ORCHYD

HORIZON 2020

"Novel Drilling Technology Combining Hydro-Jet and Percussion for ROP Improvement in deep geothermal drilling"

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101006752

DELIVERABLE 3.1

"Report on Environmental Impacts"

ABSTRACT

This deliverable assesses the environmental impacts of the ORCHYD project, which aims to increase the rate of penetration (ROP) of hard rock drilling rates from the current range of 1 to 2 m/h to a range of 4 to 10 m/h by combining High Pressure Water Jetting and Percussive Drilling. Background information on onshore drilling is presented initially. Related HORIZON 2020 projects are discussed in Chapter 2. Chapter 3 discusses the environmental impacts of deep geothermal energy development on the lithosphere, atmosphere, hydrosphere, and biosphere. Chapter 4 focuses on impact characterization and quantification. The effects of ROP improvement on carbon footprint, ozone depletion, acidification potential, smog, eutrophication, and energy consumption are investigated using Life Cycle Analysis (LCA). ORCHYD's goal of increasing ROP rates will reduce these environmental impacts of deep geothermal drilling. Risk Analysis (RA) has been utilized for the assessment of induced seismicity in deep geothermal projects. The Ecological Footprint Assessment revealed that ROP enhancement had a positive impact on reducing the ecological impact of geothermal deep drilling. Overall, ORCHYD has the potential to significantly reduce environmental impacts. The report is rounded up with mitigation and prevention measures that are presented in Chapter 5.

DOCUMENT TYPE	Deliverable
DOCUMENT NAME:	Deliverable 3.1. "Report on Environmental Impacts"
VERSION:	vfinal
DATE:	31/12/2021
STATUS:	S0
DISSEMINATION LEVEL:	PU

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Review Approval:	Approved	Yes	Rejected (to be improved as indicated below)	
Remarks / Improvements:				

VERSION HISTORY			
VERSION:	**DATE:**	**COMMENTS, CHANGES, STATUS:**	**PERSON(S) / ORGANISATION SHORT NAME:**
0	6/12/2021	First draft version	John Paravantis (UPRC) Vasileios Parakostas (UPRC) Nikoletta Kontoulis (UPRC)
1	28/12/2021	After the first review	John Paravantis (UPRC) Vasileios Parakostas (UPRC) Nikoletta Kontoulis (UPRC)
vfinal	31/12/2021	Deliverable ready to be submitted	Naveen (Armines)

VERSION NUMBERING	
v0.x	draft before peer-review approval
v1.x	After the first review
v2.x	After the second review
vfinal	Deliverable ready to be submitted!

STATUS / DISSEMINATION LEVEL			
STATUS		**DISSEMINATION LEVEL**	
S0	Approved/Released/Ready to be submitted	**PU**	Public
S1	Reviewed	**CO**	

S2	Pending for review		Confidential, restricted under conditions set out in the Grant Agreement
S3	Draft for comments	**CI**	Classified, information as referred to in Commission Decision 2001/844/EC.
S4	Under preparation		

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1. Introduction

This report aims to (1) document the environmental impacts of ORCHYD qualitatively (Milestone 3.1); and (2) use appropriate methods (life cycle assessment [LCA], carbon footprint analysis, ecological footprint analysis, and risk analysis) to assess its most important impacts quantitatively (Milestone 3.2, Deliverable 3.1).

This report is structured in the following sections. Section 1 describes the project and the environmental setting. Section 2 documents related European projects. Section 3 assesses the environmental impacts of ORCHYD with subsections addressing land, soil, and groundwater; surface waters; atmospheric emissions, odors, and noise; and ecosystems, health impacts, socioeconomic issues, energy consumption, and material use. Section 4 review LCA, an important method of quantifying environmental impacts, expressing them in a unifying functional unit such as the carbon footprint, and identifying pollution hotspots that should be targeted for improvement. Section 5 proposes mitigation measures. Finally, Section 6 summarizes and concludes the report.

1.1. Description of environmental setting

Any analysis of the environmental settings adopts the conceptual model presented in Figure 1.1.

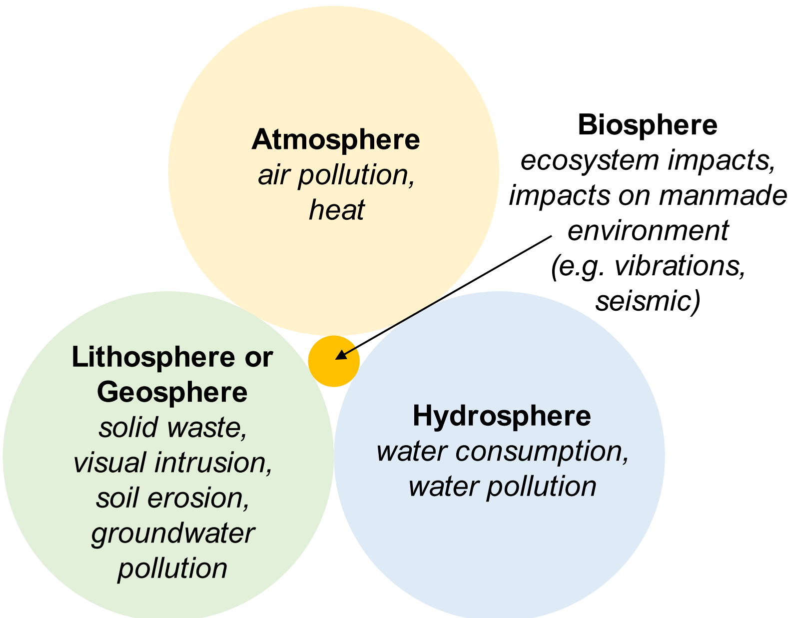


Figure 1.1. Conceptual model of the environment

In it, the environment is seen as a system of four (conceptual) spheres: atmosphere, hydrosphere, lithosphere, and the biosphere. The first three spheres contain the abiotic environment while the fourth contains the biotic environment.

Indicative environmental issues are shown underneath the name of each sphere. A complete list of impacts is analyzed in Section 3 and its subsections. Those impacts are characterized and some of those quantified in Section 4.

1.2. Description of project

ORCHYD targets the geothermal drilling of deep hard and hot rocks by increasing the rate of penetration and reducing the drilling cost, thus making the exploitation of deeper geothermal resources economical. Therefore, ORCHYD will impact the environment in the following two ways: (1) it will make drilling in established geothermal fields faster and cheaper, allowing it to reach deeper rock deposits; and (2) it will open up new areas of deep geothermal deposits to exploitation. The type of power plants that will be constructed is not an immediate concern of ORCHYD.

These considerations allow the elaboration of the following scenarios that are going to be considered in this report:

(0) *Baseline (no change in geothermal drilling)*: In this scenario (with zero indicating the status quo, without any changes), it is assumed that geothermal drilling continues to be done as it is done today, without adopting any of the innovative improvements that will be developed by ORCHYD. Any favorable or unfavorable environmental and socioeconomic effects of ORCHYD are disregarded.

(1) *Improved geothermal drilling*: In this scenario, it is assumed that geothermal drilling is carried out implementing all the innovative improvements developed by ORCHYD, thus reaching deeper hard rock deposits faster and cheaper. All favorable and unfavorable environmental and socioeconomic effects of ORCHYD are taken into account.

Exactly what will change as the world moves from Scenario 0 (baseline) to Scenario 1 (improved geothermal drilling)? Here is a partial list of such items that comes to mind:

- As the practice of geothermal drilling is improved globally, more geothermal deposits located in deep hard rocks will become economically exploitable. Energy markets and the energy security landscape of countries in Europe and near the Ring of Fire will change.
- The drilling depth of a typical geothermal well will increase, reaching up to 6 km.
- The time it takes to drill a typical geothermal well in hard rocks will decrease.
- Energy and water consumption and the use of materials for a typical geothermal well into deep hard rocks will change, probably significantly.
- The consumption and discharge of drilling fluids for a typical geothermal well into deep hard rocks will change both qualitatively (i.e., composition) and quantitatively (volume).
- The lifetime of a typical geothermal well will increase as well, as more deep dry rocks are exploited and it comes down to how long does it typically take for the host rock to cool down and the geothermal project to run out of steam (Homewood, 2018).
- Most of Europe can benefit from geothermal energy production, reducing reliance on imported energy, influencing climate change mitigation efforts, and influencing energy security and geopolitics in Europe and globally.

If it were not desired that the list be kept small, many more items, indirectly linked to ORCHYD's innovations, could be listed.

So, an important aim of this report is to catalog and analyze (qualitatively and quantitatively) the environmental (including socioeconomic) impacts that are expected from geothermal drilling utilizing the innovative technologies developed by ORCHYD (Scenario 1), as well as point out how will these environmental impacts differ from the environmental impacts of conventional geothermal drilling (Scenario 0).

Finally, this report must also examine the environmental impacts of ORCHYD, i.e., the research activities carried out in the context of the project itself, such as experiments and field tests.

2. Related European projects

A series of geothermal projects has been developed under the HORIZON 2020 initiative. A brief description of each with some findings is presented here, to help with a better understanding of recent geothermal developments. The section is complemented with Table 2.1, listing the main characteristics of each project.

2.1. H2020 projects

The DESCRAMBLE project (*Drilling in Deep, Super-Critical Ambient of Continental Europe*; Grant Agreement ID: 640573) aimed to develop a novel drilling technology for reaching ultra-high hot (up to 500°C) geothermal resources in the continental crust. It further tested and demonstrated novel drilling techniques for the control of gas emissions in an aggressive environment with high temperature and pressure. The primary goal of that project was to reduce the technical and financial risks associated with geothermal well drilling and exploitation. It focused on reducing drilling uncertainties through the use of a dependable drilling approach based on data provided during pre-drilling activities during the exploration phase. The environmental impact of the life cycle was only studied through the construction of a large power plant on a small piece of land (DESCRAMBLE, n.d.).

The GEODEPower project (*Cutting-Edge Deep Geothermal System and Drilling Technology Suitable for All Users and Locations*; Grant Agreement ID: 807809) aimed to develop a cutting-edge deep geothermal system and drilling technology which allows the exploitation of any location no matter the geological activity. Percussive air and water hammer drilling bits were investigated to improve ROP and drilling bit consumption when drilling medium depth wells. The project developed geothermal power plants capable of delivering energy in very low geothermal gradients (GEODEPower, 2018).

The GEOTech project (*Geothermal Technology for Economic Cooling and Heating*; Grant Agreement ID: 656889) aimed to develop a novel technology for economic cooling and heating through shallow geothermal ground source heat pump (GSHP)systems. The project employed drilling concepts based on the dry auger method, which requires cheaper equipment; enhances safety; and avoids risks. Cost effective and innovative drilling and ground heat exchanger technologies were also developed during the project (GEOTech, 2020). The concerns of this shallow geothermal project are far from those of ORCHYD.

The GeoTherm SWS project (*The First Truly Mobile Geothermal Drilling Rig*; Grant Agreement ID: 855257) aimed to develop the first truly mobile geothermal drilling rig. It aimed to achieve drastic cost optimization and developed an innovative compact, mobile, and easy to transport drilling rig for deep geothermal drilling. It incorporated a pioneering interchangeable drilling mechanism, which can operate under core/diamond, rotation and down-the-hole methods. This could result in a drilling cost reduction of 70% in small scale deep geothermal energy projects. The project could promote the development of small geothermal projects in isolated areas, reducing carbon emissions by 90% through the replacement of diesel generators. The development of a lightweight drilling system is regarded as an effective method of reducing the environmental impact of drilling as well as the costs of site preparation, thereby modifying the financial and environmental risks in geothermal exploration and production activities (GeoTherm SWS, 2019).

The GeoWell project (*Innovative Materials and Designs for Long-Life High-Temperature Geothermal Wells*; Grant Agreement ID: 654497) aimed to develop innovative materials for long life high temperature geothermal wells. The project addressed major bottlenecks (like high costs) and developed state-of-the-art material and design concepts. Novel cement and sealing technologies, casing materials, and flexible couplings were studied, aiming to minimize thermo-mechanical loadings. Fiber optic cable technology and applications for measuring temperature and strain in wells were also developed (GeoWell, n.d.).

The Cheap-GSHPs project (*Cheap and Efficient Application of Reliable Ground Source Heat Exchangers and Pumps*; Grant Agreement ID: 657982) aimed to develop cheap and efficient application of reliable ground source heat exchangers and pumps. Helicoidal ground source heat exchangers (GSHE) with a smaller external diameter of the heat basket were developed, for drilling operations at greater depths. The consortium complemented the design with a dry drilling technique. Coaxial steel GSHEs and improvement of existing technology for vertical borehole installation were also addressed. The main target was cost effective solutions, increasing the safety of shallow geothermal systems, and raising awareness for this technology throughout Europe. The developed technologies demonstrated increases in thermal energy exchange of 20-40% compared to the state of the art (Cheap-GSHPs, n.d.). The concerns of this shallow geothermal project are far from those of ORCHYD.

The CROWDTHERMAL project (*Crowdfunding Our Way to a Geothermal Future*; Grant agreement ID: 857830) targeted community-based development schemes for geothermal energy. The basic idea was the promotion of alternative financing schemes and social engagement tools. The public was encouraged to participate in the development and adoption of geothermal energy through social engagement tools and alternative financing schemes like crowdfunding. The project aimed to create a social acceptance model as a baseline for public support (CROWDTHERMAL, n.d.).

The DEEPEGS project (*Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business*; Grant Agreement ID: 690771) aimed to develop the idea of deploying deep enhanced geothermal systems for sustainable energy business. It targeted the delivery of innovative solutions and models for the wider deployment of enhanced geothermal systems in deep wells in different geologies across Europe. The project demonstrated Enhanced Geothermal Systems (EGS) for widespread exploitation of high enthalpy heat, targeting three different locations at Reykjanes (Iceland), Vendenheim (France), and Upper Rhine Graben (France-Germany border) (DEEPEGS, n.d.).

The DESTRESS project (*Demonstration of Soft Stimulation Treatments of Geothermal Reservoirs*; Grant Agreement ID: 691728) demonstrated methods of Enhanced Geothermal Systems (EGS), aiming to expand knowledge and provide solutions for a more economical, sustainable, and environmentally responsible exploitation of underground heat. Common and specific issues of different drilling sites were investigated, targeting a generally applicable workflow for enhanced productivity. Stimulation treatments applied in reservoirs of various geological settings with minimized environmental hazard were the main point of focus. Cost and benefit estimations, based on enhanced system performance and the environmental footprint, were applied. The fracking debate was further addressed by the application of specific concepts for the mitigation of damaging seismic effects during the construction of a productive reservoir, and the long-term operation of a sustainable system (DESTRESS, n.d.).

The GECO project (*Geothermal Emission Control*; Grant Agreement ID: 818169) focused on geothermal emission gas control. The main idea of the project was to develop an innovative technology which can limit the emissions of geothermal plants by condensation and re-injection of gases or the transformation of emissions into commercial products. Soluble gases were captured and injected in the exhaust stream (in dissolved aqueous phase). Dissolution of subsurface rocks was promoted by this acidic gas-charged fluid. Reservoir permeability was increased this way, and the fixation of dissolved gases (as stable mineral phases) was promoted. Environmentally friendly storage of waste gases was developed in this way. The cost of cleaning geothermal gases was lowered considerably, compared to standard industry solutions. This approach was tested in Iceland, Italy, Turkey, and Germany (GECO, n.d.).

The GEO4CIVHIC project (*Most Easy, Efficient and Low Cost Geothermal Systems for Retrofitting Civil and Historical Buildings*; Grant agreement ID: 792355) aimed to develop easy, efficient, and low-cost geothermal systems for retrofitting civil and historical buildings. Shallow geothermal reservoirs were exploited through different applications, fitted to the building type. Borehole heat exchangers of higher efficiency coupled with cost effective drilling techniques and equipment were developed. Building refurbishment presenting different constrains; reduction of overall drilling cost in the given geological conditions; avoiding replacement of heating terminals; and reduction of deep retrofit costs, were the main targeting points of this project. Analysis through different tools (DSS, APPs, etc.) supplied the best solution for each combination of building type, climate, and geology. It was expected that engineering costs would be reduced; design mistakes would be avoided; and the basis for a major dissemination effort would be established (GEO4CIVHIC, n.d.).

The GEMex project (Cooperation in Geothermal Energy Research Europe-Mexico for Development of Enhanced Geothermal Systems and Superhot Geothermal Systems; Grant agreement ID: 727550) targeted the development of geothermal cooperation between Europe and Mexico on super-hot enhanced geothermal systems. The joint effort was based on three pillars. Firstly, two unconventional geothermal sites (at Acoculco and Los Humeros) were resource assessed. Tectonic evolution, fracture distribution, and hydrogeology of the respective regions were studied to develop a predictive model for in situ stresses and temperatures in high depths. Secondly, characterization of reservoirs using techniques and approaches developed at conventional geothermal sites was carried out. Novel geophysical and geological methods were tested and refined for application at the two project sites. Passive seismic data in combination with ambient noise correlation methods and electromagnetic data were collected, and high pressure and high temperature laboratory experiments were conducted to derive the parameters of rock samples. Lastly, all existing and newly collected data were applied for the definition of drill paths, well completion design, suitable material selection, and enhancement of stimulation and operation procedures for safe and economic exploitation (GEMex, n.d.).

The GEOCOND project (Advanced Materials and Processes to Improve Performance and Cost-Efficiency of Shallow Geothermal systems and Underground Thermal Storage; Grant agreement ID: 727583) focused on advanced materials and processes to improve the performance and cost-efficiency of shallow geothermal systems and underground geothermal storage. The project targeted an overall cost reduction of about 25% and an increase of the thermal performance of different subsystems with shallow geothermal energy systems and underground energy storage. This involved the smart combination of different material solutions under the umbrella of sophisticated engineering, optimization, testing and on-site validation. New pipe materials; advanced grouting additives and concepts; advanced phase change materials; and system-wide stimulation and optimization were the main priorities of this project (GEOCOND, 2021).

The Geo-Drill project (*OptimisingTechnology for Geothermal Extraction*; Grant agreement ID: 815319) aimed to develop novel and cost-effective drilling technology for geothermal systems, incorporating a bi-stable fluidic amplifier driven mud hammer; low-cost 3D printed sensors and cables; a drill monitoring system; and graphene-based materials and coatings. Drilling costs are targeted to be reduced up to 60% and the consortium aimed to motivate investment and make geothermal energy more widely accessible (Geo-Drill, 2020).

The Geofit project (Geothermal Systems, Technologies, and Tools for Energy Efficient Building Retrofitting; Grant Agreement ID: 792210) aimed to deploy novel geothermal systems, technologies, and tools for energy-efficient building retrofitting. The project was an integrated industrially driven action which targeted the viability of novel EGS. Innovative enhanced geothermal systems and their components, such as non-standard heat exchanger configurations; cooling components; a novel hybrid heat pump; and an electrically driven compression heat pump were developed. A suite of tools was further developed, including low invasive risk assessment technologies; site-inspection and worksite building monitoring techniques (SHM); and control systems for cost-effective and optimized EGS in operation. The GEOBIM platform, which constituted a tool for managing geothermal based retrofitting works was also developed. Ultimately, the project was committed to novel drilling techniques, such as invasive vertical drilling and trenchless technologies (Geofit, n.d.).

The GEORISK project (*Developing Geothermal and Renewable Energy Projects by Mitigating their Risks*; Grant agreement ID: 818232) aimed to develop geothermal and renewable energy projects by mitigating their risks. The main idea was the establishment of risk insurance all over Europe (and some other countries) for the exploration and testing phases of geothermal drilling. The project sought to establish such an insurance, which would guarantee that activities will be funded before the financial institutions, and an IPP funding the confirmation drilling and surface systems (GEORISK, 2021).

The GeoSmart project (*Technologies for Geothermal to Enhance Competitiveness in Smart and Flexible Operation*; Grant Agreement ID: 818576) aimed to develop geothermal energy technologies for the enhancement of competitiveness with a smart and flexible operation. The main principle was the storage of produced geothermal energy and its release during periods of high energy demand. This would counter the fluctuations in the market caused by other renewable energy sources like sun and wind. Hybrid cooling for the Organic Rankine Cycle (ORC), which would prevent efficiency degradation, and a scaling reduction system were the main components of innovation of this project (GeoSmart, 2020).

The MATChING project (*Materials Technologies for Performance Improvement of Cooling Systems in Power Plants*; Grant Agreement ID: 686031) aimed to develop material technologies for performance improvement of cooling systems in power plants. The project aimed to reduce the cooling water demand in thermal and geothermal power plants. Innovative technological solutions would secure an overall saving of water withdrawal of 30% in thermal power generation, and a decrease of evaporative losses up to 15% in the geothermal sector. Nanomaterials were used for enhancement of economic efficiency of water saving in power plants (MATChING, 2020).

The MEET project (*Multidisciplinary and Multi-Context Demonstration of EGS Exploration and Exploitation Techniques and Potentials*; Grant Agreement ID: 792037) targeted a multidisciplinary and multi-context demonstration of Enhanced Geothermal Systems (EGS) exploration and exploitation techniques. Optimization of reservoir productivity and stimulation techniques and taking advantage of existing infrastructure formed the basis of the project's concept. Another aspect of the project was mapping of the most promising European sites where EGS could be implemented. Simultaneously, the project sought to boost the market penetration of geothermal energy in Europe through the demonstration of viability and sustainability of EGS in all kinds of geological settings (MEET, n.d.). It should be noted that the most interesting geological settings defined by the MEET project are composed of very hard or abrasive deep rocks that are difficult to drill. Indeed, the main disadvantages of EGS in these geological horizons have previously been associated with high drilling costs and a relative lack of experience due to the very limited number of power or thermal plants in operation. The ORCHYD project takes into account and investigates these types of rocks.

The REFLECT project (*Redefining Geothermal Fluid Properties at Extreme Conditions to Optimize Future Geothermal Energy Extraction*; Grant Agreement ID: 850626) aimed at redefining geothermal fluid properties at extreme conditions to optimize future geothermal energy extraction. Its main idea was to avoid problems arising from fluid chemistry rather than development of treatment techniques. The behavior of fluids that transfer heat from the geosphere to the geothermal power plant affect the efficiency of the plant. The physical and chemical properties of those fluids are often poorly defined since in situ measurements are difficult. This leads to uncertainties in current model predictions. For this reason, the project aimed to implement a European geothermal fluid atlas and predictive models which will provide recommendations on the optimum operation of geothermal systems (REFLECT, 2021).

The SURE project (*Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource*; Grant agreement ID: 654662) focused on a novel productivity enhancement concept for the sustainable utilization of geothermal resources through radial water jet drilling technique. Deep geothermal reservoir rocks at different geological settings, such as deep sedimentary basins or magmatic regions, were the target location. Laboratory tests involved rock parameters such as elastic constants, permeability, and cohesion. Advanced modeling would provide an insight into the mechanism that promotes rock destruction at the tip of the water jet (SURE, 2021). The SURE project, like the ORCHYD project, is concerned with high pressure water jets, with the primary difference being that the jet in SURE is used to increase the permeability of the well walls and thus their productivity. The jet is used in ORCHYD to help the drilling bit fragment the rock at the bottom of the hole, allowing the hole to advance faster.

The THERM project (*Transport of Heat in Heterogeneous Media*; Grant agreement ID: 838508) focused on research over the transport of heat in heterogeneous media and the thermo-hydro-mechanical processes occurring during the lifetime of a geothermal reservoir. The project's objectives were the characterization of the combined effects of fracture-scale and network-scale heterogeneity on the and heat transport phenomena. Furthermore, the project would design and execute a field experiment, which would jointly measure the thermo-hydromechanical (THM) behavior of fractures (THERM, 2019). The project does not address the improvement of drilling techniques performances.

The ThermoDrill project (*Fast Track Innovative Drilling System for Deep Geothermal Challenges in Europe*; Grant Agreement ID: 641202) developed a fast-track innovative drilling system for deep geothermal challenges in Europe. The main idea was the combination of proven and cost-effective technologies to improve the rate of penetration. Conventional rotary drilling and water jetting technology are combined to accelerate by at least 50% the rate of penetration in hard rock. The project further aimed to reduce cost by more than 30% for the subsurface construction and minimize the induced seismicity risk. Enhanced water jet drilling technology was examined as a replacement for fracking. Furthermore, high temperature and high-pressure crystalline rock jetting processes and (appropriate) drilling fluids were assessed. In addition, a systematic redesign of the drilling process, with focus on casing design and cementing was proposed. Finally, the project provided an evaluation of the proposed technology in terms of health, safety, and environmental compliance (ThermoDrill, 2020). The goal of this project is similar to that of ORCHYD, but there is a significant difference in the level of improvement in drilling speeds and thus drilling time. Indeed, ThermoDrill aims to improve ROP by 50% using a tricone tool and a water jet, whereas ORCHYD aims to improve ROP by 300% using a hydraulic hammer and a high-pressure water jet.

2.2. GEOTHERMICA initiative

A special mention is made to the GEOTHERMICA initiative (Grant agreement ID: 731117). GEOTHERMICA ERA-NET Cofund aimed to combine the financial resources and know-how of 16 independent geothermal energy research and innovation project owners from 13 countries and the identification of paths towards commercial large-scale implementation of their concepts. The project sought to identify paths to commerciality and strengthen the European geothermal energy sector by building a tightly interconnected and well-coordinated network of European funding agents (GEOTHERMICA, 2021). Several projects were developed with the support of the GEOTHERMICA initiative, as presented below.

- The CAGE project (Grant agreement ID: 252702) aimed at the development and demonstration of cost effective and output improving installation technologies, suitable for limestone areas and target depths of 1 to 2.5 km. The innovations of the project included crane-based drilling; enhanced casing installation technology; lightweight and corrosion resistant high strength composite casing; acoustic multi sensor parameter-analysis-supported radial drilling; and airlift technology to replace the costly electrical submergible pump (CAGE, n.d.).
- The DEEP project aimed at innovation for de-risking enhanced geothermal energy project through optimization of monitoring and risk assessment procedures (DEEP, n.d.).

- The DEEPEN project aimed at de-risking exploration for geothermal plays in magmatic environments, through the development and implementation of improved exploration methods and a framework for joint interpretation of exploration data, according to the Play Fairway Analysis (PFA) methodology (DEEPEN, n.d.).
- The TEST-CEM project aimed to develop sustainable geothermal well cements for challenging thermo-mechanical conditions to reduce risks associated with well integrity (TEST-CEM, n.d.).
- The SPINE project was dedicated to stress profiling in EGS. The project developed tools for stress profiling in crystalline rocks to estimate stimulation efficiency and seismicity related to subsurface heat exchangers (SPINE, n.d.).
- The RESULT project targeted urban smart wells and reservoir development. Its primary objective was the increased performance of major reservoirs for heating in urban areas of northern EU countries (RESULT, n.d.).
- The SEE4GEO project developed a seismoelectric effects technique for geothermal resource assessment and monitoring. This could help assessing the geothermal resources in place and provide data on reservoir stimulation and risk mitigation by mapping activated fractured networks (SEE4GEO, n.d.).
- The GRE-GEO project developed a glass-fiber-reinforced epoxy casing system for geothermal applications. This would constitute a cost-effective piping solution with a relatively large inside diameter and smaller outside diameter, specially designed for geothermal wells (GRE-GEO, n.d.).
- The ZODREX project developed drilling, completion, and production technologies for increased technical and economic efficiency of geothermal projects. Improved percussion drilling, zonal isolation, automation, improved corrosion protection and monitoring techniques were suggested (ZORDEX, n.d.).
- The HEATSTORE project suggested solutions regarding thermal energy storage technologies. The project's main objective was cost-effective solutions that will reduce the risks and optimize the performance of high temperature underground thermal energy storage technologies (HEATSTORE, 2021).
- The PERFORM project targeted the enhancement of geothermal plants performance through increased energy outputs and cost-effective solutions. The creation of a collective knowledge library of databases and experiences from a range of geothermal plants was the project's main objective (PERFORM, n.d.).
- The COSEISMIQ project targeted the improvement and validation of advanced monitoring techniques for the control of induced seismicity in geothermal wells. The development of a data driven adaptive decision support tool which will be used during industrial applications was the main objective of this project (COSEISMIQ, n.d.).
- The GECONNECT project aimed at increasing the reliability of the downhole construction of geothermal wells beyond the state of the art, using flexible couplings. The flexible couplings would be able to minimize the risk of casing failures (GECONNECT, 2018).
- The GEOFOOD project was related mostly to food production and the need for carbon footprint minimization. However, that project showcased the opportunities of direct use of geothermal energy to increase food production in highly productive circular systems (GEOFOOD, n.d.).
- Finally, the GEO-URBAN project demonstrated the ability to use geothermal resources for heat generation in urban areas. The commercialization strategy of geothermal resources was the main objective of this project (GEO-URBAN, n.d.).

The main characteristics of the projects are presented in Appendix A (HORIZON 2020 Geothermal Projects [project coordinator listed first in consortium]).

2.3. GEOENVI project

This section focuses on the GEOENVI project (*Tackling the Environmental Concerns for Deploying Geothermal Energy in Europe*; Grant Agreement ID: 818242), an H2020 project that examined the environmental concerns for deploying geothermal energy in Europe. The main idea was the engagement of all geothermal stakeholders to ensure the exchange of best practices; testing harmonized methods in selected areas; and facilitating their replication across Europe. GEOENVI sought to establish geothermal energy as a basic pillar in a sustainable future energy supply of Europe. The creation of a robust strategy to respond to environmental impacts and risks was designed, including various steps. Firstly, the project assessed the environmental impacts and risks of operational or under development geothermal projects in Europe. Secondly, the project prepared a robust framework of recommendations on environmental regulations to decision makers and project developers. Finally, the project communicated environmental concerns to the general public. GEOENVI targeted the implementation of LCA technology by geothermal stakeholders (GEOENVI, n.d.).

The GEOENVI project is of particular interest for this deliverable of ORCHYD, because it addresses environmental impacts and makes available online a complete set of its deliverables. Some of these deliverables are reviewed next.

GEOENVI allotted the criticality factors shown in Table 2.1 for the different levels of gravity and probability of an impact.

