the main focus of this report on the environmental assessment. The modification from HSAP to GSAP was kept to a minimum, to maintain the international acceptance and multi-stakeholder consensus obtained for the HSAP (Johannesson, et al., 2020). The objective of the protocol is to be globally acceptable and consistent (Orka náttúrunnar, 2018).

The four project stages, with separate protocol documents are: Early stage, preparation, implementation and operation (Figure 2). Currently no stage has been made for end of life. Protocol drafts have only been made for two of the stages: Preparation and operation.

The modification of topics from HSAP to GSAP were based on replacing hydropower related specifics with relevant information and topics for geothermal (e.g GHG emissions, unique volcanic geological features, hazardous gas emissions, induced seismicity) (Johannesson, et al., 2020).

The GSAP sustainability and management tool is of high value since it provides independent review and guidance of sustainability issues, it allows comparison with international best practice, it improves communication with stakeholders as well as facilitating licensing and access to finance, and last but certainly not least, it leads to improved projects, procedures and performance, and therefore enhances public acceptance of geothermal development.

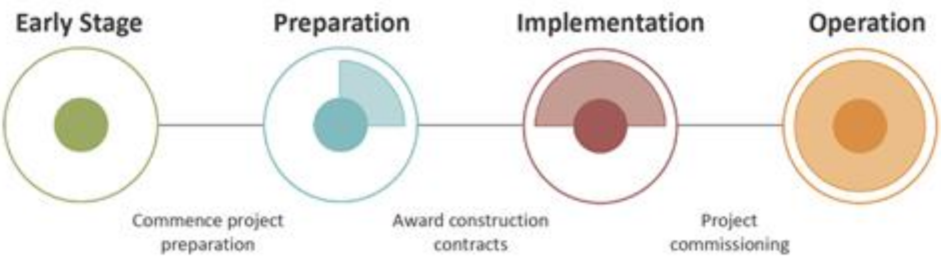


Figure 2. The four project stages in the GSAP.

The preparation stage of the GSAP includes 21 important sustainability topics (Table 1) related to social, environmental, technical and economic matters, with scoring levels from 1-5, with 1 describing significant gaps relative to basic good practice and level 5 describing the proven best practice. The experience has shown that choices made in the preparation stage of projects have usually the biggest impact on sustainability and therefore the GSAP working group had the greatest focus on developing the GSAP tool for the preparation stage.

The operational stage has 17 similar topics as the preparation stage (Table 1), addressing the social, environmental, technical and economic matters of each project. Scoring levels are also from 1-5:

1. More than one significant gap against basic good practice
2. One significant gap against basic good practice
3. Meets basic good practice with more than one significant gap against proven best practice
4. Meets basic good practice with one significant gap against proven best practice
5. Meets basic good practice and proven best practice

Each assessment relies on objective evidence to support the score for each topic that is factual, reproducible, objective and verifiable. The assessment is carried out by independent assessors who review all the relevant materials and plans for the power project. They also carry out interviews with both the developers of the project as well as relevant outside stakeholders, such as licensing authorities, local governments and NGOs. Scoring is an essential feature of the protocol, providing an easily communicated and replicable assessment of the project's strengths, limitations and opportunities. The scoring system is to ensure that a protocol assessment cannot provide an overall 'pass' or 'fail' mark for the assessed project, nor can it be used to 'certify' a certain project as sustainable. The protocol provides an effective way to continuously improve sustainability performance of geothermal projects because the results identify gaps that can be addressed, and the findings provide a consistent basis for dialogue with stakeholders (Orka náttúrunnar, 2018). Currently the GSAP is in a development stage with only two testing so far; Theistareykir (Landsvirkjun, 2017), preparational stage, and Hellisheiði, operational stage (Orka náttúrunnar, 2018). However, the HSAP, which the GSAP is based on, has been used on various projects around the world for many years with good results and acceptance by both the industry and communities.

Further development and testing of the draft GSAP for international development are under consideration, depending on agreements with IHA, which has the proprietary rights to the original Hydrothermal Sustainability Assessment Protocol.

Table 1. *Topics assessed in GSAP for preparation- and operation stage.*

Topics	Preparational stage	Operational stage
Communication & consultation	X	X
Governance	X	X
Demonstrated need & strategic fit	X	
Siting & design	X	
Environmental & social impact assessment & management	X	X
Integrated project management	X	
Geothermal resource management	X	X
Asset reliability & efficiency		X
Public health and safety	X	X
Financial viability	X	X
Project benefits	X	X
Economic Viability	X	
Procurement	X	
Project-affected communities & livelihoods	X	X
Resettlement	X	X
Indigenous peoples	X	X
Labour & working conditions	X	X
Cultural heritage	X	X
Biodiversity & invasive species	X	X
Induced seismicity & subsidence	X	X
Air quality & water quality	X	X
Climate Change Mitigation and Resilience (added in 2019)	X	X

Results

Variability between the LCA and GSAP methodology

In general, LCA and the GSAP are highly different tools, but both can be used to assess environmental aspects. LCA is a performance tool, but the GSAP has a broader scope of sustainability assessment, and is more of a management tool, used to try and improve the performance of each project, wherever in the world it is located, accounting for local regulations, based in the topics shown in Table 1. As has been previously pointed out, the GSAP has only been tested two times, in both cases in Iceland, but the HSAP has broad experience. LCA on the other hand, has extensive experience in the field of various environmental impact assessment.

Both methods (GSAP and LCA) have their validity, but which method to use should be based on the preferred outcome of the planned assessment: a potential impact assessment focused on environmental issues for the LCA based on international based impact indicators for LCA, or a relative sustainability assessment based on the performance able to address local regulations for the GSAP. To further highlight the variability between the two methods, an example of indicators for the environmental assessment related to Public health and safety (O-6, but here safety is excluded) in the GSAP is carried out for Hellisheidi (see Appendix D). Topic O-6 has resemblance to human toxicity potentials in LCA. In LCA the human toxicity potential (HTP), is a calculated index that reflects the potential harm of a unit of chemical released into the environment, based on both the inherent toxicity of a compound and its potential dose. It is used to weight emissions inventoried as part of a life-cycle assessment (Hertwich, et al., 2001)

Panorama of LCA studies

Studies of LCA in geothermal projects were collected and categorised based on several factors like geographical location, specific goal and scope, types of studies, environmental aspects, technical criteria, functional units, system boundaries and detailed LCIA methodology. In total the panorama included 33 different LCA studies collected by partners in the GEOENVI project (Appendix A and Appendix B).

The selected studies are published in the years between 2010 and 2019. Geographical coverage is mainly Europe but in a few recent studies the coverage is larger with Guadeloupe island (Marchand, et al., 2015), New-Zealand (Martínez-Corona, et al., 2017), USA (Hanbury & Vasquez, 2018; Sullivan, et al., 2010; Sullivan & Wang, 2013; Sullivan, et al., 2010) and Indonesia (Yu, et al., 2017). In Europe the geographical reference is Germany (Frick, et al., 2010; Heberle, et al., 2016; Pehnt, 2006; Pratiwi, et al., 2018), France (Pratiwi, et al., 2018), Italy (Bravi & Basosi, 2014; Parisi, et al., 2019; Chiavetta, et al., 2011), Turkey (Atilgan & Azapagic, 2016), Switzerland (Gerber & Maréchal, 2012; Treyer, et al., 2015; Bauer, et al., 2008), Iceland (Karlsdóttir, et al., 2015; Karlsdóttir, et al., 2014; Karlsdóttir, et al., 2010) and Scotland (McCay, et al., 2019).
The panorama is based on LCA case studies as well as reviews.
In general, case study is an in-depth examination for a specific geothermal installation. A review is an article that compiles and analyses the current state of understanding on a topic.
Some of the studies were however, missing some of the above-mentioned information, or had other classifications.

Goal and scope

The goal definition of each study from the panorama was highly variable focusing on e.g. comparing the environmental impacts of different geothermal systems, on identifying environmental performance indicators, assessing the life cycle environmental impacts of

electricity generation and on accounting greenhouse gas (GHG) emissions from geothermal systems and power plants in various phases of the life cycle (see
Table **2**).

The scope of each study from the panorama was categorized into one of the following groups:

1. Adopted solutions to limit impacts and risks of deep geothermal energy in Europe
2. Description of the monitoring strategies.
3. LCA: Environmental quantitative and qualitative data, data on potential environmental footprints.

The vast majority of the studies is classified in group nr. 3, total of 27 studies out of 33. One study is classified in group nr. 1, and 5 had other classifications.
Table 2 gives an overview of the goal and scope, from the panorama of LCA studies on geothermal development (excluding the review studies). This includes goal definition, functional unit (FU), system boundaries and geothermal application.

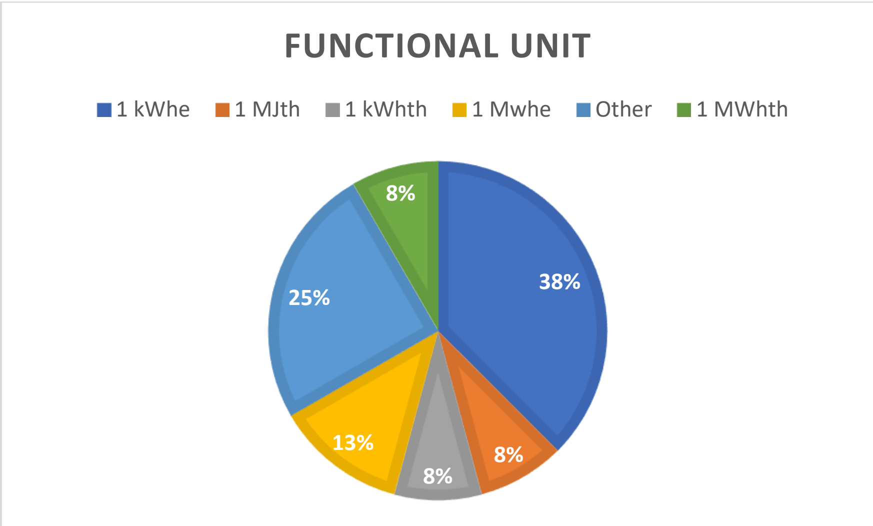
Table 2. *An overview of the goal and scope from the panorama of LCA studies, including functional unit, system boundaries and geothermal application.*

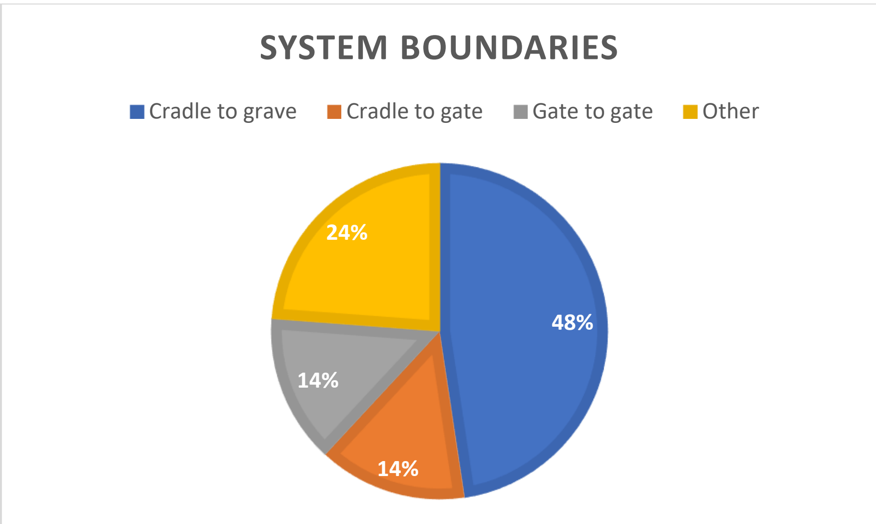
Authors	Goal definition/intended application	Functional unit	System boundaries	Geothermal application
Frick, S., et. al (2010)	Comparative analysis of environmental impacts of geothermal systems	1 kWhe or 1 MJ heat	Cradle to grave	Electricity
Martín-Gamboa, M., er, al (2015)	Comparative analysis of environmental impacts of geothermal systems	1 MWhe or 1 MWhth	Cradle to gate	Electricity
Hanbury, O., Vasquez, V, R (2018)	Identification of Environmental Performance Indicators	1 GJ of energy	Cradle to grave	Electricity
Pratiwi, A., et. al (2018)	Comparative analysis of environmental impacts of geothermal systems	1 kWhe or 1 kWhth	Cradle to grave	Heat
Bravi, M., Bassosi, R (2013)	Identification of Environmental Performance Indicators	1 MWhe	Gate to gate	Electricity
Martínez-Corona J, I., et. al (2017)	-	-	Gate to gate	Electricity
Lacirignola, M., Blanc, I (2013)	-	1 kWhe	Cradle to grave	Electricity
Gerber, L., Maréchal, F (2012)	Multi-objective optimization based on economic, energetic and environmental indicators	-	-	Heat and Electricity
Parisi, M, L., et. al (2019)	Life cycle assessment of the environmental impacts due to the exploitation of deep geothermal energy in Italy.	1 MWhe	Gate to gate	Electricity
T. Yu (2017)	Compare the environmental impacts of large-scale GTE flash system and small-scale binary GTE system for construction and operation stages	1 kWhe	Cradle to grave	Electricity
Marchand, M., et. al (2015)	Perform the LCA of in high temperature geothermal system in Guadeloupe. Compare technological alternatives to present situation to investigate potential reduction of environmental impacts	kWh of net energy produced by a geothermal plant over a period of 30 years	Cradle to grave	Electricity

Atilgan, B., Azapagic, A (2016)	Estimate the life cycle environmental impacts of electricity generation from reneable power systems in Turkey.	1kWhe and annual generation of renewable electricity	Cradle to grave	Electricity
Chiavetta, C., e.t al (2011)	-	Production of 400 l of hot water	Cradle to grave	Hot water
Karlsdottir, M, R., et. al (2014)	Create a life cycle inventory database and perform a cradle to gate LCA on Stykkisholmur's geothermal district heating system	1MWhth of district heat delivered to a consumer	Cradle to gate	Heat
Sullivan, J, L., et. al (2011)	-	lifetime of kWh delivered to the grid	Cradle to grave	Electricity
Sullivan, J, L., et. al (2010)	Present LCA results derived from our modelling of four geothermal plant types: 2 EGSs, a hydrothermal binary/flash.	lifetime of kWh delivered to the grid	Cradle to grave	Electricity
Larcignola, M., et. al I (2014)	Aims at developing such a simplified model specific to the EGS sector assessing the GHG performances	The net energy produced over the life cycle.	-	Electricity
Sullivan, J, L., et. al (2013)	Not specified	-	Cradle to gate	Electricity
Karlsdottir, M, R., et. al (2010)	Produce standardized factors for PEE and CO2 emission for GPP. to calculate the PE and CO2 factors for geothermal based power production based on data from the Hellisheidi with LCA.	1 MWhe	Operation, construction.	Electricity
Treyer, K., et. al (2015)	The quantification of environmental burdens during the complete life cycle of deep geothermal systems per unit of electricity (and heat)	1 kWh net electricity	Construction, operation and end of life	Electricity
Pehnt., M (2006)	The LCA results are analysed regarding critical life cycle segments and materials and compared to conventional systems	1 kWhe	Production, operation, maintenance, system recycling/disposal	Electricity
Karlsdottir, M, R., et. al (2015)	Describing the material and energy demand for constructing and operating a GCHP plant as well as direct emission of gases, waste water/heat	1 kWhe and 1 MJ of heat	-	Electricity
Pratiwi, A., et. al (2018)	Design a new tool to perform life cycle climate change assessment for deep geothermal power and heat productions in the Upper Rhine Valley. gives an accurate quantification of CO2 emissions.	1 kWhe and 1 kWhth	Exploration until end of life.	Heat and electricity
	Estimate the whole life cycle climate impact of direct heat	1 MWhth	Site preparation,	Heat