Table 2.1. Different levels of gravity and probability of an impact

	Probability				
Gravity	*Improbable*	*Unlikely*	*Possible*	*Probable*	*Very likely*
Minor	Low	Low	Low	Low	Low
Moderate	Low	Low	Medium	Medium	High
Serious	Medium	Medium	High	High	High

GEOENVI's D2.1 deliverable was of particular interest to ORCHYD as it reports on environmental concerns. It contains four parts that deal with: (1) effects associated with surface operations; (2) effects associated with the emission of underground material to the surface; (3) effects associated with geomechanical changes; and (4) underground physical and hydraulic modifications.

That report considered the following phases in the life of a geothermal project:

1. Exploration: exploration of subsurface by indirect means (acquisition and analysis of geophysical, geochemical, and geological data); exploratory drilling and confirmation of resource; estimates of reserves and preliminary design
2. Development: building access roads and drilling pads; drilling production and injection boreholes and carrying out production tests; stimulation (of geothermal resource); laying of pipe and transmission lines; surface installations
3. Operation: production of electricity and/or heat; drilling new wells; injection of inhibitor; stimulation; maintenance of installations and boreholes (work over)
4. Decommissioning and abandonment: deconstruction of surface facilities; sealing and permanent plugging of wells; material disposal; site clearance and restoration; monitoring of installations

The effects that were examined with their assessed gravity and criticality are shown in Table 2.2:

Table 2.2. Characterization of GEOENVI environmental effects

Impact	Identification	Exploration	Development	Operation	Decommissioning & abandonment	Gravity	Probability	Criticality
Energy and water consumption for surface operations (and related GHS and other emissions)	Impact	Limited effects	Main effects	Limited effects	Limited effects	Minor	Very likely	Low
Waste production (paper, garbage, fuel, lubricants, scrap metals, chemical and hazardous wastes, wastewater, excavated soil and rocks, etc. from surface operations)	Impact	Limited effects	Main effects	Limited effects	Main effects	Minor	Very likely	Low
Noise and vibrations (from engines and pumps), dust (from traffic), landscape effects land occupation (by roads and other infrastructure), visual disturbances (e.g., steam plum, drill pads), and odors (H_2S)	Impact	No effects	Main effects	Limited effects	Main effects	Minor	Very likely	Low
Leaks (of water, geothermal fluids, or chemicals from surface installations such as reservoirs and retention sites)	Risk	No effects	Main effects	Main effects	No effects	Minor	Unlikely	Low
Liquid and solid effusions (drilling mud and additives, diesel and lubricants, geothermal brine, cuttings, excavated earth and rocks) on the surface	Risk	Limited effects	Main effects	Limited effects	No effects	Minor to Moderate	Very likely	Low

Impact	Identification	Exploration	Development	Operation	Decommissioning & abandonment	Gravity	Probability	Criticality
Degassing (emission of non-condensable geothermal gases such as CO_2, H_2S, CH_4, NH_3, N_2, Ar, deliberately or by accident)	Impact	Limited effects	Main effects	Main effects	Limited effects	Minor to Moderate	Probable	Low to Medium
Radioactivity (from cuttings of slightly radioactive rocks like granite or scaling deposits with trapped radioactive elements, covering the inner surface of pipes)	Risk	Limited effects	Main effects	Main effects	Main effects	Minor	Probable	Low
Blowout (i.e., sudden and uncontrolled eruption of gas or fluid at the surface)	Risk	Main effects	Main effects	Limited effects	Limited effects	Minor	Unlikely	Low
Ground surface deformation (ground subsidence caused by pressure and temperature changes or uplifting caused by reinjection)	Risk	No effects	Limited effects	Main effects	No effects	Minor to Moderate	Probable	Low to Medium
Induced (micro)seismicity (caused by perturbations of drilling operations during production, stimulation, or reinjection)	Risk	No effects	Main effects	Main effects	No effects	Minor	Possible	Low
Pressure, thermal, and flow changes (e.g., pressure decline with utilization) especially with unbalanced production and reinjection in closed boundary geothermal systems	Risk	No effects	Main effects	Main effects	Main effects	Minor	Very likely	Low

Impact	Identification	Exploration	Development	Operation	Decommissioning & abandonment	Gravity	Probability	Criticality
Interconnection of aquifers and disturbance of non-targeted aquifers (e.g., aquifer and freshwater contamination, collapse, or landslide)	Risk	No effects	Main effects	Main effects	Main effects	Minor	Possible	Low

Interesting observations from GEOENVI's Deliverable 2.1 (entitled *"Report on Environmental Concerns: Overall State of the Art on Deep Geothermal Environmental Data"*) focusing on the drilling phase are listed below (GEOENVI, 2020):

- Compared to the construction and decommissioning phases, emissions (e.g., fuel burned by machines and drill pads, road construction, traffic) and resource consumption (e.g., use of cement and water) generated from surface operations during the regular operation of geothermal plants are negligible.
- Drilling activities (including traffic) are very limited during normal operation (exploitation).
- Considering the life cycle of geothermal plants, Greenhouse gas (GHG) and particle emissions due to surface operations are low and mostly related to the installation and construction of the plant and related drilling operations.
- Drilling operations have been reported to have the largest GHG emissions during the life cycle of a geothermal plant. Such emissions are mainly due to fossil fuel combustion from drilling machines on site, transportation of materials, etc.
- The exploration phase is likely to represent a small part of the total energy and resource consumption during the life cycle of a geothermal plant.
- Water is used during drilling and construction mainly to produce drilling mud (e.g., with bentonite) and cement the casing, thus relates mostly to underground operations. A total of 5 to 30 m^3 of water per meter drilled has been reported, depending on geology (mud losses in soft or fractured rocks), technology, and well design (Dhar et al., 2020).
- The recirculation of drilling mud (and the quick plugging of mud zone losses) is a good way to reduce the amount of water used for drilling. Meteoric water could be collected and used for the preparation of mud and cement slurry. Water from surface water bodies could be used after testing its quality (to avoid polluting groundwater aquifers, especially if they are a source of potable water).

ORCHYD partners consider geothermal energy to be classified into four broad categories:

1. *Very low-energy geothermal*: Temperatures below 30°C (depths frequently less than 200 m), installed at the level of individual homes and coupled with a heat pump.
2. *Low-energy geothermal*: Temperature ranges from 30 to 90°C (depths of up to 2000 m), allowing for the implementation of heat networks or industrial processes (grain drying, horticulture, fish farming).
3. *Medium energy geothermal*: Temperature between 90 and 150°C (depths of up to 3000 m), allows the generation of heat and occasionally electricity.
4. *High energy geothermal*: Temperature greater than 150°C (depth greater than 3000 m), allowing the generation of electricity and heat.

3. Assessing environmental impacts

The development phase of a geothermal power plant (including construction activities) can be broadly classified into four stages (Semedi et al., 2017): resource exploration and drilling; development; operation and maintenance; and decommissioning and rehabilitation. Geothermal drilling occurs during the initial exploration and confirmation of a geothermal reservoir, as well as later in the field development phase, during which the geothermal resource is exploited (Fridriksson et al., 2016).

Although visually there are few emissions and limited land use changes and visual impacts, the planning of a geothermal drilling operation must take into consideration impacts on soil, atmosphere, water, flora, fauna, hazardous waste, geophysical environment, land use etc. In the rest of Section 3, the research literature related to these impacts is discussed and linked to ORCHYD. Then, in Section 4, the impacts of ORCHYD are tabulated and characterized.

3.1. Lithosphere

The area occupied by a geothermal drilling site is likely between 200 and 2500 m² (Yousefi et al.,2007). Within this area, geothermal drilling operations alter the physical and chemical properties of soils.

In general, high temperature geothermal systems impact the soil more than low temperature geothermal systems, due to disturbance intensity. Usually, the main alteration occurs during the drilling and construction phases of a geothermal project. As a result of development activities, soil aeration, permeability of formation, and water holding capacity may be reduced. As suggested by Dhar et al. (2020), soil compaction and soil admixing can influence the viability of future vegetation; also, surface runoff can increase and potentially lead to more sheet, rill, and gully erosion.

Geological hazards stemming from geothermal drilling operations include landslides, subsurface subsidence, and induced seismicity.

3.1.1. Subsidence

Geothermal drilling poses site-specific threats to the geophysical environment (Yousefi et al., 2007; Armannsson et al., 2000). Soil subsidence is such a potential effect from geothermal drilling (Yousefi et al., 2007).

The withdrawal of large quantities of fluid (such as geothermal water) from the ground and groundwater (geothermal) reservoirs may cause subsidence of the ground surface. Landslides may also be caused and be quite severe for geothermal sites with thermally altered soil (Goff and Goff, 1998). This may impose constraints on the choice of sites for geothermal development (Yousefi et al., 2007). Subsidence rates of up to 40 cm per year have been reported, in a case when large amounts of hot water were discharged to a river without reinjection (Yousefi et al., 2007; Allis, 2000). The development of a geothermal plant also requires the reinjection of water under pressure for rejuvenating the geothermal resource. Coupled with the drilling operations, such reinjection can help activate or propagate small natural fractures in the drilled formations.

The following factors make subsidence likely to occur (Yousefi et al., 2007): (1) pressure drop in a reservoir as a result of fluid withdrawal; (2) presence of a highly compressible formation above or in the upper part of a shallow reservoir; and (3) presence of high permeability paths between a reservoir and a compressible formation. Reinjection is done typically at some distance from the production well to avoid the cooler rejected waste fluid from lowering the temperature of the production fluid, so it may not help prevent subsidence.

Large-scale subsidence may also be linked to microseismicity, which is discussed in the following section.

3.1.2. Seismicity

Induced seismicity manifested with mild seismic tremors known as micro-earthquakes, is a common phenomenon in oil and gas deep drilling operations, resulting from changes in the fluid pressure within fractured/faulted rock formations. *“Seismicity is the result of rapid slip on a fault plane, which is a preexisting zone of weakness in the crust. In the upper crust, faulting occurs mainly as a brittle process”*, as Buijze et al. (2020) pointed out. Critically stressed faults are the primary source of induced seismicity in a given stress regime, as small amounts of added stress can initiate large seismic events. Seismic waves are generated when energy is released and transmitted through the rock. Induced seismicity is also a relatively common occurrence during geothermal exploitation, with site-specific geophysical regime characteristics influencing the likelihood and severity of such occurrences.

Seismic events are usual in drilling operations in fractured sedimentary formations, as the diffusion of pressure through fractures overloads faults which are critically stressed. Metamorphic and volcanic formations are prone to seismic events, as well. *"Key factors for the occurrence of M>2.0 events are the presence of critically stressed faults, distance to basement and a hydraulic connection to the basement, the magnitude of pressure and temperature changes, and possibly the rock competency of target reservoir and overburden/underburden. In general, these parameters and hence the seismogenic potential increases with depth"*, as Buijze et al. (2020) suggested. Many geothermal systems have been operational for decades without seismicity incidents, while in other cases seismic events have not been felt due to very low magnitude. Many geothermal projects are located in remote areas where seismic activity does not affect communities or in areas where high natural seismicity already exists. However, induced seismicity is an issue of concern for geothermal projects located in the proximity of urban or rural communities for power supply to a heat network, since it can pose a threat to infrastructure and cause social unrest (Buijze et al., 2020).

Induced seismicity is a subject of concern for deep geothermal drilling since *"operations within crystalline basement are prone to generate felt seismicity. Crystalline basement is competent, often critically stressed, and usually must be stimulated before fluid flow between wells can be established, i.e., larger pressure changes. Relatively small stress changes (0.01-1 MPa) can be enough to cause induced seismicity on already critically stressed faults"*, as explained by Buijze et al. (2020). Pore pressure increase during the production or reinjection of geothermal fluids is the main phenomenon related to induced seismicity in geothermal operations. Post injection seismicity is possible as well, because the diffusion of liquids can continue lifting the pore pressure even after injection has stopped. Some of the larger seismic events in Enhanced Geothermal Systems (EGS) have occurred after the stimulation was stopped, e.g., Soultz-sous-Forêts and Basel (Buijze et al., 2020). Notably, Advanced Geothermal Systems (AGS) can eliminate the seismic risk associated with stimulation. AGS operates on the principle of thermal energy extraction through the use of a closed-loop system that circulates a working fluid through wellbores, conducting heat from the surrounding rock.

Poroelastic stress is another cause of induced seismicity. Volume changes that are due to pore pressure changes cause alterations in rock volume. Pressure changes and the elastic properties of the rock and its geometry affect the magnitude of poroelastic stress. *"Poroelastic stressing is expected to play a role both in geothermal systems where pressure is decreased (e.g., producing geothermal fields) or increased (e.g., stimulation in an EGS). Direct pressure effects are expected to dominate near the well, but poroelastic effects reach further at a short timescale. The volume change due to pressure drop can also cause subsidence at the surface, such as observed in many geothermal fields"*, as Buijze et al. (2020) further note.

Pore pressure decreases as rock formations cool down. Changes in temperature are the cause of thermoelastic stressing, which is significant in geothermal systems. Temperature difference between rocks and injected water can exceed 200°C, leading to tensile failure over the years. As Buijze et al. (2020) noted, cooling increases permeability, which influences the pressure distribution. Other mechanisms of fault reactivation include mass changes due to the extraction of fluids in cases where reinjection wells are not planned; excavation induced stresses; chemical changes of fault properties; static and dynamic triggering due to existing seismicity; and local geomorphology effects, e.g., subsidence caused by large-scale fluid extraction, which creates differential strain along faults.

There is a direct relationship between fluid movement, total injected volume, and stability of geologic faults (MacGarr, 2014, Zang et al., 2014). Cardiff et al. (2018) argued that *"injecting fluids in the subsurface perturbs the natural long-term stress state of a reservoir by increasing pore pressure … [which] results in a decrease in effective stress on faults, which can induce fault slip and associated seismic events"*. The ambient pore pressure can be raised both by fluid injection and cessation of long-term extraction (Cardiff et al., 2018).

Lacirignola and Blanc (2013) discussed the issue of induced seismicity, which is an important parameter in geothermal plant design. In the case of unfavorable reservoir conditions, having two production wells makes it possible to double the available thermal power for conversion to electricity, but may necessitate more reinjection wells. The reinjection of high-pressure water deep underground induces micro seismicity that can be felt by nearby local communities. In Basel (Switzerland), six days after the main stimulation (with a reinjection flow rate of 63 L/s at a pressure up to 295 bars), seismic events reached 3.4 in the Richter Scale (ML), resulting in concern among the population and the eventual suspension of the project. In Landau (Germany; reinjection flow rate equal to 70 L/s at a pressure of 80 bars) seismic disturbances resulted in complaints from residents and the German authorities defined strict limitations to prevent similar future seismic events. Unfortunately, a decision to reduce the reinjection parameters (in an effort to mitigate seismicity) after a plant has been put in operation, means that the plant has to be run outside its design conditions, which will decrease profitability.

According to the authors, empirical evidence indicates that reducing the reinjection flow rate significantly reduces the risk of induced seismicity. Additionally, with a constant reinjection pressure, the probability of induced seismicity increases proportionately to the cumulative volume of reinjected fluid. The analysis of Rothert and Shapiro (2007) suggests that *"rocks in nature are close to a critical state of stress and critical pressure (i.e., rock strength) as low as 10-3-1 MPa. This indicates a very broad range of critical stresses characterizing preexisting fractures. Many of them are characterized by very low (10-3 MPa) criticalities"*. Two wells with a flow rate of 12 L/s were used for reinjection in Soultz-sous-Forêts, with no induced seismicity. According to the authors, a flow rate of 35-40 L/s indicates a low risk of seismicity, while a flow rate of 70 L/s indicates a high risk of seismicity. Doubling the flow rate to 140 L/s was an extreme case that increased the risk of seismicity significantly. Simultaneously, reinjection is associated with the induced seismicity associated with geothermal development (Yousefi et al., 2007). When large quantities of spent geothermal fluid are injected under pressure back into the subsurface, the pore pressure and local stress fields are altered. Increased water volume does not result in larger earthquakes, but in their occurrences becoming more frequent (Yousefi et al., 2007). This is a good set of geothermal project guidelines.

Lacirignola and Blanc (2013) did not express the risk of induced seismicity numerically. For graphing purposes, levels of seismic risk represented as 100, 125, 150 and 175%, corresponded to very low, low, high, and very high. The authors argued that seismic risk increases in proportion to environmental benefits: high flowrates lead to significant energy production and low impacts but tend to require huge quantities of geothermal water at high pressure, increasing the risk of induced seismicity.

Deep drilling operations are usually demonized by the public due to negative perceptions concerning fracking for shale gas. There are some similarities, but also important differences between fracking and geothermal exploration (Homewood, 2018). Techniques used for deep geothermal drilling differ significantly from fracking, and this should be communicated to the public. Despite the common basic principles between the two techniques, it is important to notice that geothermal drilling takes place at far greater depths, in the basement up to above 4 km (much beneath the water table), while fracking is directed towards depths of 1.5 km. Surface vibrations are rare for deep geothermal drilling techniques for this reason. The geothermal process to enhance water flow in the rock (such as granite) is similar to the fracking process to capture shale gas. Fracking for shale gas uses much higher pressures to initiate new wide tensile cracks in shale rock, and then uses chemicals with additives (such as salt and chemicals) to hold them open. The process to open and enhance pr-existing fractures in rock (such as granite) is a hydro-shearing process which takes advantage of the rough surface texture or rock fractures to allow self-propping of open fractures, so there is no need to add chemical additives in the pressurized water (in the case of the site discussed by Homewood, 2018). Only some of the fluid returns to the surface, and operators are required to minimize the release of gases. Gaseous emissions from geothermal drilling may only be vented when necessary for safety.

Nevertheless, moderate to high magnitude earthquakes were reported in a study by Minetto et al. (2020), which was related to geothermal projects operating in critical conditions.

Undoubtedly, this could affect negatively public perceptions of geothermal operations. In fact, induced seismicity is especially relevant for the hot dry rock technology, where artificial reservoirs are created by hydraulic fracturing, which may induce earthquakes up to a magnitude of 2.0 to 3.0 (assumed to be local or Richter magnitude, although not mentioned by the source; Yousefi et al., 2007; Armannsson et al., 2000). Seismicity may be also linked to large-scale subsidence.

In a review of the environmental, economic, and social impacts of geothermal energy systems, Soltani et al. (2021) tabulated literature data on induced seismicity in various types of geothermal fields. The maximum local magnitude (M_L) varied from 2 to almost 5.5, with granites appearing to give seismicity below 3.5.

The maximum magnitude was also somewhat associated with the flow rate (in l/s), as shown in Figure 3.1.

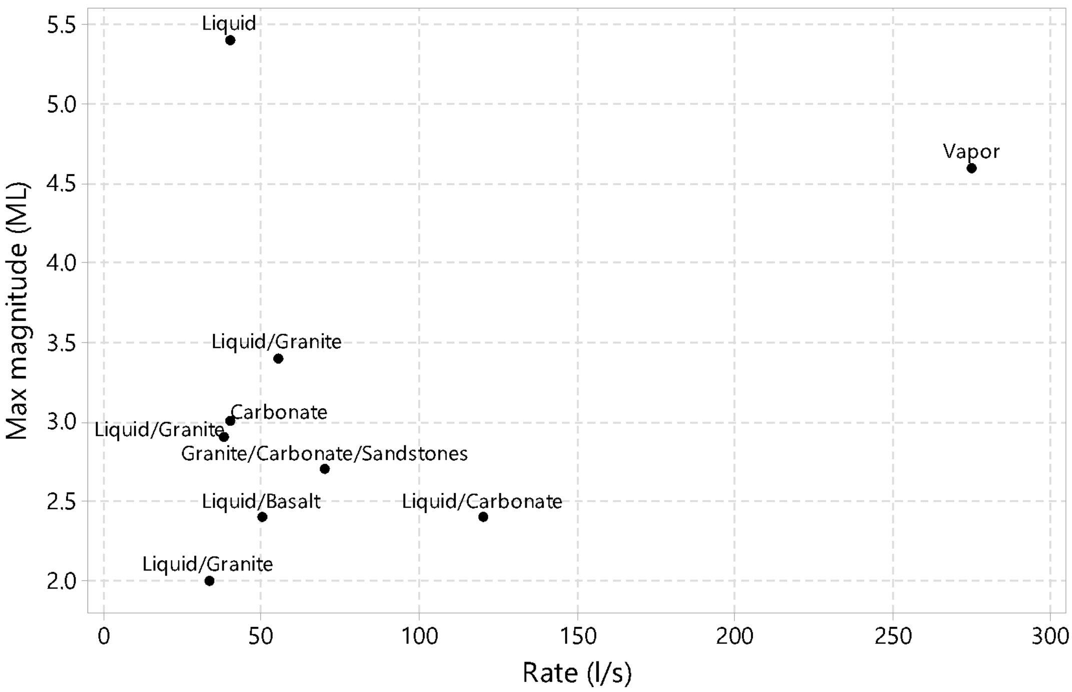


Figure 3.1. Maximum magnitude of induced seismicity vs flow rate (data from Soltani et al., 2021)

Seismicity can interfere with geothermal development as it can have serious consequences for the stability of the pipelines, drains, and well casing in a geothermal field (Yousefi et al., 2007; Noorolahi, 2005). Reinjection improves pressure decreases and lessens the likelihood of subsidence.

It is important to consider how tremors and earthquakes are perceived in different countries, e.g., some of the public may perceive them as being rare in the UK, so small ones may make big news there (Homewood, 2018). Also, there may be some concern with the old coal mines (in the UK) and how they may interfere with geothermal drilling. In some areas, a part of the public may be used to developmental projects and may not be inclined to lay down in front of bulldozers to prevent them (Homewood, 2018).

The natural stress regime, orientation, and magnitude of main components are very important for the assessment of the reactivation potential of faults, although the identification of faults and in situ stress measurements at great depth are often difficult. However, monitoring of seismicity is an integral part of geothermal operations and plays a key role in the mitigation of seismic risk for resource exploitation. *“Accurately determined acoustic emission (AE) locations* *provide significant information on fracture systems, such as the orientation of fractures in a geothermal reservoir*", as Moriya (2021) explained. *"To evaluate possible triggering processes, determination of the presence or absence of water and its migration around microseismic events is necessary. However, this cannot be determined directly without real-time excavation, which is seldom feasible owing to cost and time limitations. Knowledge of the presence or absence of water is also important in assessing the effect of water injection on the original seismicity (e.g., whether and how injection affects its activity)"*, according to Okamoto et al. (2018). This kind of analysis could distinguish fluid triggering from natural occurring events and identify possible correlations.

Geological risk assessment tools, such as routine seismic monitoring (Newbury Geothermal Energy, 2016), are used for proactive project management. Such monitoring can be required by the administrative authorities. Geothermal companies record such events, although the public may not notice them due to their low magnitude (Bošnjaković, Stojkov & Jurjević, 2019). The conditions of drilling in ORCHYD have to be documented and perhaps linked to vibrations and seismic disturbances via monitoring, so that any links between microseismicity and HPWJ are investigated.

3.1.3. Soil profile

Geothermal drilling is also linked with disturbances of the soil profile. i.e., the top meter or so of the soil surface containing the horizons shown in Figure 3.2. Of these, the B horizon is important for the subsidence of crops and trees.

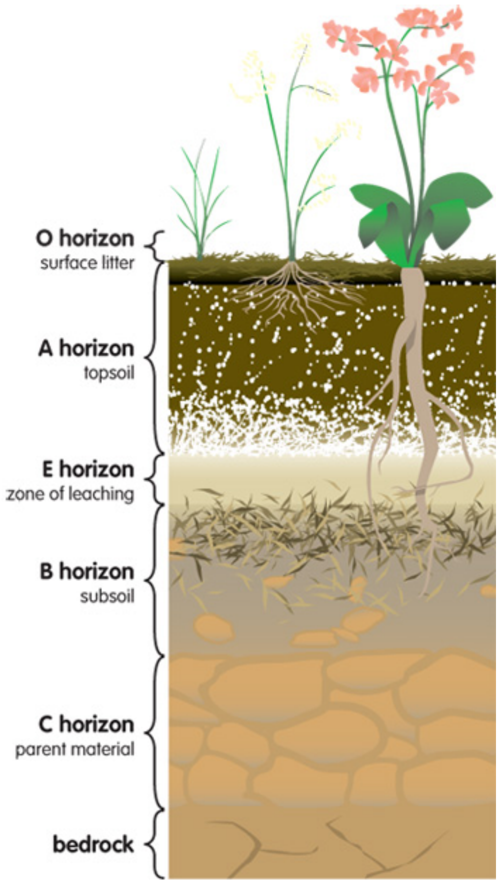


Figure 3.2. Soil horizons (USDA, 2020)

Surface disturbances and soil movement bring about soil erosion, which is the most important environmental threat in the case of the lithosphere because runaway soil erosion brings about desertification, a global environmental threat. The soil in a drilling site is likely to be compacted and changed, and near the drill there is some deposition of waste soil and drill mud (Yousefi et al., 2007). Bogging with thermal waters may be linked to flood hazards. As Dhar et al. (2020)

pointed out *“Soils are secondary receptors of emitted elements, either directly from the air or through contaminated litter fall; impacted soils lead to vegetation damage such as necrosis, defoliation, reduced growth, early senescence and chlorosis. Geothermal plants were associated with increasing concentrations of boron, ammonia, sulphur, arsenic and mercury in the surrounding soils, that decrease with increasing distance”*.

The mineralization of soil is also an important environmental concern. Depending on the unique geological properties of each area, arsenic (As), boron (B), fluorine (F), mercury (Hg), and sulfur (S) concentrations may have to be studied in the context of a soil management plan. Additional elements and compounds may leach into the soil depending on the composition of the drilling mud. More information is provided in section 3.5.

3.1.4. Groundwater

Groundwater resources are an important source of potable water for humans and feed rivers and wetlands. Water sources are subjected to a continuous change of composition according to lithological characteristics and geoclimatic conditions, which are site specific.

Geothermal drilling takes place much beneath the water table, so contamination of the water table and underground aquifers with heavy metals and other chemicals contained in thermal waters or drilling fluids is unlikely. Physical effects of fluid withdrawal are much more of concern (Yousefi et al., 2007; Armannsson et al., 2000). However, faulty geothermal well drilling and blowout mechanisms can affect the intrusion of geothermal fluids in aquifers (Rabet et al., 2016).

Garcia-Gil et al. (2018) pointed out that “*The use of vast quantities of synthetic compounds in agriculture, industrial manufacturing processes, households, animal husbandry, and human healthcare has resulted in their continuous widespread occurrence in aquatic and terrestrial environments*”. Significant concentrations of chloride and sodium as well as elevated concentrations of lithium, chromium and boron have been exhibited in groundwater and surface waters in the vicinity of geothermal wells (Tomaszewska et al., 2020). Heavy metals can also accumulate in the vicinity of a geothermal drilling site and promote contamination of freshwater which is used for irrigation.

Human health can be seriously affected through the consumption of crops and animal products which are produced nearby drilling sites (Yilmaz & Ali Kaptan, 2017). Solatani et al. (2021) suggested that the drilling and construction of wells must be very carefully designed and executed since failure in well casing is one of the most prominent reasons for groundwater rapid downflow and pollution of surface water. Shah et al. (2018) highlighted the importance of hydrochemical characteristics of water and the hydraulic properties of aquifers for planning drilling operations and groundwater management.

According to Rabet et al. (2016), surveys and assessments should be conducted prior to drilling operations, for the avoidance of incidents which can cause contamination of water resources used for irrigation or drinking purposes. Monitoring wells need to be drilled in the vicinity of geothermal drilling operations for the protection of groundwater resources. Requiring control permits for underground injection with anything other than water has been mentioned (Newbury Geothermal Energy, 2016).

3.1.5. Liquid and solid waste

A large amount of water is needed for geothermal drilling operations which in turn produces a large amount of wastewater. Most of the issues concerning disposal are related to the treatment of geothermal water rather than the drilling fluids. Kabay et al. (2017) argued that *“geothermal water that ascends to the surface reacts with the wall rocks causing mineral dissolution. Therefore, geothermal waters contain a high concentration of boron, arsenic, fluoride, and heavy metals. The presence of some elements, especially boron which exists at high concentrations, prevents the direct use of geothermal waters as irrigation or potable water and causes chemical pollution and environmental problems in groundwater and surface* *waters"*. Sayed et al. (2020) reported that fluids from geothermal fields are usually saturated with formation constituents (such as carbonate/sulfate salts, silica, and silicate salts), which precipitate when the temperature drops, and form solid wastes that require proper management.

The end use or disposition of the water is regulated by legislation and is an important aspect as well. Industrial water waste may be discharged directly to streams, rivers, and other surface water bodies. A common practice involves the use of evaporation ponds. However, Finster et al. (2015) pointed out that their use is limited by certain parameters such as large land requirements; loss of water recycling potential; time consuming processes; potential for air quality issues; and salt deposition problems.

The main source of solid wastes in geothermal sites are drill mud residues, cuttings, and other drilling additives. Drilling wastes usually include cuttings, cement residues, and drilling mud. Shale shakers are used for the separation of drilling mud from drilling cuttings. Office activities (related to geothermal drilling) also generate domestic waste such as paper, plastics, food waste etc. (Utami et al., 2020). The total amount of solid waste produced is relatively small and not posing much environmental concern (Bayer et al., 2013).

Waste management should be based on the principles of reuse, recycling, and safe disposal of wastes. Recovering and recycling wastewater is an important aspect of the design of geothermal drilling operations. Management options at a particular site vary according to the physical and chemical properties of water as well as the volume and rate of water generation. Soltani et al. (2021) wrote *"Waste generation is mitigated by correct installation of equipment and periodic inspection, soil and water monitoring, full injection, solid waste separation and storage at specific locations and hazardous waste labeling"*. Tong and Elimelech (2016) pointed that *"Wastewater reuse not only minimizes the volume and environmental risk of discharged wastewater, but also alleviates the pressure on ecosystems resulting from freshwater withdrawal. Through reuse, wastewater is no longer considered a 'pure waste' that potentially harms the environment, but rather an additional resource that can be harnessed to achieve water sustainability"*. Inadequate treatment of wastewater discharges into the aquatic environment can cause severe pollution and public health issues.