McCay, A, T., et. al (2019)	production from low-enthalpy deep geothermal projects		construction, operation	

The FU was specified in 21 of the studies and was found to be quite variable, but the one most frequently used according to Table 2, was 1 kWhe. 21 out of the 24 studies from Table 2 had specified a system boundary, where cradle to grave was the most common interpretation for the scope of the study. All the 24 studies from Table 2 had specified a geothermal application, where geothermal electricity production was dominant. Figure 3 highlights the variability of FU, system boundaries and geothermal applications from Table 2. The results clearly show that the scope of the LCA studies of geothermal development has been on geothermal electricity production (1 kWhe) with the most common system boundaries as cradle to grave.





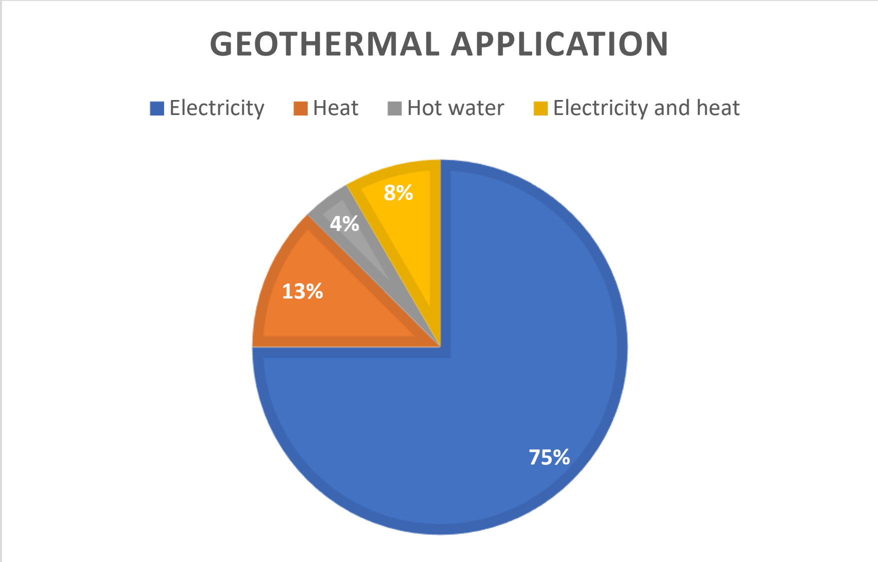


Figure 3. The Variability of FU, system boundaries and geothermal application within the LCA panorama.

Technology

To discuss and compare the impact from different geothermal power plants one must consider the technology used. The common generator technologies to utilize heat from the earth (high to low enthalpy) to produce electricity are e.g. dry steam, flash, binary, ORC and Kalina cycle. Hybrid solutions (Flash/Binary) are also encountered. The technology used depends on the type of geothermal application (electricity, heat, or combined heat and power), the site-specific properties (geological, geochemical, geophysical and thermodynamic) of the geothermal resource, and whether it is a vapor dominated system, liquid dominated system or hot dry rock.

According to (Lund, et al., 2008) geothermal systems suitable for power generation are categorized based on temperature: vapor dominated systems at temperature >240 °C, liquid dominated system with temperature up to 350°C and petro-thermal or solidified hot dry rock resources with temperature up to 650°C.
Enhanced Geothermal Systems (EGS) are associated with hydrothermal systems where hydraulic, thermal or chemical stimulation is needed to enhance the connection of wells with the hydrothermal reservoir. The preferred technology for a liquid-dominated system with temperature below 200°C is a binary cycle, while flash cycles are preferred for high temperature, vapor dominated systems. According to (Bertani, 2016) the share of these technologies of the worldwide installed capacity on geothermal energy is as follows: Binary cycle 14%, with greatest share from U.S., New Zealand, Philippines and Turkey; Dry steam, 23%, with greatest share from U.S., Italy and Indonesia; Single flash, 41%, with greatest share from Philippines, Indonesia and Iceland.

Several countries also use low enthalpy geothermal resources for heating and industrial and commercial applications, such as Iceland, France, Hungary, Romania and more. In this case the water can be used directly, or by heating fresh water using a heat exchanger.

Out of the studies in the LCA panorama, 18 specified an installed electrical capacity and six specified an installed thermal capacity. In many cases it was not a specific installed capacity that was considered, but a range of capacities with several scenarios. We have analysed these by range of capacities in order to see how big the projects are that are being studied. As can be seen from Figure 4 most of the studies focused on projects with an installed electrical capacity of less than 100 MW, and in particular, less than 10 MW. For installed thermal capacity, most focused on projects with less than 10 MW installed capacity, and the only one with over 100 MW capacity is the Hellisheidi geothermal plant in Iceland. This shows that the

LCA studies are mainly focused on smaller projects. Most of the projects studied used binary technologies for electricity production.

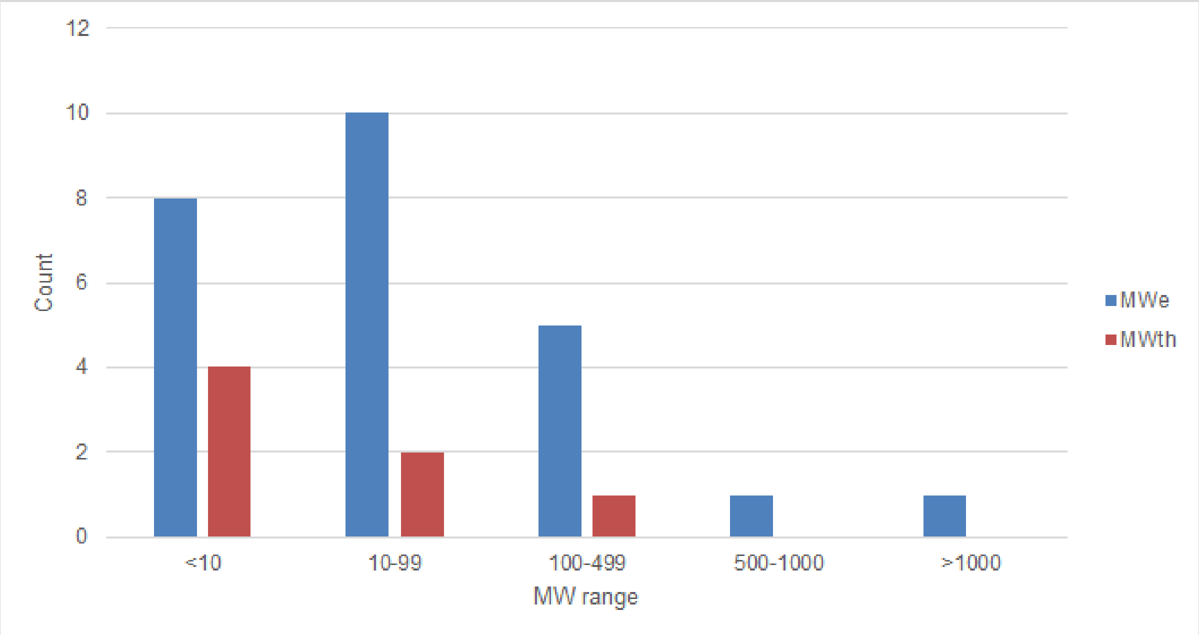


Figure 4 Installed capacities specified in the LCA panorama studies.