There are direct and indirect considerations regarding the use of materials and thus the production of solid waste, e.g., recovering and recycling. The lifetime of equipment (hammer, intensifier, bit) is an important factor. Comparing the technologies that are researched by ORCHYD (Percussive & High-Pressure Water Jet [HPWJ] drilling) to current practices (Rotary Drilling), it may be concluded (based on ORCHYD's D2.1 deliverable) that in terms of materials ORCHYD requires less drilling and tripping time (−63%), but more drill bits (+50%). The cost of drilling equipment is greatly increased (+531%), but the total drilling cost is down by almost a third (−30%). More information on liquid wastes is provided in section 3.5.

3.1.6. Land use

The area occupied by a geothermal plant (including drilling sites) is linked to land use changes. Bošnjaković, Stojkov & Jurjević (2019) have suggested that the average amount of land disruption during the construction of a power plant of 50 MW may be about 0.85 km², including 6 well pads (with single and multiple wells, e.g., by employing advanced directional or slant drilling technology), approximately 0.4 km of road per well, and 8 to 80 km long piping. Bošnjaković, Stojkov & Jurjević have also reported that a power plant of 50 MW can have up to 25 production and 10 reinjection wells, with binary-type plants being smaller, usually in the range of 0.5 to 10 MWe. With well spacing being an important part of every geothermal project, Dhar et al. (2020) pointed out that the minimum spacing of wells to avoid interference is at least 200 m.

Oftentimes, geothermal plants are constrained by land use issues. Exploration and exploitation of geothermal reservoirs is made difficult because they may be located within the vicinity of forest conservation areas; national parks; tourist areas; areas of historical importance; highly productive farmlands and/or even under a city (e.g., Paris). There exist examples of *“unobtrusive, scenically landscaped developments (Matsukawa, Japan) and integrated tourism/energy developments (Wairakei, New Zealand and Blue Lagoon, Iceland)”*, as pointed out by Goldstein et al. (2013).

Mobilization and demobilization of tracks for the transportation of drilling equipment in a span of few days also impact the transport network of a given target area, requiring a traffic management plan. Nevertheless, the development of directional drilling techniques and corresponding pipeline networks, have permitted the use of overlaying land for other purposes, such as farming, horticulture and forestry (Goldstein et al., 2013).

3.1.7. Visual intrusion

Landscape disturbances (such as land clearing and the creation of access roads) brought about by geothermal drilling (including not only the exploration and production, but also the rehabilitation phase) also create aesthetic impacts and visual intrusion. When intensive deep geothermal production necessitates many wells, the establishment of drilling sites and access infrastructures, especially in forested areas, can deface landscapes. Because drilling operates nonstop (24/7), light pollution at night may also be an issue of concern.

The drill rig is likely to be 25 to 60 m high and will be visible from outside the drilling site (Homewood, 2018). Nevertheless, the visual impact of drilling operations is likely to be small and temporary, as drilling towers remain in site only during the drilling phase (Finger & Blankenship, 2010). The construction of roads, well pads, and power plant infrastructure result in cut-and-fill slopes and other reshaping of the topography of an area (with soil movement), although these changes are also not regarded as significant (Yousefi et al., 2007).

It has been suggested that facilities be painted in colors that blend well with the environment (Newbury Geothermal Energy, 2016). It has also been suggested that, although visual/scenery impacts may act negatively, the presence of geothermal manifestations (that are related to geothermal drilling) may boost tourism and possess historic interest (Yousefi et al., 2007).

3.2. Hydrosphere

Hydrosphere issues related to geothermal drilling include water consumption; surface and storm water runoff (Newbury Geothermal Energy, 2016; also, a lithosphere issue, affecting soil erosion); thermal and chemical pollution of surface waters causing eutrophication and impacting water quality (Yousefi et al., 2007; Armannsson et al., 2000); and the unlikely event of contamination of groundwater (which was discussed in the lithosphere section).

3.2.1. Water quantity and quality

Significant water quantities are used throughout the life cycle of a geothermal plant. The quantity of the water used depends on the size of the plant; the principle of operation; the cooling technology; and the working temperature. Drilling operations also require much water. In the case of closed-loop geothermal plants, water resources are predominantly used during the drilling phase. Dhar et al. (2020) pointed out that approximately 5 to 30 m^3 of water are needed for the construction of 1 m of well. While water is widely used to extract geothermal energy, much of it is lost or wasted in underground fields due to leakages, as well (Sayed et al., 2020). High mud consumption is often observed when crossing fractured rocks.

Apart from the significant water quantities that are needed, deep geothermal drilling demands a well-designed drilling plan that minimizes the possibility of affecting ground water resources. Well casing failure, pipeline leakage, and spills are the main causes of water contamination. Furthermore, drilling can cause formation damage, which leads to connection of aquifers via boreholes and possibly connection of contaminated zones to aquifers. Goldstein et al. (2013) remarked that shallow groundwater aquifers of potable quality are protected from contamination by injected geothermal fluids by using cemented casings, while impermeable liners provide protection from leakages of temporary fluid disposal ponds.

Water produced during drilling and testing should be contained, treated, and disposed according to environmental provisions. During the stimulation process (for the rejuvenation of a geothermal aquifer), a spill protection strategy must be adopted.

3.2.2. Wastewater

A part of the wastewater of a geothermal power plant consists of water generated during the drilling operations. Its composition is site-specific, and the temperature affects the share of particular compounds. During geothermal operation, the water is circulated in a closed loop, so there can be no release of gas or minerals at the surface. Pollutants are mostly found in steams when the geothermal field is water-vapor dominant, thus easier to control and treat. Contamination from liquid waste is more prevalent in water dominant reservoirs.

Geothermal resources are commonly classified into low, medium, and high enthalpy (or temperature) systems, according to the respective characteristics of geothermal fluids (https://geothermalcommunities.eu/assets/presentation/2.Course_GT.pdf). Geothermal systems are further categorized into water (or liquid) dominated, and vapor (or dry steam) dominated (Duque, 2013). Water-dominated is the most common class of geothermal systems, with temperatures ranging up to 225°C. In vapor-dominated systems, a continuous phase of vapor and water phase co-exist, with the vapor phase controlling the pressure. In water-vapor dominant geothermal fields, most pollutants are in a steam condition, and surface water contamination is easier to control than in the water-dominant reservoirs. The most common pollutants are sodium chloride (NaCl), potassium chloride (KCl) and calcium chloride ($CaCl_2$). Smaller quantities of carbonates$\left(CO_3^{2-}\right)$, sulfates$\left(SO_4^{2-}\right)$, magnesium (Mg), lithium (Li), and mercury (Hg) may be found as well (Bošnjaković, Stojkov & Jurjević, 2019).In geothermal waters in Croatia, the dissolved mineral content varied from 1 g/l to 24 g/l, with chlorine at 13.25 g/l and sodium at 8.76 g/l being the most common elements (Bošnjaković, Stojkov & Jurjević, 2019).

As to the presence of (heavy) metals, depending on their composition and concentration, arsenic (As) and boron (B) can contaminate freshwater and cause public health issues. There is a possibility that minerals dissolved in water be economically extracted (Homewood, 2018). In fact, some lithium and silica extraction projects are based in this principle.

3.3. Atmosphere

Geothermal steam is an important source of atmospheric impacts in a geothermal plant. Other emissions are also liberated into the atmosphere during drilling operations, depending on site-specific conditions. As with all other impact categories, the atmospheric impacts of a geothermal plant are geographically and geologically dependent, so each site should be studied separately (Pratiwi, Ravier & Genter, 2018).

Greenhouse gas emissions, local air and traffic pollution, odors, and noise will be examined in the following section.

3.3.1. Greenhouse gas emissions

Green House Gas (GHG) emissions is among the most significant concerns related to geothermal drilling. As pointed out by Tomasini-Montenegro et al. (2016), the combustion of diesel that takes place during drilling is the main process that relates to global warming. Drilling depth, number of wells, and fuel consumption for drilling activities such as casing, cementation, and mud circulation were highlighted by Lacirignola et al. (2014) as variables of high importance for the total amount of GHG emissions of a geothermal project. In particular, drilling depth and the number of wells in combination with installed capacity accounted for 75% of the variance of GHG performances over sample geothermal plants studied by Lacirignola et al. (2014).

An established method of estimating direct and indirect GHG emissions (in carbon dioxide, CO_2, equivalent) is life cycle assessment (LCA), with carbon footprint being a usual choice for a functional unit. More details on this interesting paper are presented in Section 4.5 of this report.

3.3.2. Local air pollution

Gases in geysers include carbon dioxide (CO_2); methane (CH_4); hydrogen sulfide (H_2S); ammonia (NH_3); hydrogen (H_2); nitrogen (N); argon (Ar); and radon (Rn) (Windrem & Mar, 1982). Of these, hydrogen sulfide is the most dangerous (Windrem & Mar, 1982). Geothermal drilling emissions into the atmosphere include carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH_3), volatile metals, minerals, silicates, carbonates $\left(CO_3^{2-}\right)$, metal sulfides, and sulfates $\left(SO_4^{2-}\right)$ (Dhar et al., 2020). Geothermal is also responsible for thermal air pollution (Yousefi et al., 2007; Armannsson et al., 2000).

Geothermal drilling is also indirectly responsible for air pollution generated by traffic as well as the construction of roads serving the wells. Ordinary precautions such as watering dirt roads during heavy traffic periods and the summer months are a common suggestion (Newbury Geothermal Energy, 2016).

3.3.3. Odors

Odors is a common local complaint of geothermal drilling. Hydrogen sulfide (H_2S) is linked to offensive odors (Sayed et al., 2020) and it is toxic, but it is rarely present at sufficient concentrations to be harmful, after geothermal emissions are vented and dispersed (Goldstein et al., 2011). Because of this, H_2S odor emissions are rarely assessed by LCA works (Marchand et al., 2015).

3.3.4. Noise

Noise is a localized impact of geothermal development (Tarlock & Waller, 1977) that is important to consider near urban areas (Marchand et al., 2015).

Noise is certainly expected during drilling (Homewood, 2018), when new wells are drilled and when the operation of geothermal plant commences (Bayer et al., 2013). Diesel generators also generate noise, which can affect the flora and fauna of the geothermal site.

Typical noise levels while drilling have been reported by Bošnjaković, Stojkov & Jurjević (2019) and include (in decibels, dB):

Table 3.1. Typical noise levels for drilling

Operation	*Noise level*
Diesel generators (with silencers)	up to 55 dB
Well testing	70 to 110 dB
Mud drilling	80 dB
Well bleeding	85 dB
Operation of heavy machinery	up to 90 dB
Air drilling	85 dB (with suitable silencers) to 120 dB
Discharging wells after drilling	up to 120 dB

Those authors pointed out that the cumulative noise impact depends on the total number of wells under testing, usually over a protracted period of time of several months.

Typical noise levels at a distance of 15.2 m (50 feet) (Windrem & Mar, 1982) can also be very high (in adjusted decibels, dBA, that are a better representation of how the human ear perceives noise), as shown in the following table.

Table 3.2. Typical noise levels for drilling at a distance of 15.2 m

Operation	*Noise level*
Mud drilling	85 dBA
Changing wellhead master valves	114 to 125 dBA
Startup of steam transition through pipelines	120 to 125 dBA
Well cleanout without mufflers	125 dBA

The threshold of pain for human hearing is at 134 dBA, while the highest noise level that may be supported by the atmosphere is 194 dBA. Noise levels fall over distance per the following law:

$$L_r = L_0 - 10 \cdot \log(r^2)$$

where

L_r: noise level at a distance equal to r (dB)

L_0: noise level at the source of the noise (dB)

r: distance (m)

For noise levels at the source equal to 80 dB and 120 dB, the noise levels at a distance up to 100 m are graphed in Figure 3.3.

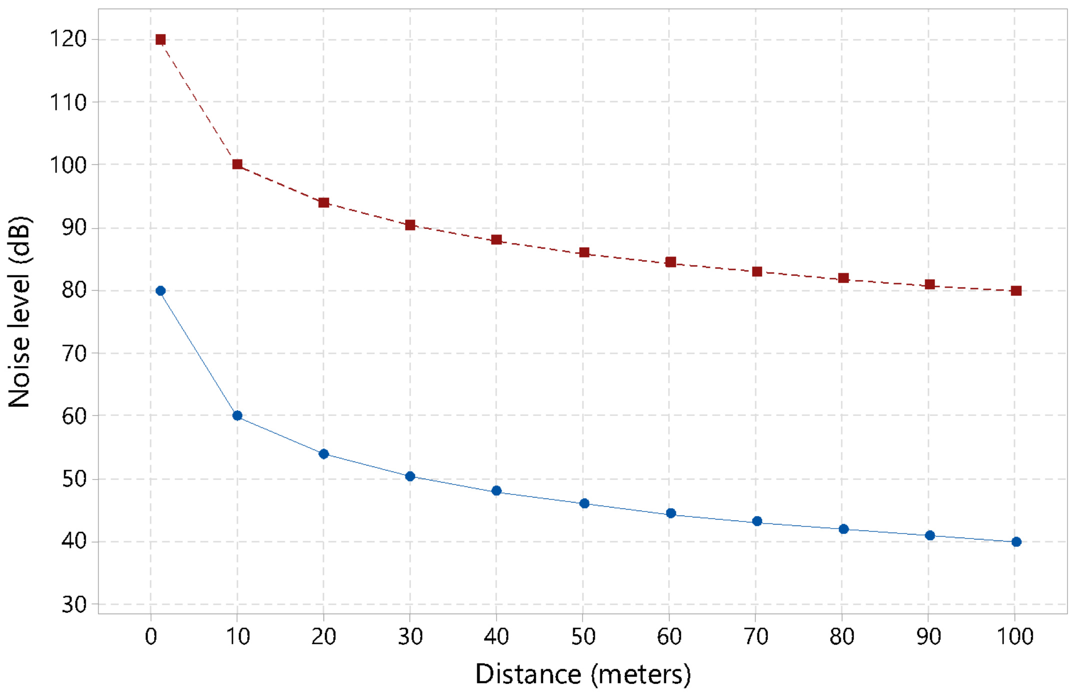


Figure 3.3. Noise levels over distance

While for noise levels of around 80 dB, the disturbance is reduced significantly in the first 10 meters, for 120 dB the noise levels are higher than 75 dB even at 100 meters.

Setup of noise barriers would minimize the impact of noisy areas of geothermal drilling operations.

3.4. Biosphere

This section covers impacts of geothermal drilling to both ecosystems and the manmade environment.

3.4.1. Ecosystems

Setting up a geothermal well often involve clearing the vegetation and impacting wildlife. Flora and fauna habitat can be disturbed or degraded by geothermal drilling, due to erosion, runoff, and noise, which can be caused by seismic surveys and the operation of machinery used during drilling operations (Sayed et al., 2020). Wildlife breeding or disturbance, foraging, migration of species in danger, seed bank depletion, and loss of native vegetation species loss may occur (Dhar et al., 2020).

Geothermal drilling could potentially pose a threat to rare ecosystems and affect biodiversity. Drilling could also impact paleontological resources.

3.4.2. Health impacts

This section examines how geothermal drilling may impact public health. Public health should be a priority for any project, and it certainly is an important issue associated with the social perception of geothermal energy. Chen et al. (2020) wrote that *"many geothermal areas are thickly populated, and some of them are adjacent to metropolises. As a consequence, approximately 500 million people were indicated to be living within the influence area of volcanoes and geothermal areas"*. Geothermal plants are considered to be environmentally friendly, due to low emissions throughout their life cycle. In comparison to coal and hydrocarbon plants, geothermal energy is not associated with severe health impacts to humans (Pan et al., 2019). It may be argued that the main human health hazards are related to microearthquakes, but they seldom reach magnitudes high enough to cause morbidity or mortality (Pellizzone et al., 2017).

However, the development of geothermal plants can be linked to health concerns for people, due to emissions or the accumulation of heavy metals, radioactive materials, and toxic gases. Additionally (as described in Section 3.3.4) geothermal drilling may generate noise, which constitutes a public nuisance and may be associated with health concerns (if long-term). Assessing the health impacts of geothermal plants and in particular geothermal drilling is a challenge for governments, investors, and scholars.

Air pollution may be associated with human health issues. Acute and chronic respiratory outcomes and cardiovascular health issues have been reported in communities in the proximity of geothermal plants (Bustaffa et al., 2020). Human health effects are mainly connected to carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4), mercury (Hg), and ammonia (NH_3) emissions (Pan et al., 2019), but their quantities are quite low to be of concern (Noorollahi et al., 2019). As with all fuel consumption, particulate matter emissions can cause respiratory concerns and even contribute to cancer. Apart from particulate matter, sulfur dioxide (SO_2) produced during drilling operations fueled by diesel, constitutes an important threat to human health, although SO_2 emissions from geothermal plants are significantly lower than those produced by fossil fuels plants.

Hydrogen sulfide has been characterized as one of the most important pollutants of human health concern in geothermal wells (Dhar et al., 2020). Manzanella et al. (2018) wrote of H_2S: *"Formed in anaerobic environments and unstable in oxidizing environments, it is found in volcanic emissions, hydrothermal manifestations and geothermal fluids, and wherever anaerobic decomposition of organic substances occurs. Although it is not possible to fix an exact lower threshold, the World Health Organization (WHO) proposed the reference value of 15 mg/m³ as the Lowest Observed Adverse Effect Level (LOAEL), in terms of the effects on* *human health (e.g., eye irritation …). H_2S forms a secondary particulate, and it can be washed by rain or it can be oxidized to SO_2".* A 30-min exposure to 500 ppm of H_2S can cause short term effects such as headache, dizziness, and diarrhea. Long term exposure can lead to coma, poisoning and death (Chen et al., 2020). However, Bustaffa et al. (2020) suggested that *"it is not possible to attribute the health challenges solely to H_2S, hence future studies should also evaluate the health effects due to co-exposures (Rn [radon] and/or particulate matter)"*.

An important impact is related to the natural radioactivity of rocks. Deep geothermal drilling is usually conducted into rock formations which include granite (as planned by ORCHYD). Radon and background radiation is naturally produced by some granites and clays; the radioactive decay is the reason such granites produce heat (Homewood, 2018). Radon and background radiation are naturally produced by this type of rocks. Levels of emitted radon during drilling operations are significantly low and do not pose a threat to humans. However, a careful plan of hazardous waste management should be adopted for the avoidance of radioactive minerals buildup. Water quality must also be monitored, although if all water is circulated in a closed circuit, no radon gas is emitted.

Filter deposits may also contain radioactive elements, which occur naturally (in low concentrations) during the reactions between the water and the rocks. As reported by Lacirignola and Blanc (2013), in Soultz-sous-Forêts, the average value of the dose in the ambient space of the plant was 0.4 to a maximum of 1.8 µSv/h (Sv stands for Sievert, a unit measuring ionizing radiation; one Sv cause illness, 8 Sv will result in death, https://www.pbs.org/wnet/need-to-know/the-daily-need/how-much-radiation-is-too-much-a-handy-guide/8124/). Accumulations of such filter deposits need to be removed periodically and stocked in specific monitored sites.

Heavy metals can escape the well casing and leach into water aquifers. Dhar et al. (2020) mentioned that *"waste fluids from drilling and testing can cause gullying, and depending on the composition, lead to contamination of freshwater bodies … thermal waters from the Yangbajing geothermal field in Tibet carried high concentrations of boron and arsenic into a downstream river and created health problems among inhabitants".*

The risk of accidents is a concern in deep geothermal drilling operations. Induced seismicity, as described, is the main category of interest. However, a broader range of risks and their associated consequences related to deep geothermal operations is manifested, including hazards and risks to public health. *"Risk assessment is the determination of the quantitative or qualitative value of risk related to a concrete situation and a recognized threat (also called hazard). A human health risk assessment is the process to estimate the nature and probability of adverse health effects in humans who may be exposed to chemicals in contaminated environmental media, now or in the future"*, as explained by Davraz et al. (2016). In their research, Chen et al. (2020) suggest that geothermal development can be linked to public health concerns due to emissions of toxic substances such as heavy metals and radioactive materials. It is important to note that human hazards are sometimes hard to define since their impacts differ depending on the population distribution, age, elevation changes, surface curvature, government policies and regulations, and site-specific conditions of any given geothermal project.

It is proposed by Spada, Sutra & Burgherr (2021) that an accident can be characterized as severe if it results in≥ 5 fatalities, ≥ 10 injuries, ≥ 10, 000 t of material release, or ≥ 5 million USD (2000) of economic losses. Fatalities are considered as the maximum consequence for human health. However, smaller accidents need to be taken into consideration as they can affect human health.

Blowout accidents are considered a risk during geothermal drilling operations since they can affect catastrophically both the entire project and the workers, as well. Blowouts are common in any kind of drilling operation, and they occur due to loss of well control. They are defined as the third most important accident category during the life cycle of a geothermal project by Spada, Sutra & Burgherr (2021). Loss of well control is a result of a combination of mismanagement and technical failures during kicks. A kick is a well control problem in which the pressure found within the drilled rock is higher than the mud hydrostatic pressure acting on the borehole or rock face. When this occurs, the greater formation pressure has a tendency to force formation fluids into the wellbore. This forced fluid flow is called a kick", as Spada, Sutra & Burgherr (2021) explain. They consist of water, mud, rocks, drilling fluid, and other substances. If the kick is controlled, then it is considered as "killed". If the kick cannot be controlled, then blowout can occur, bringing hazardous substances to the surface. During the period 1990-2017, 1 fatality from blowout has been documented in Organization for Economic Co-operation and Development (OECD) countries, according to Spada, Sutra & Burgherr (2021).

During the drilling phase, the most common hazardous substance encountered is caustic soda. In their study, Spada, Sutra & Burgherr (2021) point that it is a *"highly caustic metallic base and alkali salt and is extremely corrosive for humans (as well as for metals)"*. The use of caustic soda is not constant during the drilling phase; however, it is safe to consider a rate of 1kg per 1m drilled. This leads to a total amount of 6t for an average deep geothermal drilling well of 6km. Caustic soda is used as an additive in the drilling mud on many occasions for the control of pH and removal of cuttings. It presents a major risk for the workers since it can cause severe skin burns and eye damage. That is the reason why its transportation, storage, and usage should be implemented with major caution. During the period 1990-2017, 10 fatalities as a result of misuse of caustic soda have been documented in Organization for Economic Co-operation and Development (OECD) countries, according to Spada, Sutra & Burgherr (2021).

The health and safety of workers need special care since they are the ones most likely to be affected by accidents during geothermal drilling operations. Transportation of equipment and personnel should be carefully designed. Limitation of space should always be taken into consideration and access roads should be adequately spacious to facilitate the movement of trucks. Considerations concerning the operation of heavy machinery, movement of heavy loads, and exposure to all kinds of emissions should always be applied. These include the use of protective equipment, proper ventilation, the definition of potential explosion hazard areas, handling of chemicals, dust, fire and sparks protection, optical radiation, and release of gas (Langbaue, Schwarzenegger & Fruhwirth, 2020).

Minimizing and avoiding adverse impacts to human health by geothermal exploration demands careful site selection, strategic environmental assessment and effective monitoring and regulation. The incorporation of design lessons learned from prior development to planned projects is recommended by Pan et al. (2019). Epidemiological cohort studies characterized by continuous human biomonitoring of the communities living in geothermal areas are further suggested by Bustaffa et al. (2020). As ORCHYD aims to develop new drilling techniques that will effectively improve ROP, reduce drilling time, and lead to the minimization of diesel consumption from generators, it is reasonable to expect that this will minimize particulate matter and gaseous emissions into the atmosphere, contributing to fewer health impacts to humans.

3.4.3. Socioeconomic impacts

ORCHYD targets the development of a novel drilling technique, which will enhance energy production, decreasing the drilling cost in hard rock sections by 65% and resulting in a 30% reduction of the total cost of well construction in deep geothermal. In addition, the new coupled Intensifier-HPWJ-Hammer system has the potential to drill and steer multi-lateral wells, which increase thermal connectivity; is cheaper; use less water; and is more controllable than conventional fracking stimulations.

The socioeconomic impacts of such a project are important (Yousefi et al., 2007; Armannsson et al., 2000). Perception of local communities, governmental policies, non-governmental organizations (NGOs), and other social factors affect the development of geothermal operations in any given area. Issues related to environmental and economic impacts are decisive for the public acceptance of geothermal projects. Social acceptance depends on cultural and economic elements of local societies as well as the approach to development and policies adopted by energy companies.

Under the economic development prism, deep geothermal drilling operations can affect positively the energy and labor markets. The share of geothermal energy in the energy mix of various states will rise substantially, effectively reducing the cost of electricity production for consumers. New job openings will reduce unemployment rates in local and national level, providing well paid jobs on many occasions.

Political support for geothermal development is important for two reasons: (1) as a support to get public acceptance, and (2) as a support to get the necessary state support for the initial development phase. Presently, geothermal energy does not enjoy strong enough political support (with some exceptions).

The social acceptability of a for-profit project is the condition upon which the technical and economic objectives of the project may be pursued in due time and with the consensus of local communities. Such consensus may be gained by acting in consonance with the dynamic conditions of the environment, and in a manner respectful of the people's health, welfare, and culture.

The development of the novel drilling technique proposed by ORCHYD is expected to minimize impacts on farming. The choice of water-based drilling fluids along with the nature of deep geothermal drilling is expected to have minimal effects on soil acidification, which is most critical for farming. A careful waste disposal plan needs to be implemented in any case. Furthermore, freshwater demand for drilling operations will be reduced, effectively minimizing the conflict on water use between the industry and the farmers.

Most geothermal projects require a large area of land for the development of multiple wells. On many occasions there are conflicts of interest between local communities and corporations. ORCHYD will minimize the area needed for drilling operations, since multilateral wells development will effectively reduce surface area use. In any case, governments need to develop a legal framework, which will set specific standards on exploration and exploitation of geothermal energy, to preserve the environment and boost the social acceptance of geothermal energy. Among other issues, such a legal framework must regulate issues related to land acquisition and resettlement for the protection of local communities and the encouragement of geothermal projects development. Disturbances by drilling equipment and camps will last for a shorter amount of time than conventional drilling, due to the improved ROP.

There is a debate as to whether development of geothermal energy and tourism are compatible. In many cases, geothermal projects are developed in volcanic areas or areas of nature conservation. The example of Iceland proves that geothermal energy can co-exist with tourism. Access roads built for geothermal projects can further enhance tourism since transportation network in remote areas is usually bad or non-existent.

In closing this section, it is reminded that social impacts will be quantified in Task 3.2, with milestone M3.3 marking the completion of the online social survey, and D3.2 reporting on the analysis of responses.

3.4.4. Energy security

Improved access to geothermal energy will also affect the energy security of states.

Adiansyah, Biswas and Haque (2021) wrote about geothermal being distributed into more than 30 countries worldwide, with the ten countries with the highest geothermal capacity being the US, Indonesia, Philippines, Turkey, Kenya, Mexico, New Zealand, Italy, Japan, and Iceland. Indonesia's geothermal potential contains the largest resources worldwide, with potential sites located in Java, Sumatera, Sulawesi, and East Nusa Tenggara. Those authors concurred that that geothermal power could strengthen the energy security of a nation. Turning to another source (Lacirignola and Blanc, 2013), most installed geothermal capacity has been shared among a few countries, including the US (29%), the Philippines (17.8%), Indonesia (11%), Mexico (9%), and Italy (7.8%).

Enhanced Geothermal Systems (EGS) can help valorize low-temperature geothermal resources which may be reached with deep boreholes (Lacirignola et al., 2014). EGS can also enhance geothermal resources through hydraulic stimulation at depths over 2.5 km in hot crystalline rocks (150-200°C). EGS is of interest in Central Europe, especially in the Rhine Graben, between France and Germany. Those authors mention the pilot plant in Soultz-sous-Forêts (France), an EGS plant in Landau (Germany), and one (that at the time of writing was under construction) near Rittershoffen (northeastern France). The authors argued that many other areas in Europe (like Hungary, Serbia, Romania, Spain, and Turkey) present favorable conditions for EGS applications, and they foresee a rapid expansion. Large areas of Europe are characterized by a high vertical gradient, a geothermal anomaly that makes them suitably for EGS, including France, Germany, Italy, Hungary, Serbia, Romania, Spain, and Turkey.

Since the work of ORCHYD will expand the areas that have geothermal resources worth exploring, and make drilling cheater and faster, it is expected that ORCHYD will enhance the energy security of certain states and regions globally.

3.4.5. Energy consumption

Drilling geothermal wells is the most energy intensive stage of the life cycle of a geothermal project, with the energy consumption during geothermal drilling being a significant factor of the overall energy recovery process efficiency. The total energy consumption during the drilling phase is a sum of the energy used for driving and moving the drill string; installing casings; applying the cementation; pumping the mud; and transporting materials and equipment. Diesel is the primary source of energy used in most geothermal drilling operations. Karlsdóttir et al. (2015) suggested that 96% of the diesel consumption throughout the life cycle of a geothermal project construction occurs during drilling operations. However, *“the drilling alone (rock penetration and tripping) is responsible for the major part of that consumption. Completion work and other drill site operations play a minor role … due to the smaller time share of the processes and their lesser energy intensity”*, as Legarth and Saadat (2005) pointed out.

Different energy consumption rates for geothermal drilling have been assessed in the literature. The drilling operations for a 6 km geothermal well require a total of 0.384 TJ/day and thus, given the specific chemical energy of diesel (45.3 MJ/kg), a daily consumption of 8475 kg/day, as suggested by Li & Lior (2015). An indicative amount of 3785 L per day has been proposed by McKay, Feliks, and Roberts (2019) for drilling boreholes in granite formations. A study by Frick, Kaltschmitt and Schröder (2010) suggested a rate between 6 and 8 GJ per drilled meter, while a far lower value of 2 MJ/m was suggested by Paulillo, Striolo and Lettieri (2019). A linear relationship between drilling depth and diesel fuel used was suggested by Karlsdóttir et al. (2015) and Legarth and Saadat (2005). Drill selection and geological conditions are decisive for diesel use in different geothermal sites (Karlsdóttir et al., 2015). However, *“for different types of soil and underground rock stresses, the rate of penetration (ROP, m/day) would differ, and so would the time required to drill wells of the same depth”*, as Li and Lior (2015) pointed out.

The energy consumption of geothermal drilling can be reduced by *“increasing the overall drilling process efficiency (optimize well design, tool selection, minimize frictional losses), realizing an ‘as-slim-as-possible’ well design and selecting drill sites and paths with less developed energy intensive formations”,* as Legarth and Saadat (2005) suggested. Increasing the overall drilling efficiency is limited by geological conditions and available technology. ORCHYD targets the increase of drilling process efficiency by increasing the ROP, which is expected to reduce energy consumption.

Alternative sources of energy should be considered in areas where this is possible. Biodiesel has been suggested as an alternative fuel to geothermal drilling (Paulilo, Striolo & Lettieri, 2019). Direct connection of equipment to local electricity grids is an environmentally friendly but typically more expensive alternative (Stober & Bucher, 2021). Electricity provided to the grid by environmentally friendly technologies reduces the carbon footprint of geothermal drilling (Menberg et al., 2016; Menberg et al., 2021).

3.4.6. Material use

Geothermal drilling operations uses a wide variety of materials. The full list of specific materials that will be used in ORCHYD has not been finalized. However, an indicative list of materials for drilling operations includes material use in drilling rigs; well casing and cementing; drilling fluids; and materials used by the workers.

Metals constitute an important part of the materials used in geothermal drilling. Soft and low alloyed metals; stainless steel; titanium and titanium alloys; nickel alloys; copper-based alloys; cobalt alloys; and aluminum alloys are used in different applications and quantities. An indicative steel casing amount of 124.4 kg/m±5% has been suggested by Menberg et al. (2021). Drilling bits are also manufactured with metal and other materials, including tungsten carbide, diamond, and graded materials. Drill-hole used metals have zero recycling potential. Surface-used metals could be recycled.

Concrete and cement are widely used in drilling operations, as well. Silica, sand, and Portland cement are included in concrete, while phosphate glass cements are used for casing. The amount of cement ranges between 180 and 400 t for wells drilled to depths ranging between 1800 and 3000 m (McKay, Feliks & Roberts 2019). Again, drill-hole used cement and concrete has zero recycling potential, while surface used cement and concrete amounts could be recycled.

Elastomers, such as fluorine-elastomer, are used as connection components for pipelines. Other elastomers can be used as sealing in valves. Fiber reinforced materials are used as anti-corrosives in water lines. The recycling potential of these materials is very low.

Water and bentonite are the basis for drilling fluids in most of occasions. Other additives include salts, xanthan gum, and barite in various compositions. Specific quantities and compositions vary according to the geological regime of drilling operations.

It is worth mentioning that SINTEF has established a generic technology platform to develop functionalized polyhedral oligomeric silsesquioxanes (POSS) as additives to tailor or improve material properties. Functionalization of POSS on graphene derivatives via covalent bonding has also been achieved. Coatings prepared from graphene incorporated POSS sol-gel coatings have shown promising lubricating properties. One of the objectives is to select environmentally friendly additives with high thermal stability, in an attempt to reduce friction and adjust wettability. Additives of interest as friction reducers include: (1) POSS based additives;(2) graphene and its derivatives; and (3) their composites. Functionalization of graphene will be conducted to improve the processability and compatibility with the selected drilling fluids. It is planned that SINTEF make access available to material and property data, through a generic database platform in the context of the ORCHYD project.

Progress with the development of new technologies for percussive hammers with new designs and new materials resistant to mud abrasion has been made by DrillStar.

Materials used by the workers depend on the climate and seasonal conditions, occupational background, and other factors. These cannot be easily quantified, but it may be assumed that paper, plastic, and aluminum will be used and present recycling potential.

The contribution of various processes throughout the life cycle of a geothermal plant is illustrated in Figure 3.4 (Martín-Gamboa, Iribarren & Dufour, 2015). Diesel production and steel production are the highest contributors to environmental impacts in the context of drilling operations. Diesel use seems to be a decisive factor for abiotic depletion potential, acidification potential, and cumulative energy demand. Its effect is lower but significant on global warming potential, and photochemical oxidant formation potential. Steel has a high impact on photochemical oxidant formation potential and lower impacts on abiotic depletion potential, global warming potential, acidification potential, and cumulative energy demand.

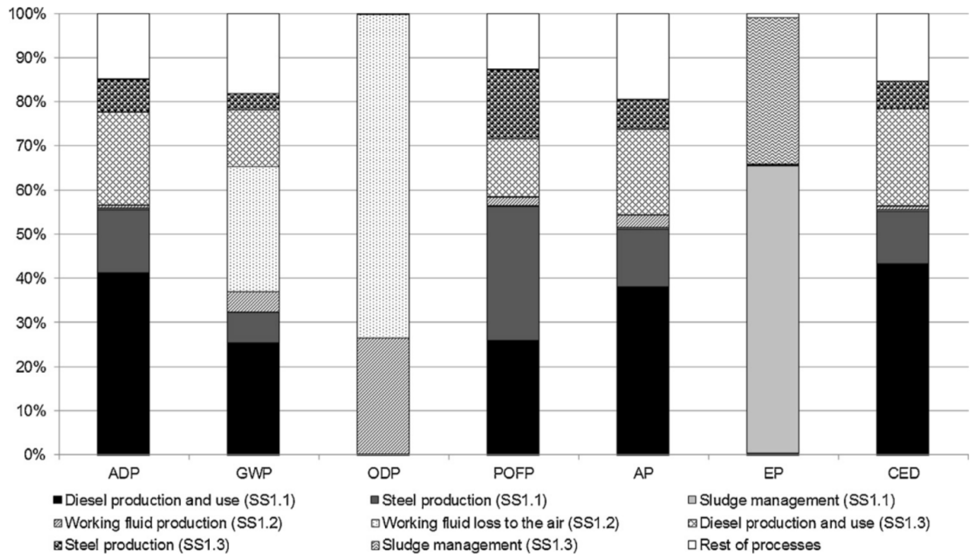


Figure 3.4. Contribution of different materials used in geothermal processes to environmental impacts (ADP: abiotic depletion potential; GWP: global warming potential; ODP: ozone layer depletion potential; POFP: photochemical oxidant formation potential; AP: acidification potential; CED: cumulative energy demand) (Martín-Gamboa, Iribarren & Dufour, 2015)

A more specific idea about the use of materials important for a typical geothermal well is given in section 4.5. of this report.

3.5. Report on geothermal drilling fluids

3.5.1. Introduction

This report focuses on geothermal fluids that are considered for use in the H2020 project entitled ORCHYD, which aims to develop a novel drilling technology combining Hydro-Jet and Percussion for improved rate of penetration (ROP) in deep geothermal drilling. Lost circulation in particular is of great importance to the project.

It is noted that this report does not correspond to a milestone or a deliverable. It was requested by the partners to aid them in the selection of environmentally friendly drilling fluids.

The section is structured as follows. Sections 3.5.2 (Background) and 3.5.3 provide some background details as to how the literature depicts the drilling process, the role of drilling muds, and the environmental aspects of drilling discharges. Although it is expected that ORCHYD will focus on onshore drilling, it was decided that offshore drilling be covered as well. Section 3.5.4 reviews general information on drilling fluids. Section 3.5.5 focuses on water-based muds (WBMs), with separate subsections covering water, bentonite and xanthan gum, graphene (oxide), calcium and potassium chlorides, and barite. The report is concluded with Section 3.5.6.

3.5.2 Background

An early report on oil drilling (UNEP, 1985) described the composition and uses of water-based drilling muds; reviewed the fate and effect of the discharge of aqueous materials to the environment; and discussed disposal techniques for the mud and the cuttings. Many of the issues discussed are similar to those faced in geothermal drilling and are presented in the following paragraphs.

Drilling mud is used to remove cuttings (i.e., drilled solids) from the bottom of the well hole, and carry them to the surface; cool the drill bit and string; transfer hydraulic power to downhole equipment and stabilize the wellbore. Additionally, lost circulation materials (LCM) are used to seal the fractures present in the formation, to mitigate the loss of mud into the formations

Very deep wells drilled over long periods of time generate 1000s of barrels of mud. In addition, an onshore reserve pit collects precipitation through the life of the well, which dilutes the waste mud and results in significantly larger volumes of total waste materials requiring disposal. In the case of exploratory drilling, the remaining mud is discharged once the drilling is concluded.

Drilling mud is expensive, so it is reused as much as possible. As drilling continues, the continuous influx of drilled solids may thicken (viscosify) the mud, which then may require discarding part of the mud, diluting with water, and/or adding thinners and dispersants to improve its rheological properties. On the other hand, high specific gravity materials (such as barite) are sometimes added to the mud to control downhole pressure. Because the mud carries drill cuttings, it passes through solids control equipment (such as shakers, centrifuges, and hydrocyclones) to remove the cuttings, and then it is recirculated down the hole. The solids that are discharged with the mud contain the small formation cuttings that were generated by the drilling and were not removed by the solids control equipment plus most of the mud additives (e.g., a small portion of the barite). These solids with part of the mud that could not be separated are discharged to a reserve pit usually at the location of the well (or the ocean, in the case of offshore drilling).

Drilling muds are dense colloidal slurries that may be fresh, or salt water based; low solids polymer fluids; oil-based fluids; and oil emulsion fluids. The majority of all mud systems (85 to 90%) are water based. Fresh water muds start with water, bentonite, and caustic soda (sodium hydroxide, NaOH). Salt waters may be seawater or solutions of sodium chloride, potassium chloride, magnesium chloride, calcium chloride/bromide, or zinc chloride/bromide. Saltwater muds may use attapulgite clay instead of bentonite.

There may be areas where drilling with clear water fluids is desirable. Such fluids in fact contain less than 5% solids, bentonite, and various polymers (absorbants or viscosifiers). The majority of wells are drilled using water-based drilling fluids, i.e., a suspension of clay in water. These muds usually contain barite for density control and low concentration chemicals that control viscosity, fluid loss, corrosion etc.

A well selected and properly designed drilling fluid should deposit a filter cake on the well bore wall to retard the passage of the liquid phase into the formation. Bentonite and drilled clays are the prime filter cake builders. Bentonite is a good fluid loss control additive that may be added to the mud in the case of extremely porous formations.

The drilling mud is also useful (and usually enough) for lubricating the drilling bit. Under conditions of extreme bit loading, a lubricant (such as graphene oxide) may be added to the mud to improve bit life and performance. Chemicals may also be added to the mud to minimize drill pipe corrosion or scaling, while solvents may be added for fluidity and freezing point depression. Bactericides may be added to the mud to avert bacterial degradation.

This concludes (for now) the discussion of background issues raised by UNEP (1985).

Geothermal resources may be categorized as conventional or unconventional. Conventional resources are found in hydrothermal systems related to magmatic activity and extensional faulting. *“Unconventional resources include Hot Sedimentary Aquifers (HSAs) with permeable layers at great depth (2–5 km), as well as Hot Dry Rocks (HDRs)”*, as Somma et al. (2021) explain. The latter ones are often referred to as Enhanced Geothermal Systems (EGS) and are described as low permeability and high temperature reservoirs, stimulated for hot water generation. Advanced Geothermal Systems (AGS) is another geothermal concept that generates *“electrical power using closed-loop systems, by circulating a working fluid through a long wellbore and extracting geothermal heat only via conduction from the surrounding rock. Closed-loop geothermal systems are advantageous because they may be constructed in most geographic locations; long wells are drilled to collect the heat and no specific subsurface geology is required”*, as Malek et al. (2021) suggest. Working fluids, unlike other traditional open loop geothermal concepts, do not directly conduct heat from the rocks, eliminating the risks of fluid loss, mineral scaling, chemical reactions, and induced seismicity.

"Natural geothermal systems are characterized by heterogeneous geology, which includes alteration zones and mineralized fracture networks in the form of veins. Veins are open fractures that are completely or partially occluded by mineral precipitates", as Kolawole et al. (2021) point out. However, differences in geological, petrophysical, thermal, hydraulic, and geomechanical environments suggest that a typical EGS system does not exist, as Breede et al. (2013) argue.

Supercritical fluids are another category of geothermal resources. They exist at depths near or below the transition zone (Yadav & Sircar, 2017) and their temperature ranges between 390 and 600°C. They are processed by superheated dry steam plants, unlike EGS and hot sedimentary aquifer (HAS), which are treated in binary power plants (Somma et al., 2021).

Geothermal drilling is carried out under high temperature conditions, into naturally fractured formations or deep hot crystalline rocks in depths beyond 5 km. In the first case, large amounts of loss of circulation and degradation take place. The hot dry rock (HDR) concept is based on the nearly dry nature of deep crystalline rock formations. Those formations are impermeable for fluids due to excessive pressure regimes caused by the overburden rocks. Therefore, artificial fractures are induced in the formation to create a closed loop of heat exchange surfaces. Geothermal fluid is circulated through this loop and maintained in a temperature and pressure regime which does not permit boiling. Steam is produced in a secondary loop in an Organic Rankine cycle at a low-pressure regime or by the use of a secondary fluid with low boiling temperature. As a result, a significant percentage of the cost of geothermal projects is attributed to drilling. Drilling costs can rise either due to a low ROP or issues such as lost circulation and wellbore stability. Exploration of deep geothermal wells brings about the need for enhanced drilling fluids. Due to the high complexity of deep drilling operations, research is focused on fluids that have high mechanical, chemical, and thermal stability.

Geothermal reservoirs are usually under pressured, i.e., the pore pressure is less than normal or hydrostatic pressure. This pressure regime is connected with one of the key issues encountered in geothermal drilling: lost circulation. Lost circulation is identified as the loss of drilling fluids in the rock formations through rock fractures or pores.

Lost circulation is a major problem in the oil and gas industry as well. The two industries share similar principles concerning drilling operations. However, there are two main differences between oil and gas on the one hand and geothermal on the other. The first difference pertains to the fact that lost circulation is more common in geothermal drilling operations, due to the fact that they are usually implemented through cavernous hard rocks in under pressured regimes of multiple zones of highly fractured and altered materials. The second difference is that cementing is completely different in geothermal projects than oil and gas, rising the likelihood of fluid losses during the process (Saleh et al., 2020). Qalandari & Qalandari (2018) noted that lost circulation occurs when the weight of the mud is greater than the fracture resistance of the formation, and this results in the volume of circulated fluids being less than that of its input.

Lost circulation, the loss of large quantities of drilling fluid to an extremely porous or cavernous (referred to as "thief") formation is one of the most severe drilling problems (UNEP, 1985). Lost circulation additives are added to plug the holes and gaps that allow the mud to escape into the formation. These additives are mainly natural materials or a fibrous, filamentous, or granular/flaky nature (such as diatomaceous earth, mica or even ground nutshells, cotton seed hulls, or shredded/ground paper).

There are problems that may occur during drilling operation in HDR, as well. A first such problem is the low rate of penetration, which is connected to the difficulty of the rock breaking process due to the nature of the formations. A second problem is the loss of circulation in the fault or natural fracture formation zones. Finally, borehole instability issues may occur due to high thermal stress which can propagate cracks in the formation. Cold drilling fluids cool the borehole walls rapidly and the temperature difference between the borehole and the formation can result in a reduction of the rock strength and the wall of the shaft peeling off and falling in blocks (Zhu et al., 2021).

A great environmental concern (discussed previously in this report) while drilling in HDR is the radioactive heat generation of rocks. This is mainly caused *"by the decay of the radioactive elements U, Th and K"*, as Wang et al. (2018) pointed out. *"The radioactive heat generation is an important index for priority selection of HDR target areas. Since the radioactivity of granite is 1 to 2 orders of magnitude higher than that of basalt and other basic-ultrabasic rocks, the radioactive generation of rocks is a slow process, whose heat generated during the radioactivity process is a major factor to prolong the cooling and crystallization of the granite",* Wang et al. (2018) explained. The HDR concept involves cooling and depressurizing of water at the the surface, which may result into solid deposition in the form of scales and sludges. Precipitated radionuclides are the cause of radioactivity of some of these deposits. Substitution of radium for barium and strontium in the solids creates radioactive waste materials, which can expose workers to gamma radiation and inhalation of radioactive dust during the waste removal processes.

Stability of deep borehole walls is maintained by the use of high density and high temperature resistant drilling fluids. High temperatures can affect the rheological properties of drilling fluids, such as density, viscosity, shear force, and sand content. The relationship between temperature and viscosity can illustrate the effect of high temperatures of water-based drilling fluids. Three scenarios can occur, as Zhang et al. (2021) describe. Firstly, viscosity decreases as temperature increases, leading to reduction of the dynamic shear force of the drilling fluid. Secondly, loss of fluidity at high temperatures can cause solidification of the drilling fluid. Lastly, the viscosity of the drilling fluid can decrease initially and then increase as the temperature rises.

Many geothermal projects have been abandoned because of lost circulation, which has a major economic impact. According to Saleh et al. (2020) lost circulation represents *"an average of 10% of total well costs in mature geothermal areas"* while it often accounts for *"more than 20% of the costs in exploratory wells and developing fields."*

3.5.3. Environmental effects of drilling discharges

Getting back to the issues discussed by UNEP (1985), expected impacts to the different spheres of the environment (lithosphere, hydrosphere, atmosphere, and biosphere, as presented in the ORCHYD proposal) are organized below. Impacts on the biosphere in particular are discussed organized into separate onshore and offshore drilling subsections.

Impacts related to the use of geothermal drilling fluids and the lithosphere (or geosphere) concern (a) the soil profile (where drilling muds may be applied), (b) deeper formations that are drilled through (which may be affected by the intrusion of drilling mud), and (c) groundwater (which may be contaminated by chemicals in the drilling mud).

Due to their alkaline nature, the application of drilling muds onto the soil is least detrimental to acidic, highly organic, and sandy soils; and more detrimental to alkaline loam and soils with high clay content. The geographical distribution of soil types (countries, regions and how environmental impacts relate to energy security) will be examined when ORCHYD considers the geopolitical implications of its research (third year of the project).

UNEP (1985) reported no adverse environmental impacts resulting from the disposal of drilling mud on certain soil types. In fact, the water holding capacity of soils increased while the lowest drilling mud application rates were associated with increased vegetative production.

Most drilling muds cause soil dispersion that results in surface crusting. Water leached into the soil (helped by heavy precipitation) may leach salts into deeper less productive soil layers (i.e., below the B horizon). Heavy metals are an important environmental concern (with more to be discussed later in this report). Nevertheless, UNEP (1985) reported that even at the highest level of drilling mud application, no heavy metal problems were detected, and there was no movement of heavy metals in the soil profile.

With the hydrosphere, the obvious concerns are for surface waters and particularly groundwater to be contaminated by drilling fluids. In this respect, UNEP (1985) found that arid regions (with less than about 50 cm of annual precipitation) have a higher potential for adverse effects than regions with wetter climates.

Environmental concerns related to drilling fluids and the atmosphere would relate to odors emanating from reserve pits as well as the application of muds onto the soil (i.e., landfarming). As far as traffic emissions related to the processing of drilling fluids, they should be largely unrelated to the type of drilling mud employed (but will be examined in depth in the context of the environmental assessment report due by the end of the first year of ORCHYD).

3.5.3.1. Onshore drilling

ORCHYD concentrates on onshore geothermal drilling, with offshore geothermal activities expected to be very limited. This environmental assessment report is concerned with European and national regulations governing the disposal/discharge of geothermal drilling fluids in primarily onshore environments.

The literature reports that the used mud and solids from onshore drilling wells are usually discharged to earthen sumps (reserve pits) that are excavated adjacent to the well site (UNEP, 1985). Such reserve pits are normally used for storage and final disposal of water-based drilling fluids and drilled solids.

Siting parameters that are considered (for locating reserve pits) include: hydrogeology, drilling mud composition, site accessibility, age of site, soil types, land use, groundwater depth, well depth and chemical history, and climate (UNEP, 1985). An impervious liner may be required under certain geographical and environmental conditions.

Almost all of the solids in a reserve pit settle quite rapidly, but the longer a reserve pit exists, the more water it accumulates because of precipitation. This water need handling, therefore an accelerated method of drying and reclaiming open reserve pits is desirable.

Closed drilling mud pits (reserve pits) have environmental impacts to surface waters, groundwater, soils, and vegetation. The constituents of drilling mud may leak in sufficient quantities to pose an environmental hazard to human health or the environment, e.g., drilling mud and its components may affect the growth rates of plants (mainly due to the soluble salts they contain).

Backfilling a reserve pit is a common method of final disposal, with landfarming being the second most common disposal method (UNEP, 1985). Important characteristics of a location considered for landfarming reserve pit contents include: soil chemistry (pH, conductivity, sodium, calcium, and potassium content, per cent clay content); climatic conditions (annual precipitation); physical and chemical characteristics of the contents of the reserve pit; presence of nearby surface waters and terrains; location and depths of usable groundwater; and original or intended use of area indented for landfarming.

After appropriate treatment, the mud and cuttings are incorporated into the soil without significant nor permanent adverse environmental impacts. The contents of the reserve pit are spread evenly over the intended landfarming area, and the soil is tilled for better incorporation into the soil profile. The high-water retention capacity of bentonite-based drilling muds could be utilized to speed the reclamation and revegetation of certain coarse textured soils. In the case of pristine ecosystems, the mud and cuttings may have to be transported to approved disposal sites. Soil per mud ratios of 1:1 result in plant yield reductions, so a soil to mud ratio equal to or greater than 4:1 (using high grade barites) is highly desirable and will not result in decreased plant yields (UNEP, 1985).

As mentioned before, the presence of heavy metals in some drilling fluids is an important environmental concern. These may include chromium (from additives intended to prevent corrosion) and barium (from barite and natural formations). Although drilling mud metals have only limited bioavailability because of the form they are in (insoluble salts, chemically bound to organic molecules of high molecular weight, or absorbed in clays), metal uptake in plants growing in soil that has been amended by mud is unlikely but not impossible (UNEP, 1985). Older oil drilling studies reported by UNEP (1985) found no significant heavy metal accumulations in plants, and no adverse impacts to livestock grazing.

Cadmium (Cd), zinc (Zn), copper (Cu), arsenic (As), and lead (Pb) were present in drilling mud and partially available for plant uptake (UNEP, 1985). Mercury (Hg), chromium (Cr), and barium (Ba) present in drilling mud were not available for uptake. Chromium in particular is present in its most stable state (Cr^{+3}) which is unavailable for plant uptake. The total levels of chromium in the soil increased slightly, but the resulting concentrations were still within the levels typically found in nature. The concentration of manganese (Mn) also increased slightly, but again within the levels typically found in nature. It was noted that organic mercury and selenium (Se, not found in drilling mud) are the only metals having bioconcentration potential.

The chemical composition of drilling muds used by ORCHYD is known, but it remains to be determined as to which heavy metals are present in drilling fluids in the form of impurities. In the case of bentonite and barite, literature reference values may be used.

Toxicity is another important environmental concern. Regarding toxic effects, some species are more sensitive than others and juveniles are more sensitive than adults. The majority of drilling muds tested by an older oil well study (UNEP, 1985) had LC_{50}s (96-hour LC_{50}, which refers to the concentration required to kill 50% of the test organisms in 96 hours) that fell into the practically nontoxic range (10,000 to 100,000 ppm). Bentonite and barite are essentially nontoxic while lignite and lignosulphonate are practically nontoxic (i.e., slightly toxic).

3.5.3.2. Offshore drilling

Even though offshore geothermal drilling is not a primary concern of ORCHYD or the industry as a whole, it was decided to include this short section of the report for completeness.

Of technical, environmental, and geopolitical concern in the case of offshore geothermal drilling affected by ORCHYD technologies would be issues like: Where will offshore geothermal sites be located? What depths is offshore drilling likely to reach and at what distance from shore? What drilling fluids will be used? What are the environmental impacts of offshore drilling and how will they be affected by technologies developed by ORCHYD? The energy security of which countries will be affected?

In the case of oil wells, clay-chrome lignosulphonate muds were used in over 95% of offshore oil wells drilled in the US (UNEP, 1985). In practice, the drilling mud and cuttings are released through a pipe extending below the surface of the water near the sea floor. A pipeline may be employed to move discharged mud and cuttings away from environmentally sensitive areas.

In the case of offshore wells, environmental concerns relate to drilling fluids and their disposal pertains to water quality and effects on benthic ecosystems. UNEP (1985) noted that much research had addressed short-term impacts. Monitoring sediments and biota throughout an area for several years after (exploratory) drilling would be needed to determine if any significant long-term effects occur. Models that consider resuspension and bottom transport could help predict the long-term fate.

For offshore wells, benthic discharges of drilling fluids had a negligible effect on water quality, but they did impact benthic communities, e.g., bringing about a substantial increase of megabenthos (UNEP, 1985). UNEP (1985) also cited studies that examined areas (such as the Cook Inlet and Tanner Bank) with water depths of 62 and 55 m, as well as the mid-Atlantic with water depths of 120 m. At approximate water depths of 120 m, currents may be weak and the sea floor may be characterized as a low energy environment. The degree of benthic impact depends on environmental factors (regime, water depth) that dictate how long the settled material remains concentrated at the well site.

As mentioned previously (UNEP, 1985), drilling discharges are not particularly toxic but may affect adversely the benthic community near offshore well sites. Such effects may be of a physical rather than a chemical nature. A zone of visible accumulations (e.g., formation clays) may be observed in the vicinity of the well site. Megabenthos (demersal fish and crabs) may be subjected to burial by drill cuttings within the immediate vicinity of the well site, although little change in species diversity will accompany the decreased abundance.

Marine organisms can bioaccumulate mud-associated metals, however under realistic exposure conditions accumulation does not occur to a degree sufficient to cause a toxic effect in the accumulating organisms (UNEP, 1985). No relationship was detected between microbenthic abundance and the barium content of sediments.

In the Cook Inlet (with a ware depth of 62 m), there was no increase in barium levels in the well site area sediment, because the barite particles were swept away rapidly by the current. Barium concentrations in the sediment were increased in post-drilling surveys, with concentrations 10-30 times their background values observed near the well site. All other metals (and extractable hydrocarbons, since the source examined oil wells) were unchanged from pre-drilling levels.

3.5.4. Drilling fluids

In order to prevent fluid loss, engineers have developed various drilling fluids aiming to create an impermeable mudcake downhole. Drilling fluids are also called drilling muds, because the first ones used in the drilling industry were plain mud.

The drilling fluid program of a well requires mud pits, mixing equipment, mud pumps, shakers, de-gassers, centrifuges and hydrocyclones. Drilling fluids contain chemicals used for the transportation of cuttings to the surface of the well; lubrication and cooling of the drilling bit; stabilization of the well walls; and maintenance of downhole pressure. A matter of high importance is the re-use of the drilling fluid, which requires carefully designed separation processes on the surface to remove cuttings.

Drilling fluids are classified into water-based muds (WBMs), oil-based muds (OBMs) and synthetic-based muds (SBMs). The main difference between oil and geothermal wells is temperature, with geothermal drilling using mostly WBMs.

Their main functions are the removal of rock cuttings from the borehole of wells and transport to the surface; lubrication and cooling of bits and drill strings; creation of a thin filter cake with low permeability for sealing pores of rock formation in wells; prevention of entrance of formation fluid into wells by providing hydrostatic pressure, and reduction of the coefficient of friction between the hole and the drilling string (Cheraghian, 2021). Ma et al. (2021) point out that *"Good rheological and filtration properties are necessary conditions for drilling fluids to maintain the above basic functions."* Husin et al. (2018) mentioned that *"The synthesizing and preparation of drilling muds must become more complex to satisfy the various operational demands and challenges … attributed to formation characteristics … degradation of drilling mud additives, gelation or breakdown of polymeric additives during drilling operation can affect the performance of conventional water-based muds."*

During the initial stage of a drilling operation, called spudding, the drilling fluids are usually water-bentonite muds. In this stage there is no return of drilling fluids to the surface. After the introduction of a steeling case and the first cementing phase, usually the drilling fluid program changes. Conditions such as formation properties, depth, temperature, and pressure are important for the choice of an appropriate drilling fluid.

WBMs typically consist of clay particles suspended in water. Qalandari & Qalandari (2018) note that nanoparticles used with WBMs outperform the same nanoparticles used with oil-based muds. This is attributed to the higher affinity with organophilic clays and dispersion (e.g., electrostatic and Van der Waals) forces performing better in WBMs. OBMs are considered to be more suitable for harsh environments due to the fact that they can retain their rheological parameters at high temperatures. However, they are characterized by adverse environmental impacts, and it is recommended that they be avoided in most cases.

The pH of most drilling muds is alkaline, with their design depending on the rocks that are drilled, e.g., for shale (clay), a mud should not be (too) acidic because it would weather (corrode) the rock.

The ORCHYD project will focus mainly on field tests and modelling efforts with water, WBMs (with bentonite and xanthan gum), calcium chloride, and potassium chloride. An initial analysis of such muds and additive materials is presented in this report, starting with the next section. The kind of ecosystems affected by geothermal drilling and the discharge of used mud and cuttings (in the context of the field tests and the technological improvements developed by ORCHYD) will be considered in the full environmental assessment report.

3.5.5. Water-based muds and additives

The design and utilization of drilling fluids plays a key role in the success of a geothermal project. Prixton & Hall (2002) suggest the use of *"a variety of drilling fluids, from water to … bentonite/barite mud"*, which is along the lines of what ORCHYD intends to do. An inappropriate selection or design of drilling fluids would lead to more nonproductive time.

Several factors need to be taken into consideration during the preparation of the proper drilling fluid for a geothermal well (Capuano, 2016). Lithology is one of the key aspects that need to be considered. Thickness, strength, permeability, and pore pressure of formations need to be analyzed. Water quality and accessibility are also important.

Another serious issue that renders conventional drilling difficult and costly is the high temperatures encountered in geothermal sites. These conditions favor the corrosion and oxidation of drill bits and drill string (Goff et al., 1995). The thermal profile of geothermal reservoirs induces changes in rheology which affect the efficiency of the drilling fluid. According to Ali et al. (2020), among the issues that need to be dealt with, are high temperature gelation; high temperature fluid loss; rheological property control; material degradation; sagging of barite; and gas solubility. The downhole temperature profile needs to be assessed as it can seriously affect the properties of the mud. At temperatures above 350 F (176.7°C), large amounts of water can be absorbed by the solids, leading to a raise in viscosity and gelation tendencies.