Impact assessment method

Several Life Cycle Impact Assessment Methods (LCIA) are found in the panorama. Table 3 describes the most common impact categories (not specific to geothermal systems) that can be found from the different methods (Acero, et al., 16 March 2015). There are also several softwares that can be used to perform a Life Cycle Assessment. The most common ones are SimaPro, GaBi, and OpenLCA.

Table 3. *The most common impact categories from the different LCA methods.*

Methods	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy use	Eutrophication	Human Toxicity	Ionising Radiation	Land Use	Odour	Ozon Layer Depletion	Particulate Matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	X	X	X	X	-	X	X	-	-	-	X	-	X
CML (non baseline)	X	X	X	X	-	X	X	X	X	-	X	X-	X
Cumulative Energy Demand	-	-	-	-	X	-	-	-	-	X	-	-	-
eco-indicator 99 (E)	X	X	X	X	-	X	X	X	X	-	X	X	-
eco-indicator 99 (H)	X	X	X	X	-	X	X	X	X	-	X	X	-
eco-indicator 99 (I)	X	X	X	X	-	X	X	X	X	-	X	X	-
Eco-Scarcity 2006	-	-	X	-	-	-	-	-	-	-	-	-	-
ILCD 2011, endpoint	X	X	-	-	-	X	X	X	X	-	X	X	X
ILCD 2011, midpoint	X	X	X	X	-	X	X	X	X	-	X	X	X
ReCiPe Endpoint (E)	X	X	X	X	-	X	X	X	X	-	X	X	X
ReCiPe Endpoint (H)	X	X	X	X	-	X	X	X	X	-	X	X	X
ReCiPe Endpoint (I)	X	X	X	X	-	X	X	X	X	-	X	X	X
ReCiPe Midpoint (E)	X	X	X	X	-	X	X	X	X	-	X	X	X
ReCiPe Midpoint (H)	X	X	X	X	-	X	X	X	X	-	X	X	X
ReCiPe Midpoint (I)	X	X	X	X	-	X	X	X	X	-	X	X	X
TRACI 2.1	X	X	X	X	-	X	X	-	-	-	X	X	X
USEtox	-	-	-	X	-	-	X	-	-	-	-	-	-

Based on the panorama of the LCA studies, the majority of the impact categories used in the studies on geothermal power projects are shown in Figure 5 and listed in Table 4. The main emphasis has been set on climate change. The four most common impact categories in LCIA of geothermal systems are:

- Climate change
- Acidification Potential
- Terrestrial Eutrophication Potential
- Human Toxicity

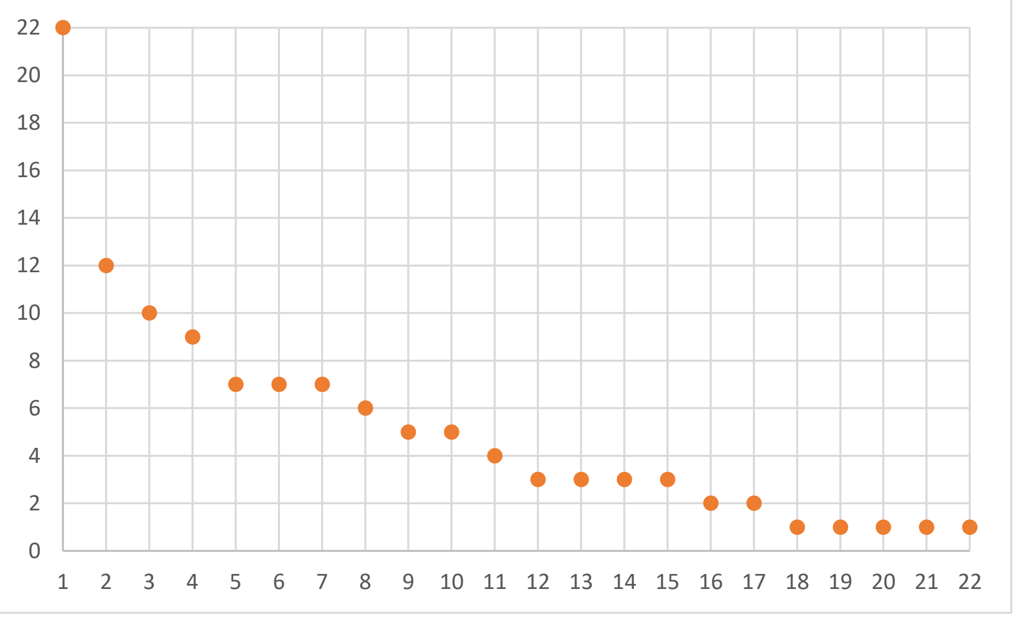


Figure 5. Frequency of the impact catagories used in the panorama of LCA studies on geothermal power projects.

Table 4. *Representative names for the impact catagories on Figure 5.*

Number	Impact Categories
1	Climate change
2	Acidification Potential
3	Terrestrial Eutrophication Potential
4	Human Toxicity
5	Abiotic Depletion Potential
6	Cumulative Energy Demand Renewable
7	Photochemical Oxidant Formation Potential
8	Ozone layer Depletion Potential
9	Fresh Water Aquatic Ecotoxicity Potential
10	Terrestrial Ecotoxicity Potential
11	Marine Aquatic Ecotoxicity Potential
12	Cumulative Energy Demand Non - Renewable
13	Natural land transformation (Land Use)
14	Particulate matter formation
15	Water consumption / water depletion
16	Fossil depletion
17	Metal depletion
18	Agricultural and Urban occupation
19	Energy Pay-Back Time (EPBT)
20	Freshwater Eutrophication Potential
21	Ionizing radiation
22	Marine Eutrophication Potential

In the cases where the LCIA methodology used for the various studies was specified in the panorama (excluding review studies), high variability was observed with 16 different methods used. The only method used in more than 1 study was ILCD 2011, midpoint (Table 5).

Table 5. *LCIA methodology used in the panorama studies*

LCIA methodology	Occurrence in studies
CML 2 baseline 2000 v 2.05	1
CML 2001	1
CML 2002	1
CML baseline 2000	1
CML method	1
CML-IA (mid-point level)	1
Cumulative Energy Demand (CED) v 1.08	1
Ecoindicator99-(h,a)	1
ILCD 2011, midpoint	3
Impact2002+ & seismicity risk	1
IPCC 2007	1
IPCC 2007 GWP 100 Midpoint	1
IPCC 2008	1
ReCiPe (H) Midpoints, Europe	1
THEMIS	1
TRACI	1

Comparison of GSAP and results from WP2 in GEOENVI

The aim is to challenge the environmental topics of the GSAP against the environmental aspects related to geothermal development addressed in WP2 (impacting phenomena and consequences) (GeoEnvi, 2019). This is done by observing if all the environmental aspects in the database of WP2 on environmental impacts are assessed in the preparation and operational stage in GSAP.

The comparison revealed that several of the impacting phenomena and consequences mentioned in database of WP2 are also mentioned (however, not in the same detail as in the database) and assessed in the GSAP. Figure 6 gives information on each impacting phenomena and consequences from the wiki sheet database, and under which topic in the GSAP they are assessed.

These impacting phenomena are:

- Surface wastes production (**risk**)
- Disturbance from surface operations (**impact**)
- Energy consumption and emissions to the environment from surface operations (**impact**)
- Liquid or solid effusions and wastes (impact/risk)
- Degassing (**impact**)
- Radioactivity (**impact**)
- Ground surface deformation (**impact/risk**)
- Induced seismicity (**impact/risk**)
- Pressure and flow changes in reservoir (**impact**)
- Interconnection of aquifers and disturbance of non-targeted aquifers (**risk**)

- Thermal changes (**impact**)
- Chemical changes (**impact/risk**)

The impacting phenomena or consequences that are however, **not specifically addressed in GSAP** but are given attention in the wiki sheet database on environmental aspects are:

- Blowout (relatively rare phenomena, **risk**)
- Leak due to surface operation (**risk**)
- Depletion of drinking water aquifer (consequence, **risk**)

Further information on each topic from the GSAP, including e.g. scoring card, issues related to the topic and avoidance/ mitigation measures can be found in Appendix C

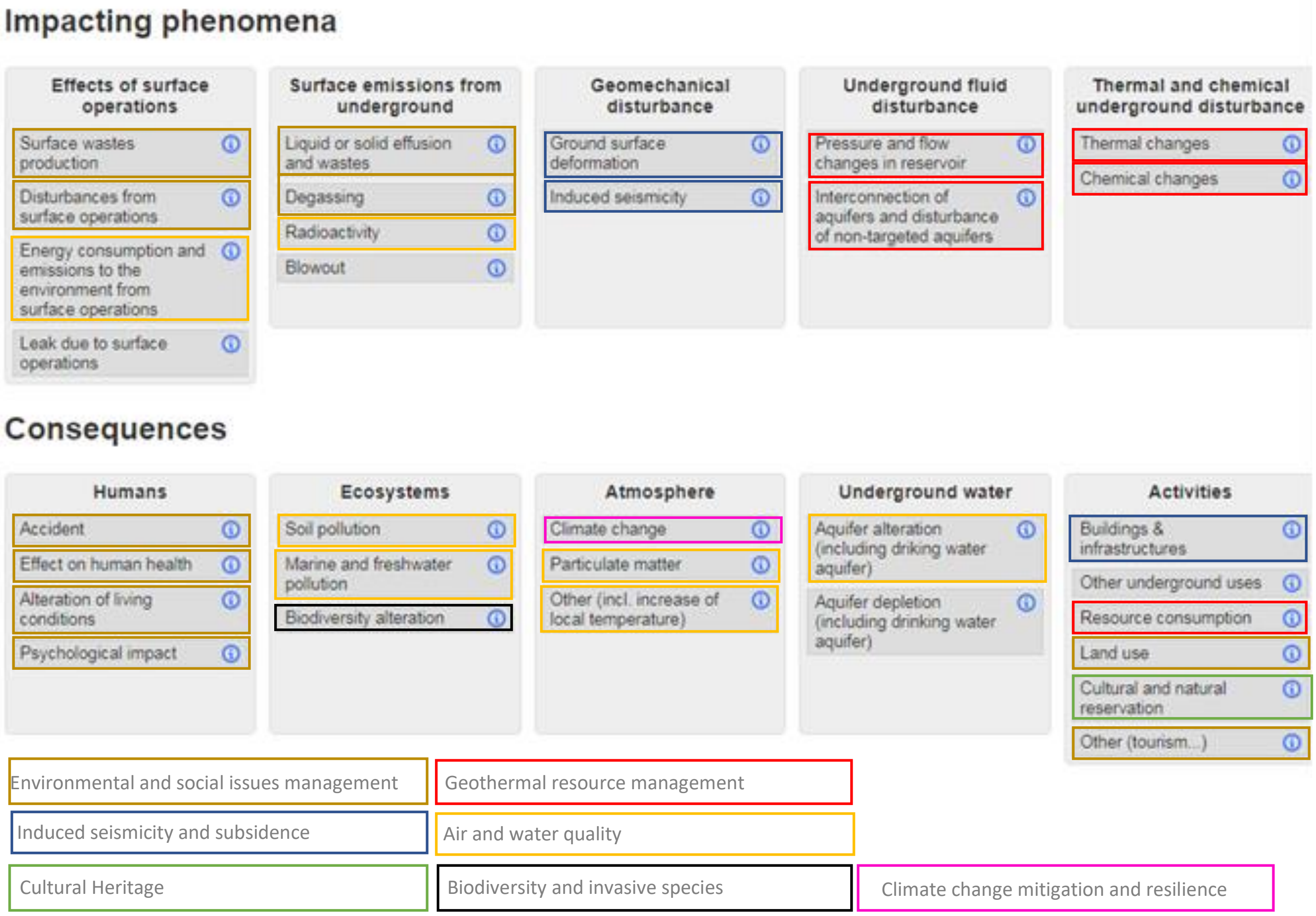


Figure 6. information on each impacting phenomena and consequences from the wiki sheet database, and under which topic in the GSAP they are assessed

Discussion

Analysis of a panorama of LCA studies

The objective of the panorama analysis is to address the variability among the LCA studies based on goal and scope, technology and methodology. Here below we will discuss and highlight the impacting phenomena that are not assessed in the LCA method or needs further adjustment to fit the application to the geothermal sector, based on the results from WP2.

The environmental impacting phenomena, according to the wiki sheet database of WP2, that **cannot be addressed** in the LCA methodology on geothermal development, due to the **lack of impact indicators** to quantify the impacts or because the topic is considered a **risk** are:

- Geomechanical disturbance: **Seismicity:** Low level of induced seismicity (i.e. micro seismicity) is an **impact** of some geothermal projects but **risk** in others. It means micro seismicity will be an unavoidable consequence of some geothermal projects. If the seismicity reaches a given threshold in magnitude (or any other parameter measuring the severity of an event) it becomes **a risk**. This limit between risk and impact is not fixed but depends on local considerations (GeoEnvi, 2019). **Ground surface deformation:** Ground subsidence because of extraction of geothermal fluids is an **impact** of human activity. There is a **risk** of larger deformation than anticipated depending on the compressibility of geological layers within the reservoir (GeoEnvi, 2019).
- Blowout is a **risk.**
- Disturbance from surface operations, where geothermal activities cause various disturbances due to surface operations during construction work, drilling and maintenance or decommissioning of a plant is an **impact.**
- Leaks due to surface installation and operations is a **risk.**
- Underground fluid disturbance: **Pressure and flow changes** due to geothermal utilization in a reservoir are an **impact** and **interconnection of aquifers and disturbance of non-targeted aquifers** is a **risk**.
- Reservoir thermal modifications related to geothermal utilization are an **impact.**

As for the consequences of the environmental impacts mentioned, these are the topics that **cannot be addressed in LCA** methodology due to the same reasons as above:

- On humans (Accident, Alteration of living conditions, Physiological impact)
- On atmosphere (other, e.g. local increase in temperature)
- For activities (Buildings and infrastructures, cultural and natural reservation, other e.g. tourism.)

The impact of *"Disturbance from surface operations"* seems to partly be covered in the LCA methodology, based on the classification of the wiki sheet database (Figure 6). Surface disturbance including vibration, noise, visual, dust is generally not a part of LCA impact assessment, but land use is (Table 3), see e.g. (Karlsdóttir, et al., 2015).
Regarding the impacting phenomena of *"Chemical changes",* clogging of pipes due to deposition and corrosion of equipment are considered **impacts,** and so is the contamination of surface waters due to magmatic fluids, but the content of toxic elements in liquid and solid (e.g. clean from scaling deposits) waste is an environmental **risk** (GeoEnvi, 2019). The matter of pipe scaling and corrosion is possible to be treated in LCA. Lacking an impact indicator in the LCA methodology is the impact/risk of *"Geomechanical disturbance"* (ground surface deformation and seismicity). Reservoir pressure and flow changes, and reservoir thermal modifications caused directly by geothermal utilization are also lacking an impact indicator in the LCA methodology (GeoEnvi, 2019).