Mud viscosity needs to be adjusted to a level where cuttings will be able to be transported to the surface and loss of circulation is prevented. Capuano (2016) notes that *"the primary recommended viscosifier for geothermal drilling is API grade bentonite (sodium montmorillonite)."* Lignite has been used as filtrate reducer in geothermal drilling in the past, but in recent years polymer filtrate reducers are becoming more popular due to their resistance to high temperature alterations. Proper lubrication and cooling of the drill bit is of high importance as well, which is achieved mainly by the use of graphite.

The presence and coexistence of hydrogen sulfide (H_2S) and carbon dioxide (CO_2) need to be taken into consideration seriously as their dissolution in water can alter the mud pH and cause serious implications. The alkalinity of the drilling fluids can control the contaminating effects of H_2S and CO_2, reduce corrosion rates and cause additives like lignite and polymers to react. Capuano (2016) recommends that the pH is kept near 10.5 by the addition of sodium hydroxide (NaOH) or potassium hydroxide (KOH) to the mud. Given the above, it is safe to point that the pH level of the mud is crucial for the safety and economic viability of any geothermal project.

Furthermore, the mud needs to be monitored at all stages and adjusted accordingly if needed. The mud density is of particular importance as augmentation may be needed, depending on the downhole pressure. However, this should be done cautiously as the pressure regime in geothermal wells is relatively low and mud should be prevented from entering the surrounding rock, causing the loss of drilling fluid and polluting the subsoil. A study by Feng et al. (2018) addressed the importance of the proper choice of a mudcake during drilling operations, stating that *"an optimal mudcake for wellbore strengthening applications should have a moderate thickness, low permeability, and high strength."* The existence of water sources for the preparation of the WBMs close to the site is important both for economic and technical reasons.

According to Avci & Mert (2019), *"… geothermal water ascends to the surface by reacting with the subsurface formations causing mineral dissolution, so the variety and concentration of dissolved constituents in the geothermal waters are higher than those of freshwaters. The geothermal water composition is characterized by the macroelements of the reservoir rock and the subsurface environment to which it is exposed most … The most frequently observed ions with high concentrations are Na^+ [sodium], K^+ [potassium], Ca^{2+} [calcium], Mg^{2+} [magnesium], HCO_3^- [bicarbonate], CO_3^{2-}, SO_4^{2-} [sulfate] and CO_2. [carbon dioxide]. Other micropollutants are heavy metals such as mercury [Hg], copper [Cu], lead [Pb], silver [Ag], iron [Fe], zinc [Zn], arsenic [As], manganese [Mn], chromium [Cr], beryllium [Be], selenium [Se], vanadium [Va], cadmium [Cd], nickel [Ni], strontium [Sr], uranium [Ur], cobalt [Co], gallium [Ga], and antimony [Sb]. Some other elements of boron [B] and silica [Si] could be present in geothermal waters as well. Therefore, these waters are likely to affect the drilling fluid properties such as rheology, fluid loss, shale inhibition, and lubricity*". The quality and source of the water base for WBM is of particular importance. Avci & Mert (2019) conclude "*Therefore, it is recommended that geothermal spring water should not be used to prepare drilling mud in terms of effectiveness and cost of drilling."*

The use of fluid loss additives is of high importance to WBM. These additives should reduce the volume of fluid loss, form a thin and dense filter cake, and maintain their performance in high temperature and salinity conditions.

The most common additives in WBMs are clay, lignite, asphaltite or organic polymers such as bentonite. As Ma et al. (2021) wrote, *"various natural and synthetic polymers have been applied to improve the filtration property of drilling fluids, including xanthan gum, wild Jujube pit powder, tea polyphenols, starch, cellulose, synthetic polymers, cationic copolyelectrolyte, etc."* Degradation of natural polymers at high temperature renders them unsuitable for deep geothermal drilling environments. Capuano (2016) noted that *"Synthetic polymers have been added to the drilling fluid as viscosifiers since they provide instantaneous viscosity increase and encapsulate cuttings making the separation process easier. Unfortunately, these synthetic polymers often lose their advantageous properties within a short time under elevated temperatures."*

Polymer/nanocomposites on the other hand, show a better potential of use in drilling fluids in harsh environments due to their ability to combine the toughness of polymers and the rigidity of inorganic materials (Ma et al., 2021). According to Vryzas & Kelesidis (2017), the most important benefit of using nanoparticles in drilling fluids is *"the significant enhancement of fluid loss particularly at HP [High Pressure]/HT [High Temperature] conditions. This can lead the drilling industry to great cost savings."* A study by Mady et al. (2020) notes that *"The best cake characteristics were obtained at NPs-concentrations of less 0.3-0.5 wt.%. Metal oxide NPs [nanoparticles] are the most promising types in the field of drilling fluids industry. The higher NPs-stability in suspensions, suitable surface charge, in addition to the size of NPs are the most dominant parameters in proper functionality. NPs, especially nanosilica, can effectively plug the shale formations and perform as a bridging material when mixing with water-based drilling fluids in suitable concentrations, which can provide better wellbore stability and a potential solution for environmentally-sensitive areas where the oil-based mud is commonly used."* Katende et al. (2019) suggested that *"the optimum concentration of nanosilica that can optimally enhance the rheological properties of WBM is 1.0 ppb."* Seyedmohammadi (2017) claimed that *"When WBMs are used, only limited environmental harm is likely to occur. WBM ingredients can be divided into 16 functional categories. Each category of additives may contain several alternative materials with slightly different properties".* A summary of chemicals used in WBMs is presented in Table 3.3. (Seyedmohammadi, 2017).

Table 3.3. Chemicals used in WBM (Seyedmohammadi, 2017)

Category	*Function*	*Typical chemical composition*
Weighting materials	Increase density (weight) of mud Balance formation pressure Prevent blowout	Barite Hematite Calcite Ilmenite
Viscosifiers	Increase viscosity of mud to suspend cuttings and weight agent in mud	Bentonite or attapulgite clay Carboxymethyl cellulose Other polymers
Thinners, dispersants, and temperature stability agents	Help clays become deflocculated to optimize viscosity and gel strength of mud	Tannins Polyphosphates Lignite Lignosulfonates
Flocculants	Increase viscosity & gel strength of clays or clarify or dewater low-solids muds	Inorganic salts Hydrated lime Gypsum Sodium carbonate & bicarbonate Sodium tetraphosphate Acrylamide-based polymers
Filtrate reducers	Decrease fluid loss to the formation through the filter cake on the wellbore wall	Bentonite clay Lignite Na-carboxymethyl cellulose Polyacrylate Pregelatinized starch
Alkalinity, pH control additives	Optimize pH and alkalinity of mud Control mud properties	Calcium oxide (CaO) Caustic soda (NaOH) Soda ash (Na_2CO_3) Sodium bicarbonate ($NaHCO_3$) Other acids and bases
Lost circulation materials	Plug leaks in the wellbore wall Prevent loss of drilling mud to the formation	Nut shells Natural fibrous materials Inorganic solids Other inert insoluble solids
Lubricants	Reduce torque and drag on the drill string	Oils Synthetic liquids Graphite Surfactants Glycols Glycerin
Shale control materials	Control hydration of shales that cause swelling and dispersion, collapsing the wellbore wall	Soluble calcium and potassium salts Other inorganic salts Organics such as glycols
Emulsifiers & surfactants	Facilitate formation of stable dispersion of insoluble liquids in water phase of mud	Anionic Cationic Nonionic detergents Soaps Organic acids Water-based detergents
Bactericides	Prevent biodegradation of organic additives	Glutaraldehyde Other aldehydes
Defoamers	Reduce mud foaming	Alcohols

Category	*Function*	*Typical chemical composition*
		silicones Aluminum stearate ($C_{54}H_{105}AlO_6$) Alkyl phosphates
Pipe-freeing agents	Prevent pipe from sticking to wellbore wall or free stuck pipe	Detergents Soaps Oils Surfactants
Calcium reducers	Counteract effects of calcium from seawater, cement, formation anhydrites and gypsum on mud properties	Sodium carbonate and bicarbonate (Na_2CO_3 and $NaHCO_3$) Sodium hydroxide (NaOH) Polyphosphates
Corrosion inhibitors	Prevent corrosion of drill string by formation acids and acid gases	Amines Phosphates Specialty mixtures
Temperature stability agents	Increase stability of mud dispersions, emulsion, and rheological properties at high temperatures	Acrylic or sulfonated polymers or copolymers Lignite Lignosulfonate Tannins

Certain additives that are considered to be environmentally friendly (or at least neutral) may be used for enhanced thermal and rheological properties of WBMs. As reported by the European Technology and Innovation Platform on Deep Geothermal (2019), those can be traditional additives, nonconventional drilling fluids, nanoparticles, and green or eco-friendly additives.

Traditional additives include bentonite, xanthan gum, starch, synthetic polymers, copolymers and tetrapolymers. Nonconventional drilling fluids include carbon dioxide (CO_2) foam as circulation fluid, ionic liquids, and vegetable oils. Nanoparticles include nano zinc oxide, carbon nanotubes, silica nanoparticles, aluminum oxide nanoparticles, graphene, and hollow glass spheres. Green or eco-friendly additives include pistachio shells, sugar cane ash, tamarind gum, ground coca bean shells, rice fractions, cotton seed hull, coconut coir, natural fibers, ground peach seeds, ground nut shells, and nut flour.

3.5.5.1. Water

Water (in the form of fresh water or geothermal brine) constitutes a cost-effective base fluid in a variety of muds (density = 998 kg/m³ as communicated by ORCHYD partners). Reduced cost is a major advantage of water as a drilling fluid since it is cheaper than any mud. In addition, water reduces the temperature further, prolonging the bit life; reducing the possibility of a differential sticking and a kick; and improving penetration rates. Disadvantages include large water volume requirements; increased risk of stuck drill string; reduced permeability; and long well recovery periods. A regular mud cleaning system must also be present to allow for the recycling and reuse of water through pumps.

Despite the obvious environmental benefits of water, geothermal drilling cannot always use only water due to the pressure regime. Something more substantial may be required, which explains the use of bentonite, barite, and other substances used to lift the cuttings. Additionally, in ORCHYD, the drilling fluids must assist in activating the mud hammer.

Due to the fact that geothermal drilling takes place usually in an under pressured regime, large water quantities may be lost in the formation, causing damage and inadequate cuttings removal after a certain depth. For this reason, various solids are inserted in the water to help achieve the desired values for certain properties like viscosity. Clays and polymers may also be inserted as viscosifiers. However, contaminants of steam emissions, such as hydrogen sulfide (H_2S), boron (B), ammonia (NH_3) and mercury (Hg) can accumulate on drilling fluids. In addition, metals such as arsenic (As), lead (Pb), cadmium (Cd), iron (Fe), zinc (Zn), antimony (Sb), lithium (Li), barium (Ba) and aluminum (Al) can accumulate, as well. In the event of discharge of the drilling mud, a cleaning process must take place, in order to avoid the leakage of harmful elements such as arsenic and mercury in the environment. A study by Bayer et al. (2013) claimed that *“holding ponds for temporary discharges can be sizeable, although their contribution to the land footprint is judged minimal.”*

3.5.5.2. Bentonite and xanthan gum

Bentonite (density = 2300 kg/m³ as communicated by ORCHYD partners) and organic polymers such as xanthan gum (density = 1500 kg/m³ as communicated by ORCHYD partners) are introduced as additives to WBMs mainly for viscosity control.

Bentonite is a colloidal aluminum clay mainly composed of montmorillonite (Lewis, 1993) that may be written as $Al_2O_3 \cdot 2SiO_2 \cdot H_2O$ or $Al_2H_2O_6Si$ (https://www.americanelements.com/bentonite-1302-78-9) and is a common oil well drilling fluid. It comes it two varieties: (1) sodium bentonite, which has high swelling capacity in water; and (2) calcium bentonite, which has negligible swelling capacity. Bentonite forms colloidal suspension in water, with strongly thixotropic properties.

As Kwast-Kotlarek et al. (2018) mentioned, bentonite is a product of volcanic ash settled in alkaline environment such as the seabed. Bentonite is usually found along other clay minerals such as kaolinite and illite. Due to their highly water absorptive and swelling minerals properties, they are used to hinder and remove toxic pollutants from the environment. Bentonite is also used in wastewater treatment for the removal of various contaminants. Mahmoud et al. (2021) point out that *“The flexibility of bentonite makes it a good sealant to be used in GE [geothermal energy] and water well systems. Common types of bentonite used are sodium, calcium, and potassium. It is considered as one of the best fluid barriers due to its low permeability preventing fluids from passing easily. In many cases, bentonite is mixed with other materials forming a grout mix aiming to enhance the thermal conductivity. Cement, water, sand, and graphite are the commonly used bentonite additives.”*

Xanthan is a synthetic, water-soluble biopolymer that is made by fermentation of carbohydrates (Lewis, 1993). Xanthan gum’s chemical formula is $C_8H_{14}Cl_2N_2O_2$ (https://www.chemicalbook.com/ChemicalProductProperty_EN_CB3735028.htm). It is a thickening and suspending agent that remains stable over a wide temperature range, with good tolerance for strongly acidic or basic solutions. Xanthan gum is *“abundantly available, biodegradable, hydrophilic, low-cost and have carboxyl and hydroxyl functional groups”* (Ahmad & Mirza, 2018) and is also used as a thickener and source of dietary fiber in the food industry (Wang et al., 2018).

Xanthan gum is a good viscosity control polymer. As Echt & Plank (2019) pointed out, *“xanthan gum is a commonly used drilling fluid additive which … ensures excellent hole cleaning and carrying capacity for drill solids. It is routinely used as viscosifier when drilling geothermal wells in continental Europe. The viscosifying mechanism of xanthan gum is based on the formation of a large network due to the entanglement of the individual hydrocolloid chains when present in sufficient concentration. As these chains are only weakly bound to one another, they flow easily when stress is applied … Loss of viscosity after aging at high temperatures is caused by radical degradation of the polymer.”* A study by Paydar & Ahmadi (2017) asserted that *“by increasing the polymer concentration the plastic viscosity increases and this increase is negligible until 1.5 grams of xanthan gum concentration. But after that it has a sharp increase in plastic viscosity.”*

The combination of bentonite and polymers like xanthan gum in WBMs is often advantageous. Filtration properties of bentonite doubled by low viscosity of xanthan gum makes this kind of mud suitable for deep geothermal drilling conditions. It is important that it can reduce the risk of friction related complications while lifting cuttings adequately. Its properties can also reduce the problem of lost circulation. It can adequately stabilize the borehole and minimize water loss, which is very important when clay rich formations are drilled. Lastly, due to the mud's lower slip velocities compared to water, the risk of a stuck drill string can be reduced significantly.

However, there are certain disadvantages related to the disposal of drilling mud; clogging of borehole; formation damage; reduction of ROP; and differential sticking (if the choice of drilling mud is not optimum).

From an environmental standpoint, xanthan gum can potentially adsorb small quantities of carbon dioxide (Park et al., 2007). Regarding offshore drilling, according to the OSPAR commission's (for protecting and conserving the North-East Atlantic) list of substances or preparations used and discharged offshore which are considered to pose little or no risk to the environment (PLONOR) (CEFAS, 2019), both bentonite and xanthan gum are considered as substances which pose little to no risk to the environment in terms of bioaccumulation potential, acute toxicity, and possibility of endocrine effects.

3.5.5.3. Graphene and graphene oxide

Graphene ($C_{140}H_{42}O_{20}$) is a nanomaterial that was isolated in 2004 by Konstantin Novoselov and Andre Geim, who received a Nobel Prize in Physics six years later (density = 2267 kg/m³). Graphene has been widely researched and used in multiple applications, including drilling and completion fluids, due to its thermal, electrical, chemical, and mechanical properties.

Qalandari & Qalandari (2018) noted that *"The hexagonal arrangement of carbon atoms in graphene sheet has caused the material to pose an extraordinarily flexible behavior … effective in sealing the fractures that can occur during drilling operations … sealing the fractures induced in wellbore is termed wellbore strengthening…"* Its addition in the mudcake improves stability and reduces formation damage due to minimization of fluid loss. Cheraghian (2021) notes *that "Due to the graphene dispersion problem in aqueous media, the graphene has poor performance in water base drilling fluids, while graphene oxide has suitable stability in an aqueous medium."*

There is rising interest in the use of graphene and graphene oxide in the drilling industry. Graphene nanoparticles are chosen due to rheology-enhancing properties they may attribute to WBMs. Temperature, pH, and salinity affect the physical behavior of graphene.

An older study (Kosynkin et al., 2011) claimed that *"GO [graphene oxide] is an effective fluid-loss-control additive in WBMs. By methylating the GO through an esterification reaction, the stability of GO in saline environments is increased. GO has the potential for industrial scalability through production from abundant graphite sources and common reagents. GO's unique properties make it an ideal candidate for the next generation of fluid-loss-control additives".*

A study by Husin et al. (2018) documented the utilization of graphene nanoplatelets and nanosilver to enhance water-based drilling mud properties and suggested that *"the presence of graphene nanoplatelet and nanosilver gave insignificant effect on mud weight (density). The drilling mud with added graphene nanoplatelet exhibits an increment of its plastic viscosity by up to 89.2%. Unlike the nanographene platelet, the nanosilver increased the mud plastic viscosity by only 64.2%. Both graphene nanoplatelet and nanosilver reduced the yield point by 13.1% and 58.3%, respectively … A similar effect is observed with the fluid loss measurement (volume of filtrate) where the graphene nanoplatelet and nanosilver reduced the fluid loss by 89.0% and 77.7%, respectively. It was also found that both the mud filter cake without the presence of nanoparticles and the mud filter cake with added graphene nanoplatelet or nanosilver are similar in which the texture is thin and smooth. In the future, these nanoparticles will be utilized at elevated temperatures and pressures for water-based drilling mud's performance enhancement".*

Another study by Kusrini et al. (2018) suggested that *"Graphene is more suitable for wells with high formation pressures, GO [graphene oxide] is more suitable for low pressure well".* A study by Jassim et al. (2020) verified that *"graphene powder showed superior ability to disperse and seal porosity of filter paper compared to other nanoparticles".* Another study by Ikram et al.

(2020) suggested that *“graphene-derived nanocomposites, particularly, GO-nanocomposites, as additives enhanced the rheological properties of WBDF”*. However, the same study (Ikram et al., 2020) pointed out that *“they have been observed to be expensive and found to be produced in small amounts”.*

According to Fu et al. (2020) graphene shows good biocompatibility but at the same time it has high biological toxicity. Due to the likelihood of graphene nanoparticles releasing to the environment and impacting the biosphere, its toxicity must be considered carefully.

Schinwald et al. (2012) pointed out that graphene particles are easily inhalable and can cause severe toxic effects in the lungs such as pulmonary fibrosis and cysts. A study by Jamrozik (2017) suggested that graphene can have toxic impact on human and mouse epidermis: *“GO [graphene oxide] in concentration 400 µg/ml showed chronic toxicity, i.e., 4/9 analyzed mice died or developed granulomatosis. GO accumulated mainly in the lungs, liver, spleen, and kidneys and could not be removed from the kidneys. Therefore, special care should be taken when handling graphene and its derivatives, gloves, special overcoats and masks should be used”.*

Fu et al. (2020) claimed that *“Graphene materials have also shown some toxic effects on animals. At present, most of the studies focus on mammals such as rats and mice. The lower protozoa and nematodes, as well as zebrafish and other aquatic animals have also been studied. The toxicity of graphene materials to animals is closely related to its action position, action mode and action concentration, as well as the size of itself and the types of surface functional groups. The toxicity of graphene to mammal is manifested as low acute toxicity. GO [graphene oxide] is more toxic to the lungs of mammals than graphene, however, the surface modification can avoid the toxic effects of GO”.*

The toxicity of graphene to terrestrial plants and algae seems to be high, according to a study by Begum et al. (2011). Concerning algae, studies by Nogueira et al. (2015) and Ouyang et al. (2015) have suggested that damage is caused due to the increase in the presence of reactive oxygen which enhanced by the graphene accumulation (which renders oxygen radicals, Jarosz et al., 2016), affect seriously the growth of algae species. A study by Hu et al. (2010) addressed the antibacterial activity of graphene-based nanomaterials and found that it can affect the growth of *E. Coli*.

Concerning toxicity, it is important to examine cytotoxicity, plant and animal toxicity, and the antibacterial properties of graphene and graphene oxide. Cytotoxicity in particular is a highly important factor for the evaluation of the safety of any pollutant. As Fu et al. (2020) point out, *“graphene nanomaterials have certain cytotoxicity, and their toxicities are closely related to their physical and chemical properties and the types of cells, and it also has a significant concentration dependence”*.

A study by Wang et al. (2010) supported that the toxicity of GO aqueous solution is very low at concentrations below 20 µg/mL, but significant at concentrations above 50 µg/mL. Due to GO’s high surface activity, which yields a high number of Reactive Oxygen Radicals (ROS), DNA fragmentation, cell membrane damage and mitochondrial dysfunction may be caused (Jarosz et al., 2016). A study by Qu et al. (2013) found that GO’s interaction with the toll-like receptor 4 (TLR4) may trigger an inflammatory response which leads to programmed cell death. The same study further claimed that GO can directly damage the cytoskeleton and affect the morphology and normal function of cells.

On the other hand, graphene is an efficient adsorbent that can help remove heavy metals from the aquatic solution (Zhang et al., 2019). Graphene may also help make carbon capture cheaper and more efficient (Huang et al., 2021).

All in all, graphene and graphene oxide are good lost circulation materials: they are quite effective plugging formation holes. As a result, they are difficult to do without, so to mitigate any negative impacts they would have to be used selectively.

3.5.5.4. Barite

An important component of WBM is the weighting agent, which increases the mud density. This is important for blowout control during drilling operations. The most widely used weighting agent is barium sulfate ($BaSO_4$), most commonly referred as barite (density = 4480 kg/m³). Barite is a high specific gravity mineral related to barium sulfate, barytes, and heavy spar (Lewis, 1993).

Barite is *"by far the largest ingredient of drilling fluids"* and has a specific gravity of 4.2 to 4.5 (Noorollahi & Sahzabi, 2005, and https://www.mindat.org/min-549.html). It is widespread in the industry due to its low cost, inertness, high specific gravity, and low abrasive tendencies. Mohamed et al. (2020) have argued that a disadvantage of its use is that *"barite is prone to sag, and so requires viscosifiers and other gellants to keep it in suspension. Also, drilled solids that incorporate into a drilling fluid quickly assume the particle size of API specified barite, resulting in reduced solids separation efficiency at the shakers and centrifuges"*.

Another drawback of barite is its impurity content. As Ibrahim et al. (2016) noted, *"commercial barite, which is usually impure, is of lower specific gravity because of the presence of other minerals such as quartz, chert, calcite, anhydrite, celestite, and various silicates. In addition, it usually contains several iron minerals, some of which may increase the average specific gravity of the product"*. Barite is a mineral extracted by mining and can also contain heavy metals (Norwegian Oil & Gas, 2017).

Barite has low water solubility and does not interact with other mud components. Although it is not considered a toxic component of WBMs, a major concern is its mercury content. According to Neff (2008), metals in drilling fluids are traced primarily as impurities in barite. The toxicity of some of them (heavy metals including cadmium [Cd], chromium [Cr], copper [Cu], mercury [Hg], lead [Pb], and zinc [Zn]) is of great environmental concern. Often their concentration can be over 10 times higher than their naturally occurring concentration in formation sediments. High concentrations of aluminum (Al), iron (Fe) and silicon (Si) are also observed in barites, although those are not considered as toxic. Excess barium (found in barite) may act as proxy for eutrophication (Gooday et al., 2009).

There exist literature studies that have proposed alternatives to the use of barite. Abdou et al. (2018) found that *"Mud sample treated with barite/ilmenite mixture showed appropriate filtration loss and mud cake characters. Alternative weighting materials should be in demand to offer superior properties such as barite, available in sufficient reserves to meet field requirements and be competitively priced. A weighting material that can be sourced locally to substitute barite would be a good innovation in the drilling industry"*. Another study by Mohamed et al. (2020) claimed that *"perlite was proved effective in improving the drilling fluid performance at elevated temperatures".*

3.5.5.5. Calcium chloride

Calcium chloride (density = 2150 kg/m³) is a high-volume chemical that comes in various forms ($CaCl_2$, $CaCl_2{\cdot}H_2O$, $CaCl_2{\cdot}2H_2O$, and $CaCl_2{\cdot}6H_2O$) all of which are soluble in water and alcohol (Lewis, 1993).

Calcium chloride is used often in the drilling industry for the creation of brine and completion fuels. Lime mud, gyp mud (a calcium-based water mud containing gypsum) and calcium chloride mud are water-based drilling fluids that utilize dissolved Ca^{+2} as a component. Calcium chloride is a suitable salt for solid-free brines (used as drilling fluids). Solid-free brines improve the ROP, the stabilization of sensitive formations, and the density and abrasion or friction (Gowida et al., 2019).

The water phase salinity of mud needs to be controlled during drilling operations. As Redburn & Heath (2017) explained, *"water activity is a measurement of inhibition to prevent migration of fresh water into the formation, an important characteristic within water-based drilling fluids"*. The activity level of mud needs to be equal or lower to that of the formation's water. Chloride concentration is inversely proportionate to the activity level of mud. Therefore, adding calcium chloride will prevent mud losses into the formation and clay swelling issues. Dankwa et al. (2018) wrote that the increase of concentration of calcium chloride decreases the plastic viscosity and yield point of WBM.

Calcium chloride is also used in the drilling mud for cooling and lubrication of the drill bit, as well as removal of cuttings from the borehole. All in all, according to Gowida et al. (2019), calcium chloride *"is considered one of the most economic brine systems, with its broad range of densities, availability, low cost, and its ability to reduce the water activity of the fluid"*.

Implications by the use of calcium chloride concern mainly the corrosion of equipment. As Redburn & Heath (2017) mentioned, *"corrosion of drillpipe, casing, downhole tools, and all the circulating system on a rig is recognized as a serious problem … especially when dealing with divalent brines like calcium chloride."*

Calcium chloride has zero toxicity in normal amounts. Calcium chloride is not biodegradable but does not bioaccumulate. However, it causes an exothermic reaction when it dissolves in water, and it has desiccating properties. Calcium chloride interacts with solution acidity and thus affect the extraction of heavy metals such as cadmium (Kuo, Lai & Kuo, 2006).

3.5.5.6. Potassium chloride

Potassium chloride (KCl, density = 1980 kg/m³) is a salt occurring naturally as sylvite, that is soluble in water and slightly soluble in alcohol (Lewis, 1993). Potassium chloride is used widely in the drilling industry due to its shale stabilizing properties (mainly hydro sensitive clays). It is a cost-effective material and efficient swelling inhibitor of WBMs. It provides ions which promote the stabilization of such reactive clays which subsequently minimizes swelling phenomena.

As the Schlumberger Oilfield Glossary (2021) provided more details: *"Potassium muds are the most widely accepted water mud system for drilling water-sensitive shales, especially hard, brittle shales. K^+ ions attach to clay surfaces and lend stability to shale exposed to drilling fluids by the bit. The ions also help hold the cuttings together, minimizing dispersion into finer particles. The presence of Na^+ ions counteracts the benefits of K^+ ions and should be minimized by using fresh water (not sea water) for make-up water. With time, Na^+, Ca^{+2} and other ions accumulate from ion exchange with clays, making the mud less effective, but regular treatment to remove Ca^{+2} improves polymer function. Potassium chloride, KCl, is the most widely used potassium source."* According to Patel (2009), *"in order to minimize clay swelling and hydration, relatively high concentrations of KCl ranging from 2% to 37% are required."*

From an environmental standpoint, regulations in many countries prohibit or set severe constraints to the release of chloride residues in croplands. High contents of KCl in the drilling mud could be toxic to the marine environment, drilling environment, and disposal area (Murtaza et al., 2020). Elevated concentration of ions can affect plants and bacteria (Burden et al., 2013). This happens as a result of the alteration of the osmotic balance of the cells of plants and bacteria which causes lack of nutrients. A plant growing in soil containing a high salt content will have yellow or brown leaves and stunted growth.

Nitrogen, phosphorus and potassium ions in high concentrations and quantities may have an immediate negative effect to the soil or water upon release. However, over a relative short amount of time, the natural environment will break them down. The use of potassium sorbate as an alternative to potassium chloride has been suggested in the literature. In particular, a study by Naemavi et al. (2019) claimed that potassium sorbate *"is a 'readily degradable' material that more than 60% of its sorbic acid degraded within 28 days and the remaining potassium ion can be useful for plant growth. Finally, it has fewer disadvantages than potassium chloride for soil. The use of potassium sorbate in drilling fluid instead of potassium chloride protects the environment from chloride ion contamination."* On the other hand, like calcium chloride, potassium chloride interacts with solution acidity and thus affect the extraction of heavy metals such as cadmium (Ma et al., 2019).

In a study by Jiang et al. (2019), a gelatin composite with potassium chloride was developed as an environmentally friendly shale hydration inhibitor (contained in WBMs), which decreased swelling. However, as pointed by Murtaza et al. (2020), potassium chloride adversely affects the properties of drilling mud, which leads to high fluid loss, flocculation of bentonite, and coagulation of the cuttings around the bit in some cases.

3.5.5.7. Sodium carbonate

Sodium carbonate (Na_2CO_3) is commonly (density = 2200 kg/m³) known in the drilling industry as soda ash. Sodium carbonate may contain impurities (up to 1%) including sodium chloride (NaCl), sodium sulfate (Na_2SO_4), calcium carbonate ($CaCO_3$), magnesium carbonate ($CaCO_3$), and sodium bicarbonate ($NaHCO_3$) (Lewis, 1993).

Sodium carbonate may be used to seal ponds, as sodium ions bind to clay particles which swell and seal leaks (Lewis, 1993). According to Schlumberger (2021), it is used during drilling operation for the treatment of calcium ion contamination of freshwater or seawater muds. Clay flocculation, polymer precipitation and reduction of pH are caused as a result of the presence of calcium ions from drilling gypsum, anhydrite and calcium sulfate. In case of cement contamination, sodium bicarbonate ($NaHCO_3$) is preferred.

Sodium carbonate is introduced in WBMs to reduce the amount of soluble calcium, increase pH and flocculate spud muds. The latter is desirable for the removal of large gravel cuttings encountered at shallow depths. As Mahmud et al. (2020) mention, *"Salt contaminants that may ruin the drilling mud include potassium chloride, KCl, sodium chloride, NaCl, magnesium chloride, $MgCl_2$, and calcium chloride, $CaCl_2$. Calcium and magnesium ions in seawater make seawater another major source for salt contamination in the drilling mud. Calcium and magnesium ions are insoluble in WBM and caustic soda additive, or any other additive, and must be mixed in the mud in order to precipice the calcium and magnesium ions".*

As Schlumberger (2021) argues, sodium carbonate's main advantages are that it constitutes a *"widely available and economical source of carbonate ions to precipitate calcium while increasing pH"* and it *"effectively removes calcium in most drilling fluids at small treatment levels*". However, sodium carbonate is less soluble at high pH and should not be used to treat cement contamination or higher pH fluids. Overtreatment can result in carbonate contamination which can cause increase in yield point, gel strength and fluid loss. Schlumberger (2021) further states that "*typical treatments of soda ash range from 0.25 to 2 lb/bbl [0.7 to 5.7 kg/m³], depending on the calcium level and water chemistry of the drilling fluid. One pound [0.45 kg] of soda ash removes the calcium from 1.283 lb [0.58 kg] calcium sulfate (anhydrite). Treatments should be made on an incremental basis to prevent over-treatment, which results in carbonate contamination"*.

A study by Anthony et al. (2020) suggests that *"the higher the sodium carbonate concentration, the higher the alkalinity (pH) of the mud sample"*. In this research it is further noted that the highest bentonite and sodium carbonate concentration, the most improved are the flow and rheological properties of the WBM.

Sodium carbonate's environmental profile was described as *"naturally occurring and commonly found in soil and water in the environment"* by the EPA (2006) and it further suggests that low level release of sodium carbonate *"is not expected to adversely affect wildlife or water resources"*. Concerning health impacts, Schlumberger (2021) notes that *"soda ash is an alkaline material that can cause irritation to eyes, skin, or respiratory tract. Soda ash should be added slowly to the mud system either by mixing through the hopper or chemical barrel"*. It is further mentioned that sodium carbonate should not be mixed with other chemicals such as caustic soda or lime.

3.5.5.8. Comparing drilling fluids

Selected environmental effects of the examined drilling fluids (excluding water) are tabulated in Table 3.4.

Table 3.4. Environmental impacts of drilling fluids (onshore)

Environmental system	*Bentonite*	*Xanthan Gum*	*Graphene (Oxide)*	*Barite*	*Calcium Chloride*	*Potassium Chloride*	*Sodium carbonate*
Soil profile	Can increase water holding capacity; high adsorption capacity of heavy metals; may speed the reclamation and revegetation of coarse textured soils	Can increase water holding capacity; can absorb heavy metals (if modified);	Can increase water holding capacity;	Contains impurities (even commercial barite) among which heavy metals (especially barium and mercury); mercury (a major concern), chromium and barium have been reported as unavailable for update	Likely to interfere with soil pH; acidic, highly organic, and sandy soils least affected & alkaline loam and soils with high clay content most affected by changes in the pH	Likely to interfere with soil pH; acidic, highly organic, and sandy soils least affected & alkaline loam and soils with high clay content most affected by changes in the pH	Commonly found in soil
Deeper formations				Heavy metals unlikely to move in the soil profile	Salts likely to leach into deeper less productive soil layers with precipitation; arid regions more likely to suffer adverse effects	Salts likely to leach into deeper less productive soil layers with precipitation; arid regions more likely to suffer adverse effects	
Groundwater	High adsorption capacity of heavy metals	Can absorb heavy metals (if modified)	Can help remove heavy metals from water solution	Could contaminate groundwater (with heavy	Interacts with solution acidity and	Interacts with solution acidity and heavy	

Environmental system	*Bentonite*	*Xanthan Gum*	*Graphene (Oxide)*	*Barite*	*Calcium Chloride*	*Potassium Chloride*	*Sodium carbonate*
				metals especially mercury), more so in the case of arid regions	heavy metal concentration	metal concentration	
Surface waters	High adsorption capacity of heavy metals	Can absorb heavy metals (if modified)	Efficient adsorbent, can help remove heavy metals from water solution	Contains impurities (even commercial barite) including heavy metals (especially mercury); excess barium may act as proxy for eutrophication	Interacts with solution acidity and heavy metal concentration	Interacts with solution acidity and heavy metal concentration; affects the extraction of heavy metals like cadmium	Commonly found in surface waters
Water acidification	Does not promote water acidification			May be dissolved easier in an acidic aquatic environment	Lowers pH of water solution	Raises pH of water solution (when in sufficient concentration; Sadovski, 2019)	Could interfere with solution pH
Eutrophication	Can help with adsorption of agents causing eutrophication	Unclear (possibly weak and indirect) connection to eutrophication	Can help with adsorption of agents causing eutrophication	Excess barium (found in barite) may function as proxy for eutrophication			
Greenhouse gas emissions	(Carbon footprint and lifecycle analysis considerations only)	Carbon footprint and lifecycle analysis considerations; can adsorb some carbon dioxide	May help make carbon capture cheaper and more efficient	(Carbon footprint and lifecycle analysis considerations only)			

Environmental system	*Bentonite*	*Xanthan Gum*	*Graphene (Oxide)*	*Barite*	*Calcium Chloride*	*Potassium Chloride*	*Sodium carbonate*
Air pollution	Bentonite-based sorbents can adsorb organic air pollutants (Lizhong & Baoliang, 2009)						
Odors	Can help reduce offensive odors	Neutral odor	Good anti-odor capabilities	Can contain carbonaceous materials and thus have a fetid odor when crushed	Odorless	Odorless	
Cytotoxicity	Essentially nontoxic		Low below 20 µg/mL; High above 50 µg/mL; graphene oxide can directly damage the cytoskeleton and affect the morphology and normal functioning of cells	Essentially nontoxic; may contain impurities (especially mercury)			
Plant toxicity	Essentially nontoxic; little bioaccumulation potential		High biological toxicity	Essentially nontoxic; little bioaccumulation potential; may contain impurities (especially mercury)	Elevated concentration of ions may deteriorate plants and bacteria; may affect the growth rate of	Elevated concentration of ions may deteriorate plants and bacteria; may affect the growth rate of	

Environmental system	*Bentonite*	*Xanthan Gum*	*Graphene (Oxide)*	*Barite*	*Calcium Chloride*	*Potassium Chloride*	*Sodium carbonate*
					plants (brown leaves, stunted growth); regulations in many countries prohibit or constraint the release of chloride residues in croplands	plants (brown leaves, stunted growth); toxic in elevated concentrations; regulations in many countries prohibit or constraint the release of chloride residues in croplands	
Human and animal toxicity	Essentially nontoxic; little bioaccumulation potential		Easily inhalable; accumulates in lungs, liver, spleen, and kidneys; can cause severe toxic effects in the lungs (graphene oxide more toxic to the lungs of mammals than graphene); toxic impact on human and mouse epidermis	Essentially nontoxic; little bioaccumulation potential; may contain impurities (especially mercury)			Could irritate skin, eyes, and respiratory tract (as air pollutant)

Considering the lithosphere, bentonite and xanthan gum should have no adverse impacts on the soil profile – in fact, they should increase the water holding capacity, and help adsorb heavy metals. Barite may contain heavy metals as impurities and these could contaminate groundwater, although they may not be readily available for plant uptake. Calcium and potassium chloride may leach into deeper soil formations and interfere with soil acidity. Graphene (oxide) may also increase water holding capacity and help with the removal of heavy metals. So, as far as the lithosphere is concerned, bentonite, xanthan gum, and graphene (oxide) would be better choices from an environmental standpoint.

Similar considerations are valid for the hydrosphere, with bentonite, xanthan gum, and graphene (oxide) being good environmental choices that can help adsorb heavy metals. Bentonite and graphene (oxide) in particular may help prevent or reduce eutrophication. In the case of surface waters though (more so than in the soil solution), calcium and potassium chloride may affect the speciation and precipitation of heavy metals, so they may potentially play a favorable environmental role by helping with their removal. Barium present in barite may aid eutrophication, which would result in less dissolved oxygen. If calcium chloride reduced the pH of a surface water body, barite may be dissolved easier (along with its impurities), so complex interactions among the drilling muds may be expected here.

Turning to the atmosphere, regarding greenhouse gas emissions (and air pollution) there appear to exist minimal differences among the drilling muds examined, although their role in processes unrelated to geotherm drilling may make a difference – more in-depth analyses will be considered later in the project. Barite may be the only drilling mud that can potentially have an unpleasant odor (when crushed). In fact, bentonite and graphene (oxide) possess good anti-odor capabilities.

Finally, turning to the biosphere, graphene (oxide) appears to be the only drilling mud with some cytotoxicity, high plant toxicity, and several potential toxic effects on humans. Calcium and potassium chloride may affect the growth of plants negatively. Barite may have some toxicity potential due to its impurities (especially mercury). Xanthan gum and bentonite are the drilling muds with little bioaccumulation potential, and the least toxicity potential.

3.5.5.9. Life Cycle Analysis of geothermal drilling fluids

The findings of this report will likely need to be supplemented with the results of life cycle analysis (LCA) and/or carbon/ecological footprint methods that will be carried out later in ORCHYD.

An LCA for a geothermal well depends on the drilling plan, technology and (most importantly) the duration of drilling and operation. Menberg et al. (2016) pointed out that environmental impacts depend on *"site-specific conditions such as subsurface properties, which strongly influence the required drilling depth, drilling time and number of boreholes. In addition, a shift from diesel-driven drilling rigs to electric rigs can be observed. Thus, the environmental impact increasingly depends on the national electricity mix and the embedded environmental burdens from different energy technologies".* In this sense, drilling fluids constitute an aspect of importance for the LCA of geothermal wells.

Jiang et al. (2013) argued that *"a challenge of using LCA for water use impacts is the local nature of water impacts. Consuming the same amount of water has different effects in watersheds with different water availability". Clark et al. (2012) pointed out that "geothermal power plants consume less water per kilowatt-hour of lifetime energy output compared to other electric power generation technologies."* Energy consumption of drilling mud pumps is the issue of interest in this case.

Depending on the materials included and their mixture, WBMs impact power consumption accordingly. There are also indirect energy considerations that may have to be taken into consideration. For example, Bayer et al. (2013) underscored that "*the USEPA calculates a range of about 0.75–1.15 m^3/MWh of total water volume consumed for electricity generation from geothermal resources".* The same study further pointed out a water withdrawal and consumption rate of 38 m^3/MWh for a flash steam plant. However, the variation in these numbers occurs due to the fact that the second one is calculated under the consideration of *"all geothermal fluid consumption due to vapor losses during flashing of the geofluid. A critical aspect here is that apparently geofluids, which are often brines, are equated with water, and the role of reinjection, discharge and evaporation is roughly considered. The use of freshwater, which is of prime interest within LCA, is not distinguished, and in some cases low quality water may be applied to support cooling and/or as make-up",* as Bayer et al. (2013) further note.

Concerning the reinjection of drilling fluid into reservoir, a critical aspect that needs to be investigated in terms of LCA is micro seismicity which can seriously affect a geothermal drilling project, especially in densely populated areas.

3.5.6. Conclusions and recommendations

The goal of this section is to make preliminary recommendations by reviewing the research literature on the environmental impacts of geothermal drilling muds that are (likely to be) used for the novel drilling technology that will be developed by ORCHYD, combining Hydro-Jet and Percussion for improved ROP in deep geothermal drilling.

A background section aimed to describe the geothermal drilling process as depicted in the literature, highlighting the role of drilling muds (dense colloidal slurries) and the problem of lost circulation. Feedback by the partners on this section will help the UPRC team correct and clarify the details of the drilling process and crystalize the concept of any changes in the environmental impacts brought about by the improvements to be achieved by ORCHYD. The environmental effects of discharges emanating from onshore (and offshore) geothermal drilling were also described, with references to reserve pits, landfarming, (plant uptake of) heavy metals, and toxicity.

The section then focused on water-based muds and additives, encompassing water; bentonite and xanthan gum; graphene (oxide); calcium and potassium chloride; sodium carbonate; and barite. These are commonly used in geothermal drilling operations and their impact has been documented in various studies. Their environmental impacts were grouped into the soil profile; deeper formations; groundwater; surface waters; water acidification; eutrophication; greenhouse gas emissions; air pollution; odors; cytotoxicity; plant toxicity; and human and animal toxicity.

All in all, a preliminary grouped ranking of the examined drilling muds in increasing environmental concern would be as follows:

1. Bentonite and xanthan gum: no adverse environmental impacts
2. Calcium/potassium chloride and sodium carbonate: limited adverse environmental impacts
3. Barite and graphene/graphene oxide: heavy metals (in impurities) and biological toxicity

although this will have to be revised in the context of the full report on environmental impacts, especially when selected impacts are quantifies (potentially via risk analysis, life cycle analysis, carbon footprint, and ecological footprint analysis).

Internal ORCHYD communication has indicated that water with xanthan gum (4%) and calcium chloride were used in previous field tests, but that this composition may not be ideal for percussive deep geothermal drilling at depths over 2 km. With graphene (oxide), it is understood that due to its unique properties it is a promising material for use in geothermal drilling. In fact, its negative environmental impacts are limited to its biological toxicity, so it could be used with measures taken to protect living organisms.

4. Impact characterization and quantification

4.1. Scoping survey

A list of the environmental impacts presented and discussed in Section 3 of this report was submitted to the judgment of the partners of ORCHYD via an online questionnaire. In it, respondents were required to evaluate the importance of each impact in a Likert scale ranging from 1 to 5.

The analysis of responses was considered alongside the characterization of the impacts and guided the University of Piraeus team in setting priorities for the quantification of the most important impacts. In this respect, the survey assumed the role of scoping in a traditional environmental impact assessment study.

A bar chart of the responses received by researchers in the partner organizations is shown in Figure 4.1. ARMINES and SINTEF provided 4 responses each, followed by Imperial College London (ICL) and the University of Piraeus (UPRC), each of which provided 3 responses. Drillstar provided 2 responses.

Although not all partners provided responses, a good variety of educational backgrounds and experience was accounted for by the responses, including university professors, (postdoctoral) researchers, and professionals, many of whom has previous experience in Horizon 2020 projects.

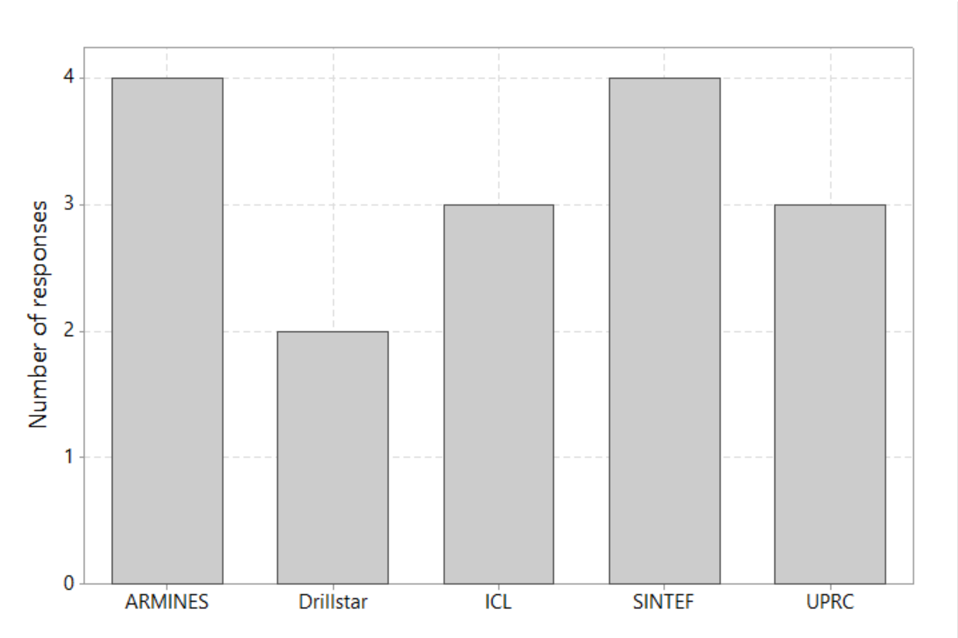


Figure 4.1. Bar chart of responses per partner

Partner countries were represented as shown in Figure 4.2. A total of 7 responses were from researchers located in France, followed by 3 researchers in Greece, Norway, and the UK.

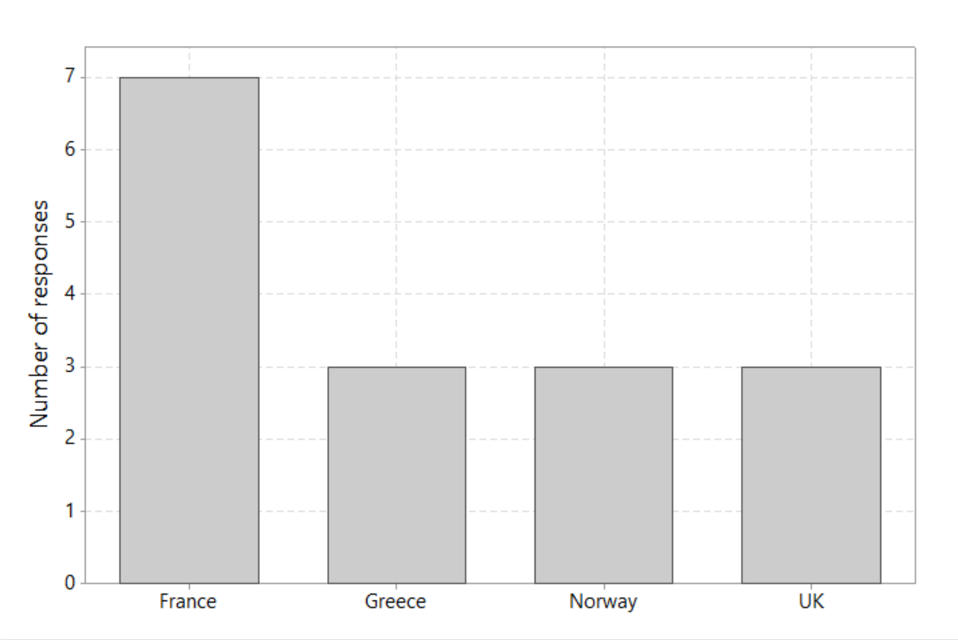


Figure 4.2. Bar chart of responses per country

A complete list of the mean, the minimum, and the maximum value for each item is shown in Table 4.1 (each item is listed with an abbreviated textual description). A higher mean value showed that respondents thought that the environmental and socioeconomic aspects of the specific item were important; a lower mean value showed the opposite. So, more effort was invested in this report to analyze the most important items in depth and with the aid of quantitative approaches (where possible).

Table 4.1. Descriptive statistics of response items

	Item	*Mean*	*Minimum*	*Maximum*
1	Overall environmental	3.75	2	5
2	Overall socioeconomic 1	3.94	3	5
ATMOSPHERE				
3	Greenhouse gases	3.50	2	5
4	Gaseous pollutants drilling	3.00	1	5
5	Local air pollution	2.94	1	4
6	Odors	2.56	1	5
7	Noise	3.63	2	5
GEOSPHERE/LITHOSPHERE				
8	Subsidence landslide	2.93	1	5
9	Microseismicity	4.00	2	5
10	Soil erosion	2.33	1	4
11	Soil mineralization	2.81	1	5
12	Soil water logging flooding	2.79	1	4
13	Groundwater pollution	3.50	2	5
14	Liquid solid waste	3.31	1	5
15	Land use	2.56	1	4
16	Aesthetics visual intrusion	2.27	1	5
HYDROSPHERE				
17	Quantity water aquifers	2.88	1	5
18	Water consumption drilling	3.00	1	5
19	Quality water aquifers	3.25	1	5
20	Pollution surface waters	3.19	1	5
21	Eutrophication	2.29	1	5
22	Generation disposal wastewater	3.13	2	5
BIOSPHERE (Ecosystems and manmade environment)				
23	Ecosystems vegetation wildlife	2.94	1	5
24	Biodiversity flora fauna	2.00	1	4
25	Paleontological resources drilling	2.00	1	4
26	Human public health	2.44	1	5
27	Overall socioeconomic 2	3.38	1	4
28	Local communities	3.06	1	5
29	Unemployment	2.69	1	5
30	Farming	2.38	1	4
31	Tourism	2.00	1	4
32	Energy markets	4.00	1	5
33	Energy security	3.63	1	5
34	Energy consumption drilling	3.56	1	5
35	Materials cement metal muds	2.75	1	4
36	Traffic networks	2.38	1	5
37	Public perceptions	3.88	1	5
38	Public health explosions	2.50	1	4
39	Public health radioactive	2.13	1	5
40	Incidents accidents	3.00	1	5

A number of conclusions were drawn from the table.

1. Microseismicity and impacts on energy markets were considered to be the most important items (mean=4), with microseismicity having a minimum rating of 2 (compared to the minimum rating of 1 for the impacts on energy markets. An attempt is made to elucidate the microseismicity risk in this report, while the impact on energy

markets will also be a concern in years 2 and 3 of the project, in the context of Tasks 3.2 (Social impact assessment), 3.3 (Energy security implications), and 3.4 (Expert interviews and geopolitical perspective).

2. Public perceptions were the next item in importance, with a mean rating of 3.88. Task 3.2 (Social impact assessment), which will take place in the second year of ORCHYD will address this exact issue, with an in-depth social survey (to be completed by Milestone 3.3), and a complete report coming as Deliverable 3.2.
3. Noise and energy security were next in importance (mean=3.63). Task 3.3 (Energy security implications), which will commence in month 23 of the project, will address energy security and will add to the geopolitical perspective with Task 3.4 (Expert interviews and geopolitical perspective).
4. Energy consumption during drilling was next in importance (mean=3.56), followed by greenhouse gas emissions (mean=3.5). These two items characterize a very important aspect of the project, its climate change emissions, which are estimated using Life Cycle Assessment (LCA) in this report. Although local air pollution was not rated with a lower importance (mean=2.94), it is also examined in the context of LCA in this report.
5. Finally, groundwater pollution was equal in importance (mean=3.5) to the previous two items, and it also examined to a greater depth in this report.

Of the rest of the items, some fall under the purview of the aforementioned forthcoming tasks of the project, including impacts on local communities (mean=3.06); usage of materials and muds (mean=2.75); and public health impacts (three items, means equal to 2.5, 2.44, and 2.13).

The following figure shows the average importance of environmental impacts compared to the overall importance of socioeconomic issues, which was polled with two items: one at the beginning of the questionnaire ("Overall socioeconomic 1") and a second one in its biosphere section ("Overall socioeconomic 2"). Although similar responses to the two socioeconomic items would show consistency, the second item probably shows how respondents felt about the relative importance of socioeconomic compared to other biosphere aspects.

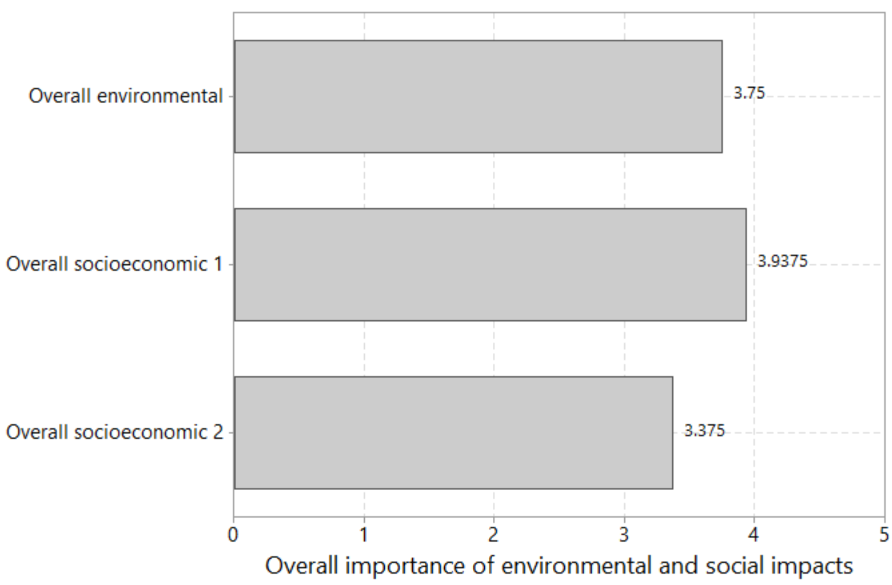


Figure 4.3. Overall importance of environmental and social impacts

The average importance of atmospheric impacts is compared in the next figure. Noise and greenhouse gases were rated as being the most important.

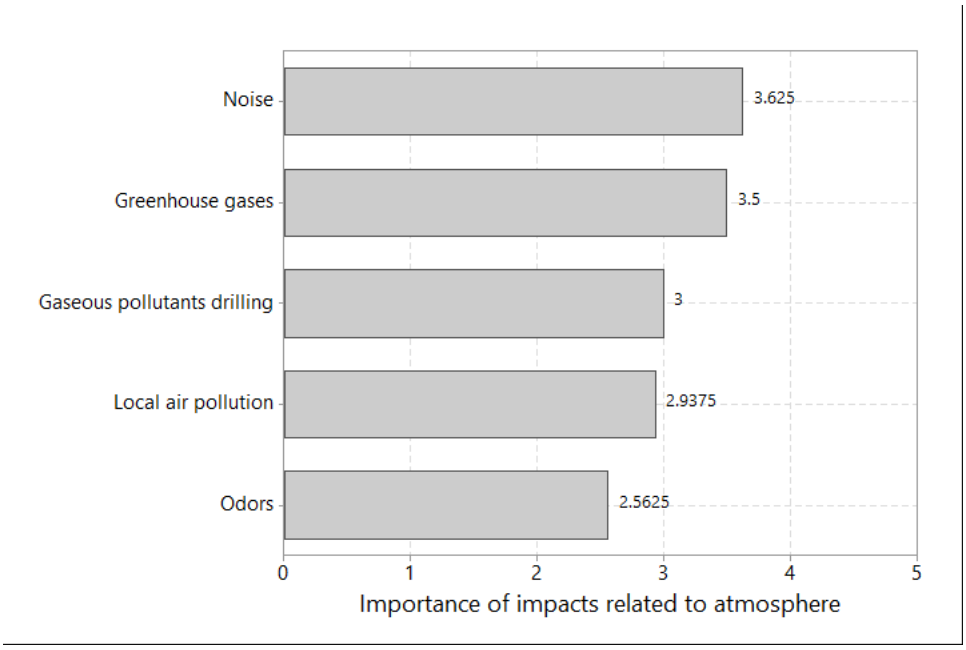


Figure 4.4. Importance of impacts related to the atmosphere

The average importance of impacts related to the geosphere (or lithosphere) are compared in the next figure. Microseismicity and groundwater pollution were rated as being the most important.

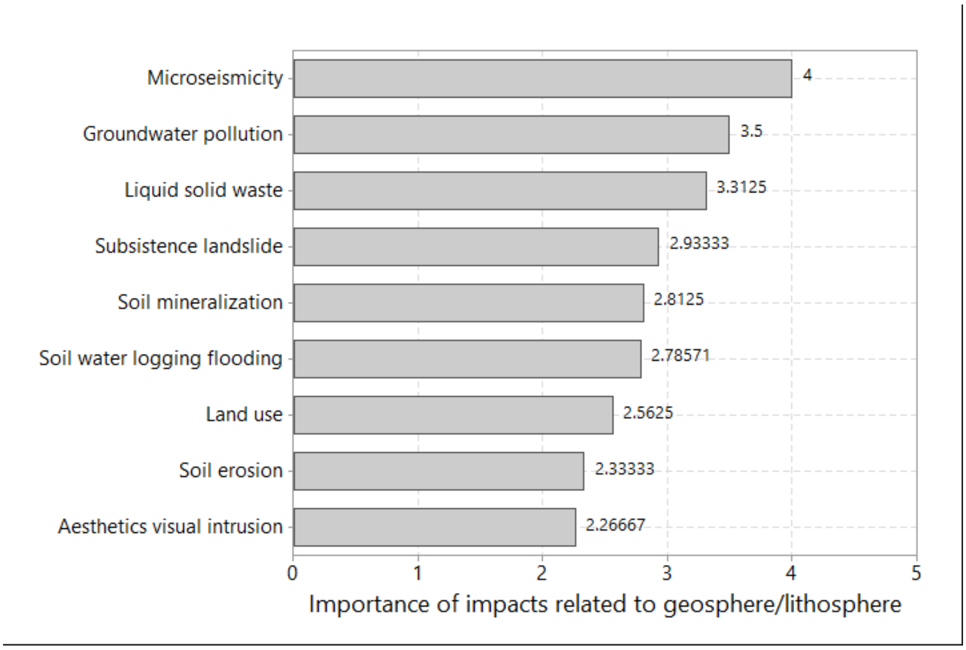


Figure 4.5. Importance of impacts related to the geosphere/lithosphere

The next figure compared the average importance of impacts related to the hydrosphere. Compared to the previous figures, none of the average ratings exceeded 3.5, but the water quality of the aquifers, the pollution of surface waters, and the generation and disposal of wastewater were considered the most important items.