Based on this, there are clearly several impacting factors in the geothermal environment that currently may not be possible to include or be adjusted into the LCA tool. It is important for the LCA tool to be able to be used effectively on geothermal projects on a local, regional and global scale, and many of these non-included impacting factors have proven to be controversial and decreased public acceptance of geothermal projects. This highlights the need for harmonized guidelines in LCA for assessment of the environmental aspects of geothermal projects, as well as the possible benefit of using other methods (e.g. GSAP) to assess those factors.

The making of harmonized guidelines for assessment of the environmental aspects of geothermal projects might be somewhat challenging e.g. due to the high variability (e.g. geological, geophysical, chemical) between project sites, different types of geothermal systems (e.g. hot dry rock, sedimentary basin, convective fracture systems, geo-pressurized systems, volcanic geothermal systems) and their behavioural pattern, technologies, and methodologies used. Operational time and number of wells of geothermal projects is also highly variable, resulting in difference in available research and experience at each project site. A problem could also arise where some of the non-included environmental impacting phenomena in the LCA methodology, based on the wiki sheet database, are in some projects an impact and in other a risk. Some of these environmental issues are considered somewhat more important to be adjusted and included into the LCA methodology, if possible. *"Geo-mechanical disturbances"* (seismicity and surface ground deformation) are considered highly important, based on the negative public opinion on the matter, where the geo-mechanical disturbance is likely to have consequences on humans, ecosystems, groundwater resources and general activities (e.g. buildings) (GeoEnvi, 2019). Also, the natural degassing regime of geothermal systems have proven to be linked to variations in natural seismicity and ground deformation. A study from Krýsuvík, Iceland, has proven the natural degassing regime to be highly variable over short timescales, with changes in fumarole activity and fluctuations in gas composition which is linked to variations in natural seismicity and ground deformation in the area (Gudjónsdóttir, et al., 2018).

In general, the impact of chemical degassing related to emissions from geothermal power plants is assessed in the LCA methodology. However, gas emissions due to geothermal utilization has other aspects as well. As discussed in the „*Degassing*" wiki sheet of WP2, extraction of fluid from deep geothermal reservoirs can affect the balance of the CO_2 processes (GeoEnvi, 2019). Withdrawal of a large volume of geothermal fluid can cause some pressure changes with pressure being lowered in the system, depending on the size of a geothermal reservoir, its permeability, reservoir storage capacity, water recharge and geological structure including formations and fractures (GeoEnvi, 2019). The lowering of pressure can create a steam cap and the uppermost part of the system can form or increase a boiling zone. This has been shown to result in an easier path for the steam up towards the surface with increased heat flow and CO_2 emissions through the soil (Óladóttir, 2012). The pressure normally declines most rapidly at the beginning of utilization, but the change is slowed down, and the pressure will reach a balance when the production from the reservoir does not exceed its recharge, natural from open boundaries and/ or from reinjection (GeoEnvi, 2019). For Reykjanes, Iceland, the CO_2 emission trough the soil increased from 13.5 +/- 1.7 tons/year to 36.6 +/- 3.9 tons/year over an 8-year period after production started from the reservoir (Óladóttir, 2012) and had not yet reached a balance. This change in the system's degassing behavioural pattern is important in an environmental impact assessment, with tools such as the LCA methodology. Mitigation measures have been used on geothermal projects, in order to minimize the power plant's emissions and pressure changes within the system. This includes e.g. technologies of partial or complete reinjection of the geothermal fluid (liquid+NCG) at operation level (GeoEnvi, 2019) and AMIS abatement system which has demonstrated its effectiveness in the reduction of H_2S, CO_2 and Hg to the atmospheric environment at commercial level (Parisi, et al., 2019).

The chemical content of the geothermal fluid can be highly variable between geothermal sites, near and far. The composition of the fluid depends on several factors e.g. source of the fluid, depth of the well, type of reservoir rock (water-rock interaction) and the system's heat source. This results in highly variable gas emissions at surface, both with various H_2O/gas ratios, as well as various individual gas species amounts (e.g. CO_2, H_2S, NH_3, CH_4). These gas species can have variable effects on the environment, as well as human health see e.g. (Karlsdottir, et al., 2019). The high variability of gas emissions from geothermal power plants has been observed on local scale in Iceland (Figure 7). Emissions of CO_2 per kWh from Svartsengi and Krafla power plants are considerably higher than emissions from Nesjavellir and Hellisheidi power plants in the Hengill geothermal area, despite Svartsengi being less than 100 km away from these power plants.

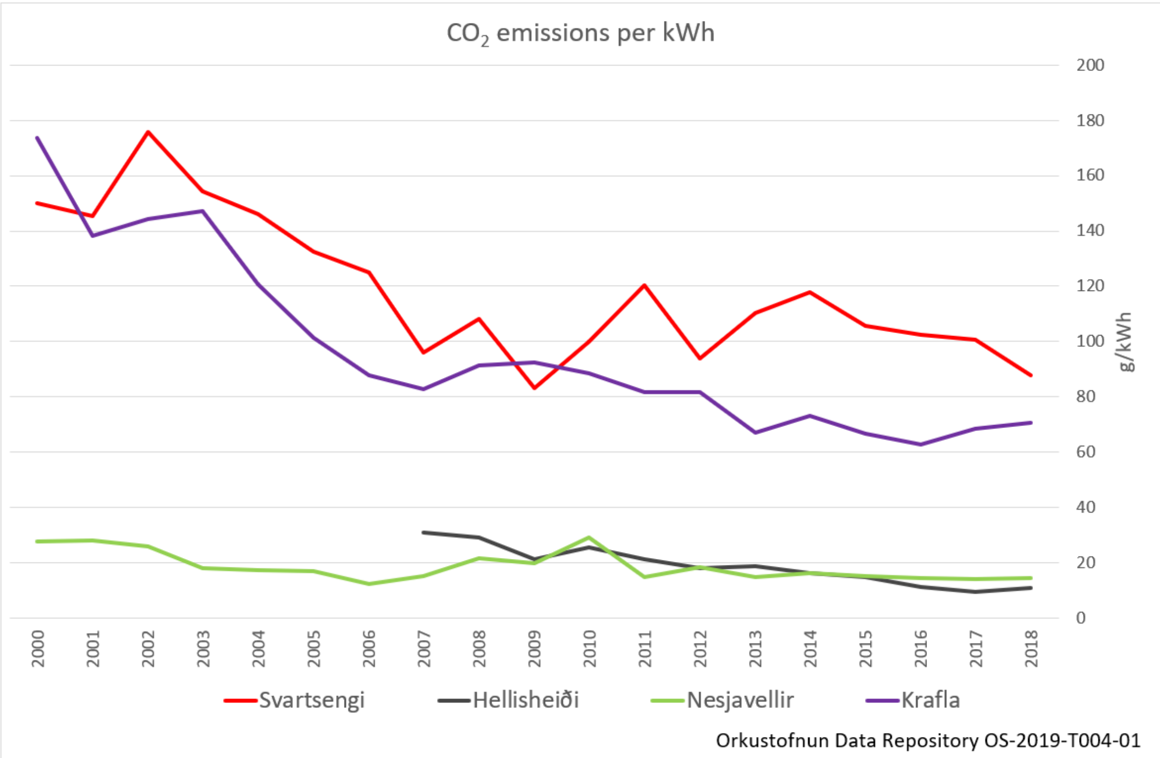


Figure 7 Showing the variability of CO_2 gas emissions per kWh from selected power plants in Iceland from 2000-2018 *(Orkustofnun, 2019)*.