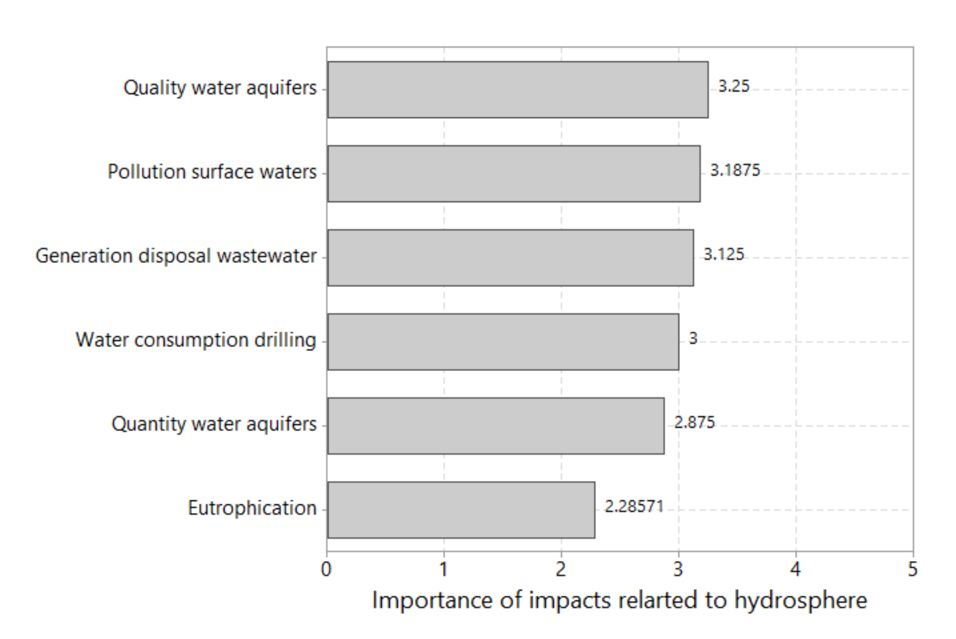


Figure 4.6. Importance of impacts related to the hydrosphere

The average importance of items in the biosphere section that related to ecosystems is compared in the next figure. Ecosystems, vegetation, and wildlife were the most important items, but none was rated as having an average importance over 3.

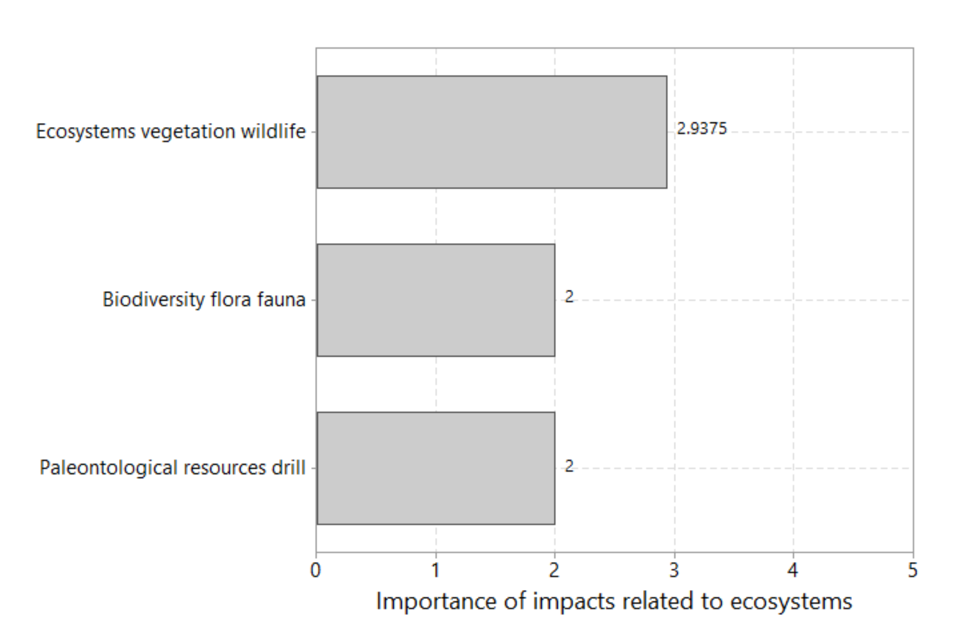


Figure 4.7. Importance of impacts related to the biosphere (ecosystems)

Coming to the average importance of items in the biosphere items belonging to the manmade environment (rather than ecosystems), impacts on energy markets; aspects of public perception; impacts on energy security; and impacts on energy consumption during drilling were considered the most important items.

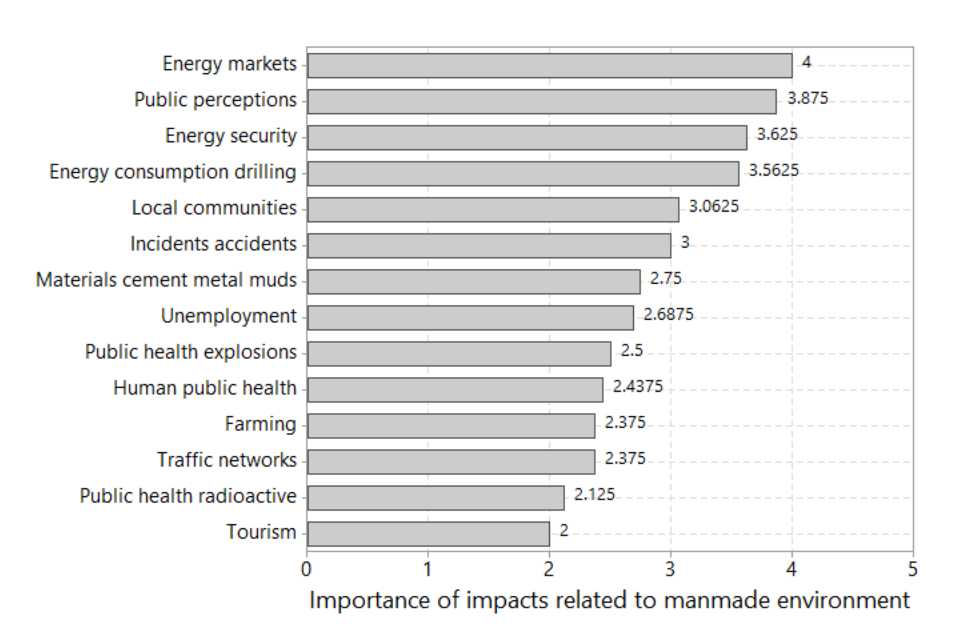


Figure 4.8. Importance of impacts related to the biosphere (manmade environment)

It is important to link some of the above items to the work planned for years 2 and 3 of the ORCHYD project.

- Task 3.2 (Social impact assessment, months 13 to 22) will examine social impacts in depth, with the help of an online survey of public attitudes etc. related to geothermal drilling. The role of public perceptions; impacts on local communities; perceptions of incidents and accidents; impacts on employment; the role of impacts on public health; impacts on farming; and impacts on tourism, will be examined in depth in the context of that work.
- Task 3.3 (Energy security implications, months 23 to 28) will work out an energy security index that allows the quantification of the impact of the improvements developed by ORCHYD in the geothermal field. In that context, impacts on energy security as well as markets will be examined in depth.
- Finally, Task 3.4 (Expert interviews and geopolitical perspective, months 29 to 33) will poll the opinion of global energy experts to add a geopolitical perspective to ORCHYD. In that context, impacts on: energy security; energy markets; employment; (traffic) networks; local communities; and tourism, will be discussed in depth, and will be evaluated from a geopolitical perspective.

The next figure completes this section by pooling all ratings together and showing them in decreasing values of average importance. Microseismicity and impacts on energy markets were the most important items overall, with an average importance of 4, with public perceptions coming next, with an average importance of 3.875. Noise; energy security; energy consumption during drilling; greenhouse gas emissions; and groundwater pollution were next, with an average importance between 3.5 and 3.6.

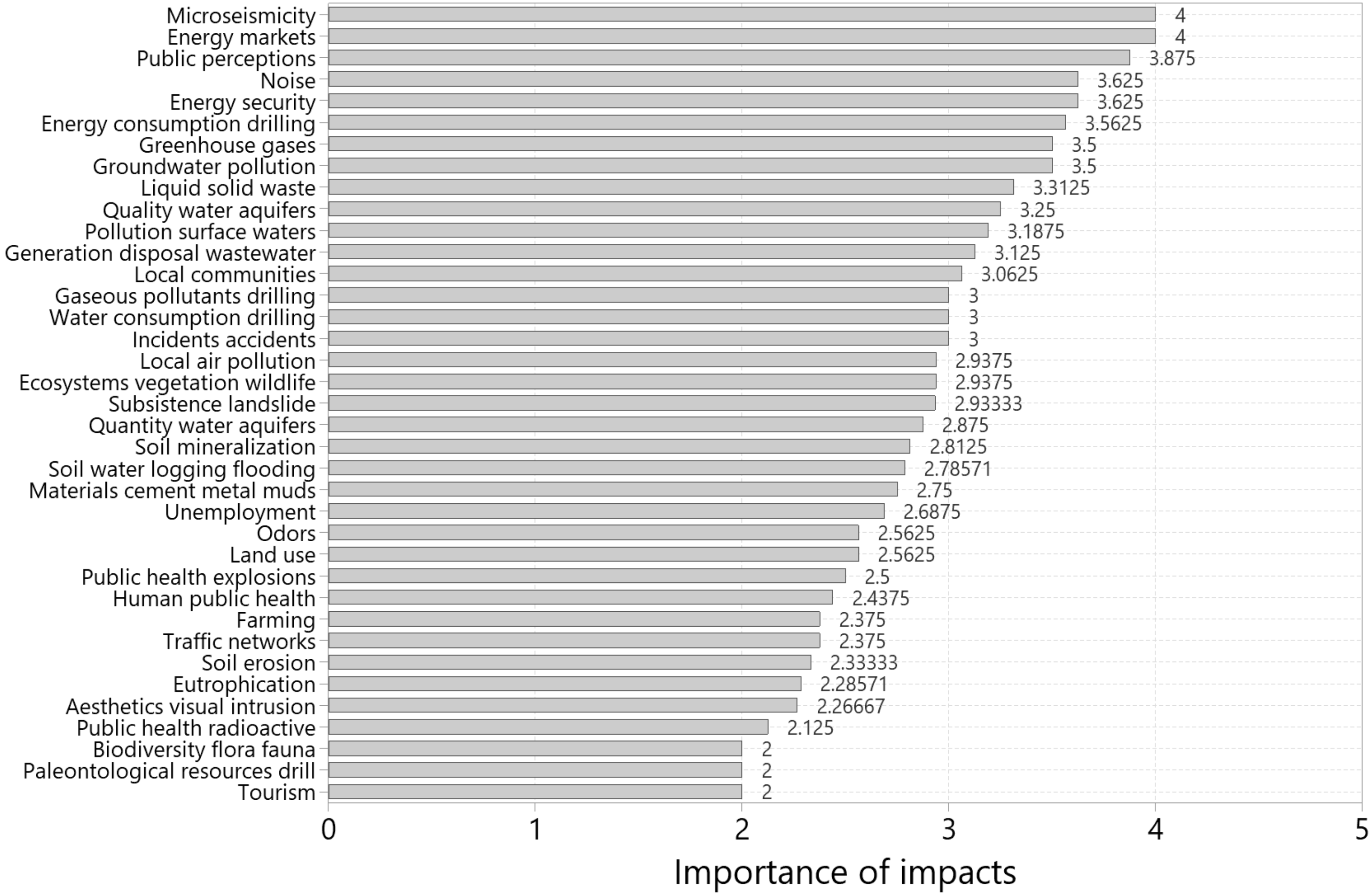


Figure 4.9. Ranked importance of all impacts

All in all, these were considered the most important environmental, socioeconomic, and geopolitical aspects of the work of ORCHYD. Some of these are examined in more detail in this report.

4.2. Characterization of environmental impacts

Impact types may be characterized as follows:

1. Positive/negative (type): favorable or unfavorable to the environment (including the viability of species, habitats and communities);
2. Temporary/long term (duration): according to the time of recovery to pre-impact levels, with the cutoff value to be determined, e.g., 3 or 5 years;
3. Reversible/irreversible (nature): depending on whether the impacted species and communities will recover (on their own) or that (special) mitigation measures (to be proposed) will be required;
4. Direct/indirect (nature): referring to the source/origin of the impact and whether it acts directly or indirectly on the environmental target;
5. Not likely/potential/certain (likelihood): with probability cutoffs to be determined, e.g., up to 10%, 10 to 70%, over 70%;
6. Local/regional/national/international (scale): characterizing geographical restrictions to specific habitats, communities, and regions.

Table 4.2. contains such a characterization of the impacts discussed in previous sections.

Table 4.2. Environmental impact characterization

Impact	*Positive (P) Negative (N)*	*Not likely (NL) Potential (P) Certain (C)*	*Temporary (T) Long term (LT)*	*Reversible (R) Irreversible (I)*	*Direct (D) Indirect (I)*	*Local (L) Regional (R) International (I)*
Soil subsidence	N	P	T	R	D	L
Induced seismicity	N	P	T	I	D& I	R
Soil erosion	N	P	LT	I	I	L
Groundwater contamination	N	NL	LT	I	D	L
Generation of solid wastes	N	C	T	I	D	R
Land use changes	N	P	LT	I	D	L
Visual intrusion	N	P	T	R	D	L
Water consumption	N	C	LT	I	D	R
Surface runoff	N	P	LT	R	I	L
Thermal pollution	N	P	T	R	D	L
Eutrophication of surface waters	N	P	LT	I	D	L
Water pollution	N	P	T	R	D	L
Greenhouse gas emissions	N	C	LT	I	D	R
Air pollution (from rig, traffic, etc.)	N	C	T	R	D	L
Odors	N	C	T	R	D	L
Noise	N	C	T	R	D	L
Ecosystem disturbance	N	P	T	I	I	L
Vegetation changes	N	P	LT	I	D	L
Biodiversity	N	P	LT	I	I	R
Effects on paleontological resources	N	P	LT	I	D	L
Effects on wildlife	N	P	LT	I	I	L
Public health (including toxicity)	N	NL	LT	R	I	L
Radiation risk from radioactive deposits	N	NL	LT	I	I	L
Effects on employment	P	C	LT	R	D	R
Effects on markets	P	C	LT	R	D	R
Effects on farming	N	P	LT	I	D	L
Resettlement	N	P	LT	I	I	R
Effects on infrastructure	N	P	LT	R	D	L
Effects on tourism	N	NL	LT	I	I	R

Impact	*Positive (P) Negative (N)*	*Not likely (NL) Potential (P) Certain (C)*	*Temporary (T) Long term (LT)*	*Reversible (R) Irreversible (I)*	*Direct (D) Indirect (I)*	*Local (L) Regional (R) International (I)*
Effects on cultural resources	N	NL	LT	I	I	R
Environmental injustice	N	NL	LT	I	I	I
Energy consumption	N	C	LT	I	D	R
Use of materials	N	C	LT	I	D	R

4.3. Quantification of environmental impacts

4.3.1. Introduction

Quantification of impacts forthcoming

1. Risk Analysis (RA) ~ risk acceptability (criteria), (semi) quantitative and qualitative techniques, interfacing with energy experts (Task 3.5 of WP3)
2. Life Cycle Analysis or Assessment (LCA) ~ raw materials and energy; manufacturing; distribution (transportation); use/consumption; recycling; and (final) disposal
3. Carbon Footprint (CF) ~ equivalent greenhouse gas emissions, often selected as the functional unit of LCA
4. Ecological Footprint Analysis (EFA) ~ resource consumption and waste generation = ecological assets (bioproductive land and sea requirements)

Life cycle assessment is used for the comparison of the environmental performance of different energy technologies or systems throughout their entire life cycle (cradle-to-grave). As Treyer et al. (2015) pointed out, the idea behind the LCA perspective is that the environmental impacts of an energy system are not only caused by the power production process itself, but are also due to the production chains of installed components, used materials, necessary services, etc.

LCA can provide a cradle-to-grave perspective to the environmental performance of geothermal plants (Lacirignola and Blanc, 2013). LCA standards ISO 14040/44 (International Organization for Standardization, 2006) have set out that LCA be carried out in four distinct steps: (1) goal and scope definition; (2) inventory analysis; (3) impact analysis; and (4) interpretation.

The main reason for carrying out LCA of deep drilling geothermal systems is to calculate the carbon intensity of geothermal operations and identify the key factors that affecting it, with the ultimate aim of identifying processes and points of potential emission reduction. Geothermal plants have negligible direct emissions during their operation but require a big amount of materials and energy for exploration, development, and construction.

4.3.2. Life cycle assessment studies

McKay, Feliks and Roberts (2019) aimed to quantify the emissions of low enthalpy deep geothermal systems (in kgCO_2eq/MWh). They focused on processes producing most emissions and attempted to establish whether low-enthalpy deep geothermal is compatible with long term, stringent, decarbonization pathways. They suggested that the majority of emissions are associated with construction and site-specific materials and factors. The drilling depth and the type and quantities of steel and cement appear to be the most important factors of interest. Soils disturbed for laying of pipelines and construction of access roads also seem to be of importance. In the case of LCA for energy resources, it is conventional to express the carbon intensity of a fuel in terms of the total GHG emissions (in CO_2 equivalent) per unit of energy, e.g., grams of CO_2 equivalent per kWh of produced energy (gCO_2eq/kWh). Despite the many studies available in the literature, not all parameters of importance are addressed explicitly. Oftentimes, LCA studies focus on combining sources from the literature for the development of a Life Cycle Inventory (LCI) which is used to estimate the GHG emissions using conversion factors.

A review of the existing literature on the environmental impacts of geothermal power was conducted by Bayer et al. (2013). The lack of studies which provided quantitative estimates of both direct and indirect environmental consequences was underscored. Those authors provided data for LCI and an insight on geological hazards, water, and land use effects.

Another study by Treyer et al. (2015) developed an LCI, which included elements of drilling energy use; material and energy use for the casing of the borehole; drilling fluid composition and treatment; drilling cuttings transport and treatment; transport of the drilling infrastructure;

casing material and drilling fluid ingredients; end of life of the borehole; and extra drilling for exploratory wells. It did not account for the energy use for pumping tests; possible emissions of natural gas from the ground during drilling; and possible radioactivity of drill cuttings.

The Italian flash technology of the Bagnore power plant was investigated by Tosti et al. (2020). A cradle-to-grave LCA was conducted, which revealed that 95% of potential environmental impacts are effected during the operational and commissioning phase. That study suggested that impacts are equally divided between well drilling and use of equipment. Copper was highlighted as the main impact contributor of the commissioning phase, and the need for further research on material use was stressed out.

The GHG emissions of the Rittershoffen geothermal plant were assessed by Pratiwi, Ravier and Genter (2018). Five different scenarios were developed to investigate the contribution of each phase and materials to the final emissions output, using hotspot analysis (intended to identify emission peaks). Drilling and stimulation phases appeared to have the highest impact on GHG emissions. Transporting of piping and equipment and metal product usage and production is suggested to be of high importance, as well.

The estimation of the carbon footprint of the exploration phase of a geothermal project in West Java (Indonesia)by LCA was documented by Adiansyah, Biswas and Haque (2021). Land clearing, access road improvement, slim-hole well pad, and standard hole well pad construction were considered. Those authors explained that the ReCiPe method of impact assessment analysis was used to convert inputs and outputs to carbon footprints per square meter of geothermal exploration area. ReCiPe is a life cycle impact assessment (LCIA) whose primary objective is to *"transform the long list of life cycle inventory results into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category"*, according to PRe (2016). The findings indicated that the total annual carbon footprint of geothermal energy exploration stages was 53.2 kgCO2eq/m². During drilling, the standard-hole well pad and slim-hole well pad were identified as carbon footprint hotspots.

The feasibility of implementing a deep direct-use (DDU) geothermal energy system (GES) was assessed by Thomas, Tinjum and Holcomb (2020). An investigation of system characteristics was conducted including an LCA with quantification of impacts and co-benefits. A spreadsheet tool was developed and used, which provided insight into cradle-to grave environmental impacts. The impact categories assessed were ozone depletion; global warming potential; smog; acidification; eutrophication; and fossil fuel depletion.

In deep geothermal drilling, the time and amount of resources required are highly dependent on site specific conditions like the geological formation. A common practice is the development of different scenarios to test the sensitivity of carbon emissions indicators (McKay, Feliks & Roberts 2019; Lacirignola & Blanc, 2013; Pratiwi, Ravier & Genter, 2018). Conditions such as low temperature, hard rocks, loss of drilling fluid, and technical mishaps should be taken into consideration. A 3 kgCO_2eq/MWh emission factor for a drill rig powered by diesel is suggested by McKay, Feliks & Roberts (2019). The availability of natural gas or electric to supply drill rigs could lower the total emissions to 5 kgCO_2eq/MWh. On unfavorable drilling conditions, this could rise to 19.7 kgCO_2eq)/MWh. Power supply, well casing and cementing, and consumption of drilling fluids are the most important factors concerning the final CO_2 emission output of deep geothermal drilling operations McKay, Feliks & Roberts (2019). Well life is also very important: as explained by Treyer et al. (2015), the necessity of drilling more wells due to lower well life (e.g., 5 instead of 30 years) result into three times higher environmental impacts per kWh.

Land use changes are an important factor for CO_2 emissions profiling. Geothermal drilling operations yield higher emissions when they are located in remote places, because of the transportation of equipment and materials. Estimates by McKay, Feliks and Roberts (2019) suggested that a development of a brownfield with no modifications required for placing equipment, would yield 7 kgCO_2eq/MWh to 14 kgCO_2eq/MWh. Doubling the required land area would result in an increase of the upper value to 15.5 kgCO_2eq/MWh. This finding is further supported by Pratiwi, Ravier and Genter (2018) who argued that reducing the total transport distance or frequency of travel is the second most impactful decision in reducing total emissions by 4%. Those authors also argued that treating post-drilling mud in nearby regions has a potential of reducing total emissions by 2.9%.

The drilling depth has also been identified as an important emission factor. A 10% reduction of drilling depth could result in the reduction of emissions by 0.7 kgCO_2eq/MWh. An extra 50% of drilling depth (e.g., in cases of temperature profile miscalculations) could raise the upper value to 15.2 kgCO_2eq/MWh (McKay, Feliks & Roberts, 2019). This has been supported by Treyer et al. (2015) who suggested that *"greater well depth leads to higher energy consumption per meter drilled and higher material needs for the casing"* although since capacity increases as well, *"deeper wells seem to be beneficial for environmental impacts"*. However, taking into consideration the fact that capacity increases with depth, *"deeper wells seem to be beneficial for environmental impacts"* since electricity generation from geothermal energy is much less polluting than electricity generation from conventional energy sources.

Fuel consumption during drilling operations varies according to the size and efficiency of the engine. McKay, Feliks, and Roberts considered diesel to be the primary source of energy (2019). According to a scenario developed by them, diesel consumption for drilling a 2000 m borehole in granite formations that took about 1500 hours to be drilled, would be 3785 L/d, and emit 2.63 kgCO2eq)/L of fuel. According to Tosti et al. (2020), diesel consumption for geothermal drilling was approximately 12 GJ/m. Diesel fuel was identified as a significant contributor to the depletion of fossil fuels due to its use in both transportation and construction phases of a geothermal project (Thomas, Tinjum & Holcomb, 2020). Menberg et al. (2021) proposed using electricity for drilling operations in order to conserve resources and mitigate negative environmental impacts. Menberg et al. estimated the demand for drilling with electricity of medium voltage as power source to be equal to 2,630 MJ/m (±10%). Additionally, Pratiwi, Ravier and Genter (2018) suggested that electricity be used as a more efficient energy source for drilling operations.

Drilling mud is also of interest for LCA of deep geothermal drilling. Most studies do not take into account emissions from bentonite and other materials included in drilling muds, focus instead on the required quantities of water. A maximum of 5000 m³ of water per well for drilling was assumed by McKay, Feliks and Roberts (2019), which may double in the case of permissive (i.e. allowing the infiltration of water) fractures in the granite formation. A study by Bayer et al. (2013) suggested that water quantity used for drilling can be up to 1000 m³/d. Another study by Clark et al. (2011) estimated that the total water consumption could range between 5 to 30 m³/m of drilling, depending on geology, technology, number of liners, and depth.

The indirect CO_2 emissions of (a) water consumption and (b) water treatment and disposal are 0.149 and 0.272 kgCO_2eq/m³respectively (Department for Business, Energy & Industrial Strategy, 2021). For materials used in drilling muds, Adiansyah, Biswas and Haque (2021) mention that the utilization of caustic soda during drilling contributed 64.5% of the total carbon footprint, followed by diesel fuel consumption (27%), bentonite (4.04%), and barium sulphate (4.43%) for standard-hole well pad construction. On the other hand, although acknowledging that the biggest amount of solid and liquid wastes results from drilling mud, Bayer et al. (2013) argued that their quantity is still relatively small and not of particular environmental concern.

The standard process of geothermal drilling requires cementation and casing. Tosti et al. (2020) argued that cement and steel are the most used materials, *"accounting for about 70% of the total weight of equipment used in this stage"*. However, McKay, Feliks and Roberts(2019) assumed partially cased boreholes, since granite formations may need to be cased only for a limited length (in the order of 30 m) in favorable conditions. Yu et al. (2015) mentioned 2.76 tCO_2eq/t for raw material steel used in casing operations. On the type of steel, Menberg et al. (2021) suggest that casing steel, low-alloyed 124.4 kg/m (±5%) is required. Casing diameter presented an optimal value of 10 cm according to Treyer et al. (2015), who further suggested that this was due to the influence of energy consumption for drilling operations as well as the amount of fluid that can be pumped through the pipe with a certain pump capacity. Doubling the pipe diameter from 25.4 to 50.8 cm led to environmental impacts around 1.7 times higher on a per kWh basis. The emission factor for cementing operations ranged between 800 to 1000 $kgCO_2eq/t$, without taking into account possible chemical additives (Salas et al., 2016). Thomas, Tinjum and Holcomb (2020) claimed that CO_2 emissions associated with the use of steel, were an order of magnitude higher than the emissions of other materials. Despite the fact that concrete has a higher embodied energy than steel, steel poses a higher environmental impact than cement due to the fact that the amount needed for casing is higher (Tinjum & Holcomb, 2020).

Lacirignola and Blanc (2013) carried out Life Cycle Assessment (LCA) for 10 hypothetical case studies of Enhanced Geothermal System (EGS) plants, representing conditions in central Europe. Due to their thermodynamics, geothermal technologies are characterized by excellent reliability and a high-capacity factor, overcoming the intermittency of other renewable energy sources (RES). Nevertheless, large quantities of energy and materials are required for geothermal plants, particularly the construction and operation of boreholes.

Lacirignola and Blanc observed that at the time of writing (2013) relatively few LCAs had been performed for geothermal power plants, which made the task of building a comprehensive database of material and energy flows difficult. Emissions of greenhouse gases (GHG) per unit of energy produced by an EGS is commonly estimated to be in the range of 40 to 60 g of CO_2-equivalent per kWh (gCO_2eq/kWh). In comparison, the GHG emissions of power plants based on fossil fuels are one magnitude higher, around 1000 gCO_2eq/kWh for coal and 500 gCO_2eq/kWh for natural gas plants. The ten case studies analyzed by those authors corresponded to combinations of the factors that determine the size of an EGS plant: number of wells; drilling (borehole) depth; geothermal fluid temperature; reinjection strategy; seismicity risk; and production flow rate. Some of the technical data were from the pilot EGS of Soultz-sous-Forêts (France) that was also considered in Deliverable D2.1 of ORCHYD. Impacts on climate change, resources, public health and ecosystem were studied. The risk of induced seismicity was added to the LCA as an important environmental indicator. The risk of seismicity is increasingly important at the design stage, especially since the cancellation of the EGS plant in Basel (Switzerland) in December 2009, and the problems encountered in Landau (Germany) in 2009 and 2010 (https://publikationen.bibliothek.kit.edu/1000051807/25900664).

As to the case studies examined by (Lacirignola and Blanc, 2013) The Soultz-sous-Forêts plant is equipped with three boreholes drilled to a depth of about 5 km, aiming to produce a nominal flow rate of 35 L/s from one well, while reinjecting into the other two, provoking low seismicity. The subsurface vertical gradient was around 100 °C /km for the first 1 km; 10 °C /km until a depth of 3.5 km; and 30 °C /km below 4 km. A temperature of 200 °C was reached at 5 km. In Landau, a granite formation was encountered at about 1 km and a very high temperature gradient was registered in the first 2 km. During production, the geothermal fluid cools off by about 5 to 15 °C, which increases with the borehole depth, but decreases with increasing flow rate. A depth of 5 km was considered too deep for EGS applications in the Rhine Graben, so those authors assumed a maximum depth of 4 km. For the five 4 km deep wells, the production temperature was set at 165°C, and for the other five 2.5 km deep wells, the production temperature was set at 145°C.The distance between the wells was assumed to be around 700 m (as in Soultz-sous-Forêts). Interestingly, those authors remarked that targeting a fractured granite zone deeper than 4 km, leads to a lower production of geothermal flow. On the contrary, it was suggested that drilling at a lower depth and reaching geological layers characterized by natural convection of the thermal fluid can lead to higher production rate. High and low flowrates were assumed to be equal to 40 and 20 L/s for the 4 km boreholes; and 70 and 35 L/s for the 2 km boreholes. It was noted that stricter safety measures may be required because of the radioactive content of thermal and drilling fluids, resulting from the circulation of the water through a granite reservoir. For all ten cases, it was assumed that the geothermal water was reinjected at a temperature of 70°C. The thermal efficiency of EGS plant is unavoidably low because of the low temperatures that characterize the cycle, assumed to be 13 or 15% when the production temperature is 145 or 165°C respectively.

Considering the lifecycle of an EGS plant, Lacirignola and Blanc (2013), many authors have assumed the lifespan of all geothermal configurations to be 25 years. Geothermal plants are characterized by a very high-capacity factor, with the number of annual operating hours at full capacity considered to be 8000. It was argued that emissions during its operation are practically negligible, compared to its construction and installation. Drilling operations have the largest impact on the EGS lifecycle, due to the combustion of hundreds of thousands of liters of fossil fuel feeding several electric generators (each producing a few hundred kW of power). This energy is required continuously for many weeks to operate the drilling equipment through several kilometers of rock. So, designing a system with two or three wells (doublet or triplet) has important environmental impacts in terms of emission consequences. Fewer wells are favorable from an economic and environmental point of view, but more wells permit higher flexibility regarding reinjection strategy, which relates to induced seismicity. Allocating two (rather than one) boreholes for reinjection allows water to be reinjected at lower pressure, reducing the risk of induced seismicity.