Many geothermal LCA studies (Bayer, et al., 2013; Tomasini-Montenegro, et al., 2017; Frick, et al., 2010; Bravi & Basosi, 2014; Pratiwi, et al., 2018) agree that the contributing factors for the high variability of environmental impacts is the local geological characteristics such as chemical content of the fluid, temperature and technology. S. Frick (2010) (Frick, et al., 2010) shows that environmental impact results are significantly influenced by the geological condition at a specific site. According to (Karlsdottir, et al., 2019) the results of her study from Hellisheidi, Iceland, cannot be generalized for other geothermal power plants due to variations in chemical content of the geothermal fluid. Other impacts of her study, that were not addressed in the LCIA, were induced seismicity, due to reinjection of geothermal fluids, local temperature changes due to release of hot geothermal fluids, and loss of biological diversity due to habitat destruction or effects of release of geothermal gases or fluids.

Actions taken in order to assess the environmental impact of geothermal development, with the LCA methodology, are a crucial step to make the geothermal industry more environmentally friendly, especially in the eye of the general public. It is considered highly necessary to continue to develop the LCA method for geothermal development.

Combability between GSAP and WP2 results

Based on the results of this study the GSAP complies over all very well to the overview of the environmental aspects covered in the wiki sheet database, with only three environmental aspects not specifically addressed in comparison to the WP2 database (blowout, leak due to surface operations and aquifer depletion). The setup and use of the protocol differ in many ways from the setup and use of the database. In the database special interest is given to each issue on environmental impact and risks, which has its own topic where each of the following sections are covered:

1. Origin
2. Risk/impact
3. Consequence
4. Project phases
5. Influencing context
6. Monitoring
7. Prevention and mitigation
8. Perception
9. Regulation
10. Illustrative example
11. References
12. To go further

Each topic of causes and consequences in the database are briefly described, but not nearly as detailed as the impacting phenomena. In the GSAP the issues related to geothermal development (incl. impacting phenomena and consequences from the wiki database) are more combined and generally addressed in an assessment guidance for each topic, relevant to the circumstances for each project. This difference is related to the different objectives of the two projects. The GSAP is a protocol and a management tool that is to be used by a specialist to assess the performance of the various geothermal power projects regarding social, environmental, technical and economic factors. The Wiki sheet database, on the other hand, is designed as an information tool on the environmental aspects of geothermal development, for the public and shareholders. Still, the database is a good tool for comparison with the GSAP as some of the GSAP topics could be somewhat adjusted better to the results of WP2.

Based on the results, it would be advised to specially address in some way the risk of the risk of "*leak during surface operation*". According to the wiki sheet database there are two main types of leaks due to surface installation 1) leakage or overflow of storage tanks containing geothermal fluids, drilling mud, fuel or any type of liquid and chemicals used during stimulation 2) leakage of a pipe belonging to the primary or secondary loop system (GeoEnvi, 2019), causing various consequences for humans, ecosystem and underground waters.

Geothermal blowouts are a relatively rare risk, caused by uncontrolled flow of reservoir fluids, whether into the well while drilling, or out of the wellbore into the formation above the reservoir, or to the surface (GeoEnvi, 2019). The risk of a blowout is not specially assessed in the GSAP (preparation and operation protocol). However, in the topic of "*integrated project management*" in the GSAP, geothermal resource management and drilling are assessed, which is concluded to cover the risk of a blowout from the wiki sheet database. Geothermal blowouts are highly likely to cause only minor and local impact and should be monitored closely with prevention and mitigation measures adjusted to the circumstances (e.g. geological, siting and design) of each project.

Depletion of groundwater aquifers is not specifically mentioned, even though the GSAP addresses aquifer alteration (water quality) and the continuous evaluation of the capacity of the reservoir that is somewhat related to this topic of consequence.

It should, however, be stated that according to the assessment guidance for environmental and social issues in the GSAP, those issues specifically mentioned in the chapter are only an example of the key environmental factors usually observed during geothermal development. The appropriate expertise is always sought from specialties prior and during each project, e.g. due to the variability between environmental areas between projects. The avoidance and mitigation process are a sequential process and measures to avoid and/or mitigate negative or adverse environmental impacts are always prioritised, and when avoidance is not possible, then minimisation of adverse impacts is sought in the appropriate way for each issue. And finally, when neither avoidance nor minimisation are practicable, then mitigation and compensation measures are identified and undertaken commensurate with the project's risk and impacts.

Need for harmonized guidelines

Since the results of this study indicate that current published LCAs have proven to be not yet fully able to cover all the environmental impacts of geothermal development, it is suggested that recommendations on the choice of adapted environmental indicators should be included in the foreseen LCA guidelines adapted to geothermal installations (D3.2). This would make the LCA tool more efficient and fitted for geothermal projects on local, regional or global scale. Therefore, there is clearly a need for harmonized guidelines for LCA in geothermal development, and some of the challenges to overstep for that work have been pointed out. The main purpose of the guidelines would be to reduce the methodological, technological and spatial variability in LCA for geothermal development. The development of these guidelines is a part of the work in WP3 of the GEOENVI project (Deliverable 3.2).

Conclusion

- The analysis of a panorama of LCA studies has highlighted the high variability related to the goal and scope of the studies, their temporal, technological and methodological variability.
- There are clearly several impacting factors in the geothermal environment that may not be possible to include into the LCA tool, and some that might need further adjustment to the geothermal environment, if possible. It is important for the LCA tool to be able to be used effectively on geothermal projects on a local, regional and global scale. Some of these impacting factors have proven to be controversial and decreased public acceptance of geothermal projects. That highlights the need of harmonized guidelines in LCA for assessment of the environmental aspects of geothermal projects.
- The making of these harmonized guidelines might be somewhat challenging due to the high variability between project sites, different types of geothermal systems and their behavioural pattern, technologies, and methodologies used. Operational time and number of wells of geothermal projects is also highly variable, resulting in difference in available research and experience at each project site. A problem could also arise where some of the non-included environmental impacting phenomena in the LCA methodology, are in some projects an impact and in other a risk.
- The Geothermal Sustainability Assessment Protocol (GSAP), is a modified management tool based on the widely accepted Hydropower Sustainability Protocol (HSAP), with the aim to measure, guide and improve the industrial performance of geothermal power projects, based on four key factors: social, environmental, technical and economic, with the main factor of this report on the environmental assessment. The GSAP draft has currently been tested twice. Theistareykir (preparation stage) and Hellisheidi (operation stage) with success.
- The GSAP complies over all very well to the overview of the environmental aspects covered in the wiki sheet database from WP2, although some of the GSAP topics could be somewhat adjusted to better cover all the environmental issues addressed. Development of protocol for end of life has not been discussed for the GSAP.
- The LCA and the GSAP are highly different tools, but both can be used to assess environmental aspects in different ways. LCA is a performance tool, but the GSAP has a much broader scope of sustainability assessment, and is more of a management tool, used to try and improve the performance of each project. Both methods have their validity, but which method to use (or a combination of the two) should be based on the preferred outcome of the planned assessment.

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Appendix

Appendix A

List of studies in the Panorama of LCA studies

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Appendix B

The panorama of LCA studies (separate excel file).

Appendix C

Geothermal Sustainability Assessment Protocol, Preparation stage and Operation stage (separate pdf files).

Appendix D

In the GSAP Public health (and safety) is, among other health and safety issues, assessed in the topic of "*Public Health and Safety"* (O-6 and P-8). The topic addresses management of hazardous and polluting impacts from geothermal operations and other health and safety issues to its specific location, available data, and national regulations. Here we will give an extraction for the assessment at operation stage at Heillisheidi (Orka náttúrunnar, 2018), focused on human health (toxicity). The assessment was divided into sub-chapters:

- Background information, where e.g. the key aspects of geothermal projects with potential impacts on public health and safety are addressed
- Detailed Topic Evaluation divided into 5 evaluation topics: Assessment, Management, Conformance/Compliance, Outcomes and Evaluation of significant gaps.
- Scoring Summary
- Relevant Evidence, interviews, documents and photos (see Appendix C)

In the Detailed Topic Evaluation all the 5 evaluation topics are given an analysis against basic good practice and analysis against proven best practice:

Assessment

Analysis against basic good practice

Scoring statement: *Routine monitoring of health and (safety) issues related to the operating facility and other infrastructure is being undertaken to identify risks and assess the effectiveness of management measures; and ongoing or emerging health and (safety) issues have been identified.*

The main issues related to public health (human toxicity, safety excluded) directly related to the Hellisheidi plant are:

- Human exposure to H_2S emissions from the plant

H_2S emissions are well monitored as described under topic O-16 (Air and Water Quality). The potential health impacts of such emissions are not well understood, but as described under O-16, Iceland has implemented **stricter regulations** those recommended by the WHO, by a factor of 3. Under this chapter results from studies e.g. reporting about increased cancer risks from the exposure to high-temperature geothermal areas in Iceland, and on the negative impacts on people who suffer from respiratory illnesses such as asthma were also assessed.

Criteria met: yes

Analysis against proven best practice

Scoring statement: *In addition, identification of ongoing or emerging health and (safety) issues for the public and neighbouring communities takes into account consideration of a broad range of scenarios and both risks and opportunities.*

For human health and toxicity in Hellisheidi, the assessment was focused on the Icelandic health system and its place to identify any negative impacts to the population as a result of typical hazards of geothermal power generation. And to identify if the project´s manager (here OR/ON) support the research by academic institutions in order to improve the tools available for the analysis of public-health issues such as H_2S exposure.

Criteria met: yes

Management

Analysis against basic good practice

Scoring statement: *Hazardous and polluting geothermal impact and other health and (safety) management plans and processes have been developed in conjunction with relevant regulatory and local authorities with no significant gaps and provide for communication of public health and (safety) measures; emergency response plans and processes include awareness and training programs and emergency response simulations.*

Regarding human health and toxicity, these were the main findings:

Staff at the Hellisheidi plant take part in the University of Iceland studies into the long-term effects on the dose response relationships for human exposure to H_2S.

Criteria met: yes

Analysis against proven best practice

Scoring statement: *In addition, processes are in place to anticipate and respond to emerging risks and opportunities; and public health and (safety) measures are widely communicated in a timely and accessible manner.*

Overall, there are well-functioning processes for the anticipation and response identification for public health and (safety) issues in place and these are also communicated in a timely and accessible manner. Some stakeholders’ express concerns regarding communications between project and Government staff as well as some academic experts on one hand, and the project-affected communities on the other. The communities do not consider the communication on public health and (safety) issues to be appropriate to them.

Criteria met: no

Conformance / Compliance

Analysis against basic good practice

Scoring statement: *Processes and objectives relating to public health and (safety) have been and are on track to be met with no major non-compliances or non-conformances, and health and (safety) related commitments have been or are on track to be met.*

All processes and objectives, as well as commitments have been or are on track to be met, without major non-compliances or non-conformances.

Criteria met: yes

Analysis against proven best practice

Scoring statement: *In addition, there are no non-compliances or non-conformances.*

There are no non-compliances or non-conformances.

Criteria met: yes

Outcomes

Analysis against basic good practice

Scoring statement*: Health and (safety) risks have been avoided, minimised and mitigated with no significant gaps*

All identified risks have been either avoided, minimised or mitigated without significant gaps at this level.

In the case of perceptions of the project-affected communities, facts are of the utmost importance and the lack of knowledge about the impacts to humans from H_2S exposure is a serious issue in need of attention. The contribution by OR/ON to research into this issue is positive but appears to need significant increase as the issue is a high-profile one suffering from inconclusive studies

Criteria met: yes

Analysis against proven best practice

Scoring statement: *In addition, health and (safety) risks have been avoided, minimised and mitigated with no identified gaps; and health and safety issues have been addressed*

All identified risks have been either avoided or minimised or mitigated without gaps, except the perception of risk on the part of project-affected communities, especially Hveragerdi, but also people in the nearby town of Selfoss and in the capital region. Evidence indicates that there is low trust among some project-affected communities in the information disseminated on, especially, health risks associated with H_2S releases. The lack of active promotion of research into exposure-response relationships in order to resolve the issue of health hazards caused by the H_2S emissions is a significant gap.

Criteria met: no

Evaluation of Significant Gaps

Analysis of significant gaps against basic good practice

There are no significant gaps against basic good practice.

0 significant gaps

Analysis of significant gaps against proven best practice

There is a lack of active promotion of research into H2S exposure-response relationships.

1 significant gap

Scoring Summary

The main significant public health risk is exposure to H_2S emissions

Some studies have been conducted on health risks such as cancer and respiratory illnesses, but they have yielded low and inconclusive results. OR/ON do support some research into the health aspects of H_2S emissions but given the high profile this issue has in the project-affected

community, and the time that has passed since the impacts were discovered, there could be a more concerted effort to encourage and support research able to resolve this issue.
There is one significant gap, resulting in a score of 4.

Overall, the test was proven to be successful (Figure 8), with results showing a range of high scores (Johannesson, et al., April 26-May 2, 2020; Náttúrunnar, 2018).

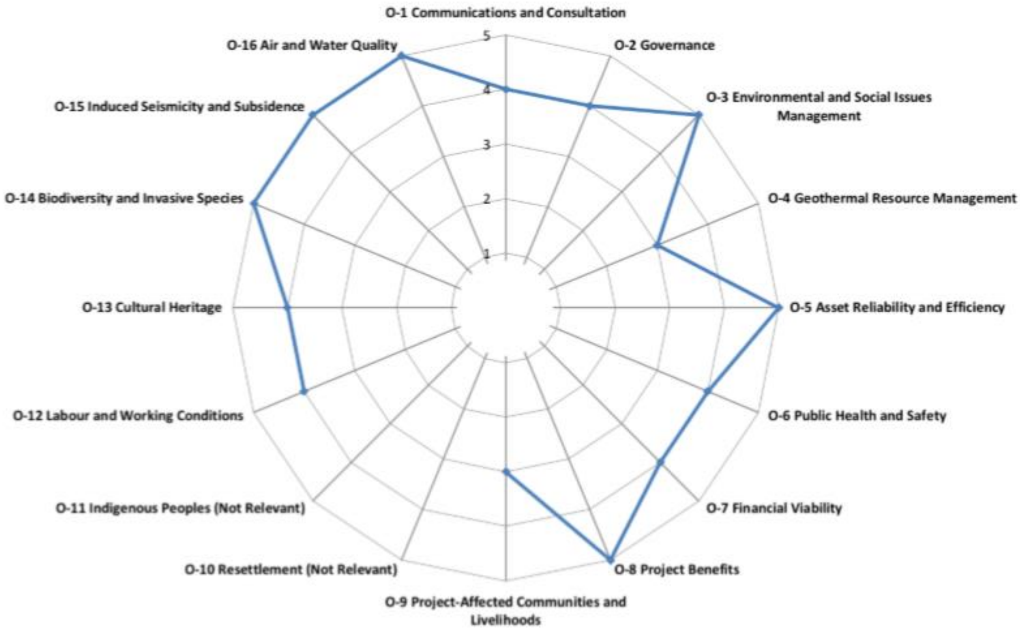

Figure 8. *The results of the GSAP assessment in Hellisheidi at operation stage.*

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