According to ISO 14040, there are four recommended phases in LCA: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and (4) critical step-by step interpretation. It is also necessary to define system boundaries and decide on a functional unit for the LCA, which in the case of Lacirignola and Blanc (2013) was the kWh of the net energy produced by a plant for an operating period of 25 years is the function unit of LCAs.

For the life cycle inventory (LCI) of the ten case studies, Lacirignola and Blanc (2013) examined technical documentation (including technical surveys from Soultz-sous-Forêts), interviewed experts, and derived data on basic processes (raw materials extraction and manufacturing as well as transport and waste treatment) from the ecoinvent 2.2 database (https://www.ecoinvent.org/).The systems analyzed in the ten cases were binary, so some equipment was related to geothermal fluid loops (wells, production, reinjection pumps, etc.) and others connected to the Organic Rankine Cycle (ORC).Geothermal water was produced from one or two wells before being reinjected underground. Drilling boreholes is the most energy demanding process, requiring large quantities of materials, including water and chemicals, to produce the mud; steel and cement for the well casing; and fuel to feed the electric generators that drive the rig. For the use of diesel that fed the electric generators, 4 GJ/m was identified after calculations on several boreholes (all elements involved in creating the well referred to 1 m of drilling, which could also be used in the case of ORCHYD).

Lacirignola and Blanc (2013) also wrote that boosting techniques may be required to boost the production of geothermal fluid. Hydraulic stimulation is produced by injecting water at high pressure. Chemical treatment may involve injecting several types of acids (e.g., hydrochloric acid, regular mud acid [RMA], nitrilotriacetic acid, and organic clay acid have been used in Soultz-sous-Forêts) in the borehole. It was noted that there is a lack of inventory data in ecoinvent for such chemical compounds, so hydrochloric acid was assumed for simplicity. At the end of a plant's life, the wells are plugged using a cementing process, and it is assumed that most of the surface equipment is disposed in landfills. Parts in contact with radioactive deposits are stored in sites appropriate for hazardous materials.

Lacirignola and Blanc (2013) addressed uncertainties of the results with Monte Carlo analysis (5000 simulations). The Monte Carlo method is a stochastic simulation process that employs random numbers and statistics to predict the likelihood of various outcomes, which can aid in addressing the impact of risk and uncertainty in prediction models. The ecoinvent database places high uncertainty boundaries for acidification and eutrophication data, which are expressed by low precision estimates for nitrogen oxides (NO_X) and particulate matter (PM) emissions. It was also considered that a single production well with a flow rate of 40 L/s and a double reinjection at low flow rate, would constitute a very low seismic risk.

Lacirignola and Blanc (2013) argued that the creation of a well is responsible for about 80% of the impact on climate change, human health, and resources; and 60% of the impact on ecosystem quality, is influenced by the construction of surface equipment. Generating electricity by burning diesel has the highest impact on climate change and human health.

Particulates and NO_x emissions are important for human health. As regards ecosystem quality, the most impactful processes are blasting operations when extracting raw materials (especially iron for the production steel) and disposing of drilling wastes (especially in the case of oil wells). Ecosystem quality is also affected by the aluminum, which is dispersed in the air during blasting operations, and in the soil when disposing drilling waste.

Comparing the ten case studies, Lacirignola and Blanc (2013) concluded that emissions of greenhouse gases were in the range of 16.9 to 49.8 gCO2eq/kWh, while the demand for finite energy resources varied from 272 to 785 kJ/kWh, values that were comparable to the literature. Because drilling has the highest impact due to its use of fossil fuels, connecting to the power grid (if possible) would be beneficial. Unfortunately, even if a triplet is recommended in terms of power output and environmental impact, the high cost of drilling is the main barrier.

Adiansyah, Biswas and Haque (2021) presented an LCA for an Indonesian geothermal energy exploration project, excluding production (like ORCHYD). Environmental impacts of geothermal include land disturbance; solid and liquid waste disposal; disturbance of flora and fauna; and depletion of ecological resources. In particular, boron has been reported to contaminate irrigation water and soils, while emissions include hydrogen sulfide and CO_2.Social impacts of geothermal electricity generation are associated with exploration, construction, operation, and post-operation. It was argued that an environmental impact assessment is required to evaluate the potential impact of a geothermal project. An LCA of a geothermal project must particularly include its exploration stage.

Adiansyah, Biswas and Haque (2021) used ReCiPe in SimaPro (given the absence of a local method) with the ecoinvent database (provided by SimaPro). A case study of a geothermal exploration project was considered. The scope of the study included land clearing; access road construction; slim-hole well pad construction; and standard-hole well pad construction. The goal of the LCA was to estimate the carbon footprint of the geothermal exploration project, and the functional unit of the LCA was the carbon footprint generated annually per m^2 of land utilized.

A Life Cycle Inventory (LCI) is a critical step in an LCA, where input and output data for the geothermal exploration lifecycle are collected. Three chemicals were required for the standard-hole construction stage: bentonite (to increase the viscosity of the mud), barium sulphate (to increase mud density), and caustic soda (to maintain the pH and alkalinity of the drilling mud), with a total usage of 380 tons (Adiansyah, Biswas and Haque, 2021). The total solid waste and wastewater generated by the geothermal exploration project were 12.411 t and 1702 m^3 respectively. It was pointed out that the lack of a local database for materials such as bentonite, barium sulphate, and caustic soda detracted from the reliability and accuracy of the analysis.

The carbon footprint of each activity was calculated, and hotspots were identified and discussed. The annual carbon footprint of the geothermal exploration project varied from 0.11 to 29 kg of CO_2eq/m^2. The highest carbon footprint was calculated for the construction of the standard-hole well pad, which took 90 workdays and represented approximately 56% of the total carbon footprint. The two inputs that resulted in the high carbon footprint for the construction of the standard-hole well pad were usage of chemicals (73%) and fuel consumption (27%). The construction of the slim-hole well pad consumed more diesel fuel (374,875 L) than that of the standard-hole well pad (288,469 L), although the latter required more caustic soda (192,000 L), resulting in a higher carbon footprint of chemical compounds. The carbon footprint generated from carbon sequestration loss due to land clearing amounted to 14.97 t of CO_2 per hectare annually, which was equivalent to 1.5 kg of CO_2eq/m^2 annually. The hotspot analysis identified caustic soda contributing 64.5%, diesel consumption 27%, barium sulphate 4.04%, and bentonite 4.04% of the total carbon footprint. It was suggested that diesel and chemicals be utilized effectively by preparing standard operating procedures (SOP). Finally, Adiansyah, Biswas and Haque (2021) estimated the total annual carbon footprint of geothermal exploration at 53.2 kg of CO_2eq/m^2.

Marchand et al. (2015) reported on the LCA of an existing high temperature geothermal system in the French Caribbean islands (Bouillante). They were motivated, among other reasons, by the fact that geothermal energy appears to be a favorable solution for supplying a high proportion of local energy needs. It was mentioned that LCA has been applied to renewable energy (RE), whose environmental performance is highly dependent on their geolocalization (i.e., well depth, water availability, reservoir temperature, geothermal fluid rate, etc.).

Marchand et al. (2015) classified published LCA studies according to the type of: energy produced (electricity vs combined heat and electricity); reservoir (conventional or hydrothermal vs unconventional or Hot Dry Rock [HDR] or Enhanced Geothermal System [EGS]); and conversion technology (single or double flash systems vs organic Rankine cycle using binary fluid).At the time of writing, only two LCA studies provided the environmental impacts of a geothermal plant producing electricity from a deep aquifer (hydrothermal reservoir) and flash systems conversion technology like the one used in the Caribbean site. Unusual characteristics of the Caribbean site were that it used sea water to cool geothermal fluid (by direct contact) and did not reinject geothermal fluid (both due to its old age).

Marchand et al. (2015) initiated the building of a general LCA model for conventional high-temperature geothermal systems with reservoir temperature ranging from 230 to 300°C.The production of electricity was chosen as the considered function of the system with the functional unit set to kWh of net energy produced (i.e., supplied to the electricity network) by the geothermal plant over a period of 30 years. The system boundaries included energy and material flows of the plant (including surface and subsurface equipment of the geothermal fluid loop). The geothermal fluid was extracted from the reservoir with production wells.

Marchand et al. (2015) reported that foreground and background activities were distinguished in the inventory. Foreground activities were directly related to the studied system and had specific data collected from reports and interviews with experts of the operating company. Background activities were those supporting system functions, such as extraction and transformation of materials and fluids, transportation, and related to the end of life of equipment. Background activities were modeled with generic data from version 2.2. of the ecoinvent database (https://www.ecoinvent.org/).

The analyzed site had the following characteristics: was based on a fractured volcanic reservoir containing groundwater at a temperature of 250°C; was at a high permeability area covered by a low permeability area allowing the thermal confinement of the system; was at a depth greater than 500 m; and was fed by marine water and precipitation (meteoric waters) rather than reinjection. The drilling scheme was based on the following diameters: $18^{5/8}$, $13^{3/8}$, $9^{5/8}$, and 7 inches. All data were reported per kWh of geothermal electricity considering the assumed 30-year lifetime of the plant.

The phases of drilling exploration and production wells were considered, with drilling operations dominating. It was pointed out that depending on geology, resource enthalpy, and depth, the drilling of wells may be unsuccessful. An average rate of success of 74% and a constant electric power of 5.4 MW per production well were assumed. The quantities of materials and fuels required for drilling operations, cementation, and casing were compiled from the drilling reports of a well. Deep exploration wells would be drilled beforehand, to confirm the existence of an important geothermal reservoir. The phase of exploratory drilling encompasses site preparation (including road construction) and drilling operations with a drilling rig. Appropriate scaling factors were assumed for cement and steel, to account for the smaller diameters of exploration wells.

Marchand et al. (2015) compiled data on the type of equipment, materials, lifespan, and quantities from reports on plant operation, environmental impacts, equipment technical sheets, delivery orders from manufacturers, as well as interviews with experts from the operating company and the French Geological Survey. Atmospheric emissions mainly included CO_2, H_2S and CH_4.Occasional purges of brine were discharged to the ground, while seawater and geothermal fluid effluents were discharged to the sea. Recycling and landfilling percentages for copper and steel were extrapolated from a UNEP report. All other materials (including plastic, concrete, and fiberglass) were assumed to be entirely landfilled.

Marchand et al. (2015) mentioned that, during the operation of a plant, supplementary wells are drilled to replace any old wells with display decreasing productivity during the lifetime of the plant. It was assumed that productivity decreased by 38% after 30 years of operation. Data on the closure of wells was approximated with data related to the closure of a 6 km deep borehole for geothermal power generation in an unspecified rock formation (from version 3 of the ecoinvent database).

Marchand et al. (2015) pointed out that geothermal reinjection involved returning the water that was extracted from the reservoir back into the geothermal system. The ratio of the production well over reinjection was assumed to be 1 to 1, with the success rate for both production and reinjection wells was assumed to be 74%. It was also assumed that no supplementary wells were necessary during the operation of the plant, because of the additional recharge provided by the fluid reinjection.

The synthesis of inputs and outputs was done so that it was relative to the production of 1 kWh of geothermal electricity. The lifecycle phases of drilling of exploration and production wells; construction and installation; operation; and decommissioning were accounted for. The temperature of the reservoir ranged from 250 to 300°C. The drilling length depends on (a) the depth of the geothermal reservoir, and (b) the depth which is necessary to drill within the geothermal reservoir to exploit the resource at the expected flow rate. The depth of the reservoir is estimated correctly (in general), although the total length of drilling is likely to vary. The quantities of used materials are related to drilling depend on the number of exploration, production, and reinjection wells. The number of production wells is related to the well potential electric power to the net power of the geothermal power plant, and the success rate related to the realization of drilling. For the number of reinjection wells, a ratio of 1:1 was assumed between reinjection and production wells. For the scenario without fluid reinjection in the geothermal reservoir, the cooling system was based on the use of seawater, and supplementary wells would offset the decreasing productivity (that was caused by the absence of reinjection). For the scenario with fluid reinjection in the geothermal reservoir, reinjection wells would be drilled with a ratio 1:1 to production wells.

The main input variables were the choice of reinjection or not; the drilling of supplementary wells; the lifetime of the geothermal installation; and the number of reinjection wells. The electricity production of a geothermal plant was considered to account for its lifetime and its load factor. The end of life dismantling of the examined geothermal plant entailed different recycling percentages for steel and copper, and no recycling for plastics.

The examined impact categories included GHG emissions; ecological scarcity and water consumption; terrestrial, freshwater, and marine eutrophication; acidification; abiotic depletion; ecotoxicity; human toxicity (including cancer and no cancer); renewable and non-renewable energy; transformation of natural land; and agricultural and urban occupation. It was found that the environmental impacts varied from 38.5 to 47 gCO_2eq/kWh depending on the scenario (Marchand et al., 2015).

The scenario with no reinjection was found to contribute more to climate change; acidification; and terrestrial and marine eutrophication. The scenarios with reinjection contributed more to agricultural and urban occupation; and transformation of natural land. The identification of key processes showed that drilling contributed more to the transformation of natural land, while the construction and operation phases contributed more to water consumption; fresh water eutrophication; ecotoxicity; abiotic depletion; energy demand; agricultural and urban occupation; and human toxicity. All of these impacts were related to background processes such as steel production. The operation phase contributed more to climate change with direct releases of CO_2 and CH_4; H_2S emissions and acidification; and NH_{4+} emissions and marine and terrestrial eutrophication.

Marchand et al. (2015) identified the following discriminating parameters: quantify of steel used; quantity of (non-condensable) gases emitted; quantity of effluents (geothermal fluid and seawater) released to the sea; and the total number of wells drilled for exploration, production, and reinjection. All in all, the power plant construction and installation phase had the greatest impact. Most environmental impacts were related to background activities, particularly to steel manufacturing. Foreground activities contributed to climate change; acidification; and marine and terrestrial eutrophication. To mitigate the emission of (non-condensable) gases (CO_2, CH_4, and H_2S) it was proposed that a gaseous treatment system was considered.

Literature values for lifecycle GHS emissions ranged from 22 to 80 gCO_2eq/kWh for EGS plants; 5 to 100 gCO_2eq/kWh for flash technology plants; and a few grams of CO_2eq/kWh for binary technology plants. To put the results of the study in perspective, Marchand et al. (2015) reported that IPCC median values for different energy pathways equaled 45 gCO_2eq/kWh for geothermal; 46 gCO_2eq/kWh for photovoltaics; 12 gCO_2eq/kWh for wind; 16 gCO_2eq/kWh for nuclear; 470 gCO_2eq/kWh for natural gas; 840 gCO_2eq/kWh for oil; and over 1000 gCO_2eq/kWh for coal. These are shown in Figure 4.10.

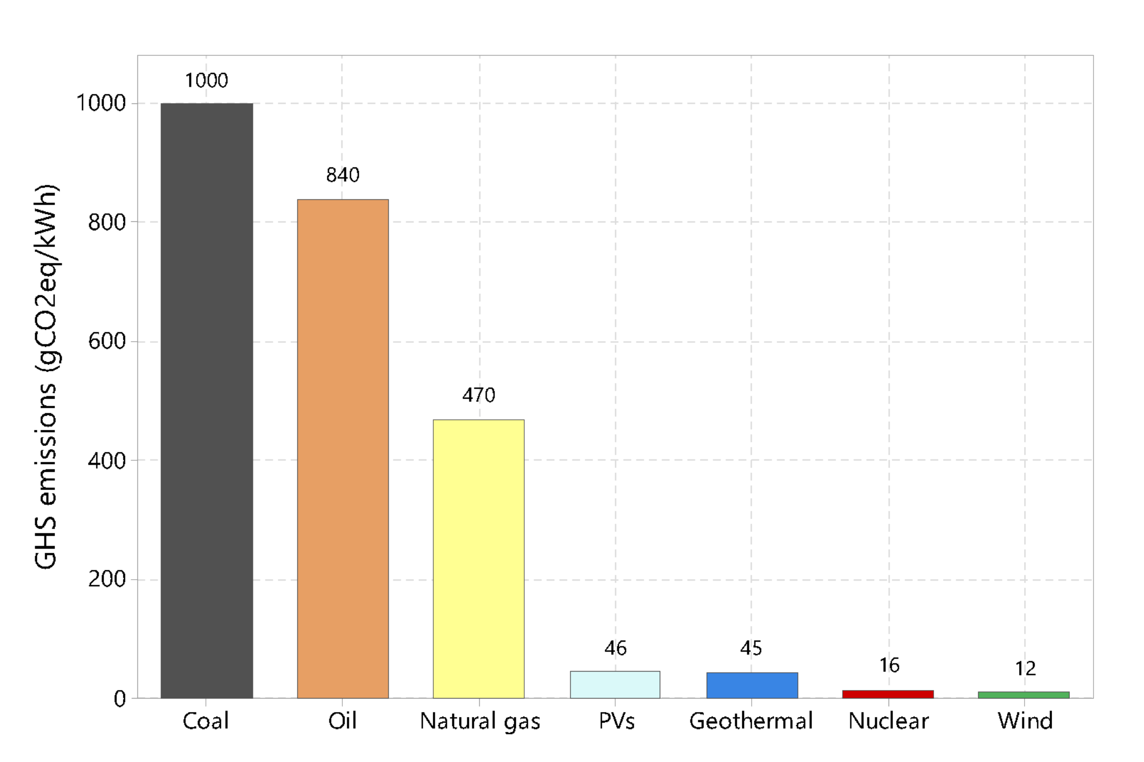


Figure 4.10. GHG emissions of energy pathways

Marchand et al. (2015) argued that modeling and scaling are very sensitive to local conditions, such as in situ characterization of the geothermal field.

As a final reference of an interesting study, Petersen et al. (2013) presented an LCA for offshore oil and gas (not geothermal) drilling. They found that rig energy controls was responsible for about half of GHG and almost all particulate matter emissions.

4.3.3. Simplified LCA approaches

Lacirignola et al. (2014) presented a simplified LCA model for the analysis of GHS emissions of enhanced geothermal system (EGS) plants.

Those authors noted that although the operation of most RE-based systems do not have direct emissions related to the combustion of fossil fuels, industrial processes related to the manufacturing and installation of equipment may have significant impacts to the environment. In particular, the construction of geothermal wells is the most influential process on environmental performance, requiring large quantities of energy and materials and emitting large quantities of GHGs.

The realization of the wells and surface facilities is an important determinant of the environmental performance of an EGS, and there is a need to consider all the lifecycle stages of a geothermal plant. Such a cradle-to-grave perspective is provided by LCA, which takes into account all lifecycle stages including extraction of raw materials; manufacturing; distribution; use; and disposal, as described in the (ISO 14040 series). Many published LCA studies compare the GHG emissions among RE technologies and conventional power plants (based on fossil fuels). For geothermal systems, 6 to 79 gCO_2eq/kWh have been reported.

To avoid the need of undertaking complete LCAs of alternative plant setups and manage to consider a panel of technical concepts in a defined geographical region, the authors present a simpler and easier tool (than a full LCA) for the estimation of GHG emissions. Those authors mention the meta-LCA methodology, which has attempted to overcome the undertaking of single detailed LCAs and has been used in the energy field. In some cases, meta-models have estimated the environmental impacts using simple linear regression.

The work of Lacirignola et al. (2014) was based on Padey at al. (2013), who presented a new framework for simplified models to estimate the GHG emissions of wind electricity. Their method relied on the identification of a restricted number of key parameters that are responsible for most of the variability of environmental performance. In this sense, it was an intermediate solution between detailed LCA and meta-LCA. Moving in the same direction, Lacirignola et al. (2014) defined two parameterized models (a reference model and a simplified model) applying the method of Padey et al. (2013) to the EGS pathway.

The study of Lacirignola et al. (2014) focused on EGS plants located in central Europe. EGS plants are binary systems, thus do not generate GHG emissions directly (unlike hydrothermal flash and dry steam plants). Their GHG emissions are only caused by processes related to their infrastructure, e.g., transport of new equipment, disposal of filter residues). The considered systems had two or three wells of depth 2 to 6 km, with an Organic Rankine Cycle (ORC) at the surface.

The authors observed that EGS project developers have been focusing on depths of about 3 km because one of the lessons learned from the pilot plant in Soultz-sous-Forêts was that drilling up to 5 km was not economically viable (at the time of writing). It was also observed that drilling to 6 km may become more economically viable in the near future, thanks to developments in exploration and drilling techniques (which is what ORCHYD hopes to achieve).

The work of Lacirignola et al. (2014) was mainly based on technical data from the Soultz-sous-Forêts site, and also assessed environmentally 10 alternative plant setups with two or three wells, and a final power output ranging from 0.8 to 3.1 MW. Like many LCA reports, those authors mentioned that the characterization factors used to calculate GHG emissions were based on IPCC reports without providing any details beyond the obvious statement that these characterization factors were used to convert quantitatively each GHG according to its respective Global Warming Potential related to CO_2 (which is the reference gas).

The sample of possible EGS plants was generated based on nine mathematically independent parameters shown in Table 4.3.

Table 4.3. Parameters of EGS plants (Lacirignola et al., 2014)

N°	*Parameter*	*Value*	*Units*	*Comments*
1	Number of wells	2 to 3		Limited because of high construction costs and the risk of induced seismicity (affected by the circulation strategy, i.e., number of wells used for reinjection); objective is to minimize the risk of induced seismicity in case of high produced flow rate
2	Drilling/borehole depth	2 to 6	km	Based on the literature and current projects; depending on the geology and techno-economic factors (considering the high costs of constructing a well)
3	Fuel consumption for drilling	3000 to 7000	$\frac{MJ}{m}$	Critical factor for the environmental performance of a plant, large variability (based on data from Soultz-sous-Forêts and the literature), intended to account for the fact that the construction of a well is the most impacting process in the lifetime of an EGS (due to the large quantity of fuel burned by electricity generators during drilling)
4	Power capacity of ORC	1250 to 3500	kW	Depends on flow rate, fluid temperature, thermal efficiency, heat capacity (which are all interrelated and depend on borehole depth and geological conditions) (Lowest value cited as equal to 1250 or 1300 at different points in the paper)
5	Produced flow rate	25 to 100	$\frac{kg}{s}$	Reasonable range of values; characteristics of geothermal resources are extremely site dependent
6	Scaling factor enhancement	0.5 to 10		Stimulation of the reservoir is site-dependent and critical for the success of an EGS project
7	Specific power of pumps	3.6 to 8.6	$\frac{kW}{\left(\frac{kg}{s}\right)}$	The power demand of the pumps of the geothermal loop is assumed to increase linearly with the flow rate
8	Load factor	0.85 to 0.95		Corresponding to 7446 to 8322 equivalent full load hours annually, since geothermal plants have load factors frequently over 90%
9	Lifetime	20 to 40	years	30 years assumed to be mean value

The Life Cycle Inventory (LCI) of the wells included information on the drilling process (e.g., fuel consumption, mud circulation), casing, and segmentation. The authors remarked that (at the time of writing) very few LCI of EGS power plants were available in the literature. Each well was equipped with either a production or reinjection pump. The well enhancement process included data on the quantity of water; salt; and hydrochloric acid for the hydraulic and chemical stimulation, intended to improve the productivity of the borehole.

The objective of the simplified LCA approach was to estimate the life cycle GHG emissions of EGS power plants. The functional unit was the net energy produced over the life cycle of the plant, which meant that the results of the LCA approach would be expressed in grams of CO_2 equivalent per electrical kWh delivered to the grid (gCO_2eq/kWh), as in other studies. Lacirignola et al. (2014) developed two models, a reference one and a simplified one. The following parameters were identified that explained most of the variability of GHG results that was caused by alternative configurations: installed power capacity; drilling depth; and number of wells. Only these three parameters were included in their simplified model.

The reference model provided the estimation of GHG emissions for EGS plants with the following equation:

$$GHG_{ref} = \frac{z \times N_w \times (a_1 + a_2 \times d) + LT \times f \times a_3 + P_{ORC} \times LT \times a_4 + Nw \times SF_e \times a_5}{LT \times LF \times \left(P_{ORC} - f \times P_p\right) \times 8{,}760}$$

where a_1 to a_5 are constants having the following values:

$a_1 = 567{,}014.8 \frac{gCO_2eq}{m}$, which was related to drilling processes (casing, cementation, mud circulation) except diesel consumption

$a_2 = 86.49 \frac{gCO_2eq}{MJ}$, which was related to diesel consumption

$$a_3 = 411{,}384 \frac{gCO_2eq \times s}{kg \times year}$$

$$a_4 = 43.139 \frac{gCO_2eq}{kW \times year}$$

$$a_5 = 65{,}017{,}978.7 gCO_2eq$$

and the other symbols are as follows (with units indicated in parentheses):

d: amount of fuel per drilling depth (MJ/m)

f: total produced flow rate (kg/s)

LF: load factor

LT: lifetime (years)

N_w: number of wells, considered a key parameter in the simplified model (see below)

P_{ORC}: ORC power output (kW), considered a key parameter in the simplified model (see below)

P_p: specific power of pumps $\left(\frac{kW}{\left(\frac{kg}{s}\right)}\right)$

SF_e: enhancement factor

z: borehole depth (m), considered a key parameter in the simplified model (see below).

Of the above parameters, the simplified model included only those three that were considered key, and provided the estimation of GHG emissions for EGS plants with the following equation:

$$GHG_{simple} = \frac{N_w \times (b_1 \times z + b_2) + b_3 \times P_{ORC} + b_4}{P_{ORC} - b_5}$$

where b_1 to b_5 are constant having the following values:

$$b_1 = 4.266 \frac{gCO_2eq}{m \times h}$$

$$b_2 = 467.3 \frac{gCO_2eq}{h}$$

$$b_3 = 5.472 \frac{gCO_2eq}{kWh}$$

$$b_4 = 3{,}261.2 \frac{gCO_2eq}{h}$$

$$b_5 = 381.2kW$$

and the other symbols are as in the previous equation.

As for the verification of the reference model, 50,000 random EGS scenarios were generated through Monte Carlo simulations and it was calculated that their GHG emissions varied from a minimum of around 17 to around 68 gCO_2eq/kWh, with a median value around 30 gCO_2eq/kWh (only boxplots were presented in the paper). Lacirignola et al. (2014) reported that these values compared well with IPCC and literature values. The IPCC LCA values, which were compiled from the literature for geothermal plants of all types, varied from a minimum of 6 to a maximum of 79 gCO_2eq/kWh; a first quartile at 20 and a third quartile at 57 gCO_2eq/kWh; and a median value at 45 gCO_2eq/kWh (values were approximated from boxplots; no other information was given in the paper).

The identification of key parameters (i.e., those responsible for most of the variability in the GHG performance of alternative EGS configurations) showed that the installed capacity (P_{ORC}) was responsible for almost half of the variability. The drilling depth (z) followed by the number of wells (N_w) were also highly relevant. This is why those three parameters were chosen for the simplified model, as together they were responsible for about 75% of the variability of GHG emissions in the simulations.

The analysis of 50,000 Monte Carlo simulations showed that, when the results of the reference model were regressed against the results of the simple model, they were close, with a coefficient of determination (R^2) equal to 0.7 and a root mean square error of 8.17 gCO_2eq/kWh. The authors concluded that, using the reference model with the equation containing nine parameters, was likely to give more accurate results, replicate the literature more closely.

4.3.4. LCA software

A prerequisite to emission estimation techniques is the understanding of emission factors themselves. Emission factors are values that link an activity related to drilling operations and a pollutant released in the atmosphere. *"These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant"*, as explained by Stuver & Alonzo (2014).

In geothermal LCAs, the most common emission factor is kg (CO_2eq)/kWh. However, due to the fact that ORCHYD is focused on drilling and not production operations, alternative expressions of kg (CO2eq) per kg of a reference material or meter of drilled borehole will be considered for the development of LCAs for various scenarios. *"In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in a particular source category"*, as noted by Stuver and Alonzo (2014).

Several LCA software packages and life cycle inventory (LCI) databases have been developed by the industry. OpenLCA, SimaPro, GaBi and Ecoinvent are such examples, and may be used for carrying out LCA in the context of WP3 of ORCHYD.

OpenLCA (https://www.openlca.org/) is a software application which was built and designed as a *"fast, reliable, high-performance, modular framework for sustainability assessment & life cycle modelling, that allows visually attractive and flexible modelling, for sophisticated and simple models, in a standard programming language, using only widely available Open Source software"*(OpenLCA, 2021).

SimaPro (https://simapro.com/) is a commercial alternative for LCA. It is a tool designed for monitoring and analyzing data related to the sustainability performance of any kind of products or services. As mentioned by SimaPro (2021), *“the software can be used for a variety of applications, such as sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators”*.

GaBi (https://gabi.sphera.com/america/index/) is another commercial piece of software used for LCA in any kind of products or services. Different issues related to sustainability can be addressed through its use. Sustainable product portfolios resulting in increased revenues can be built through it. Efficient use of resources and identification of supply-chain hotspots, including materials and processes, can be enhanced through the use of GaBi in risk mitigation studies. Finally, GaBi can provide life cycle costing and reporting services (GaBi, n.d.).

The ecoinvent database *“is a not-for-profit association dedicated to promoting and supporting the availability of environmental data worldwide”*, as mentioned by Ecoinvent (n.d.). The ecoinvent database provides LCIs through well documented products for LCAs of any kind of projects and thousands of products. Areas of interest such as energy, agriculture, transport, biofuels, biomaterials, bulk and specialty chemicals, construction materials, wood and waste treatment are covered by 18,000 distinct LCI datasets.

4.4. Other methods

The following methods may be also employed on a need basis:

1. Carbon Footprint (CF) ~ equivalent greenhouse gas emissions.
2. Ecological Footprint Analysis (EFA) ~ resource consumption and waste generation = ecological assets (bioproductive land and sea requirements).
3. Risk Analysis (RA) ~ risk acceptability (criteria), (semi) quantitative and qualitative techniques, interfacing with energy experts (Task 3.5 of WP3).

4.5. Life Cycle Analysis (LCA)

4.5.1. Setup of the LCA

Carbon footprint during the drilling operations of the proposed technology by ORCHYD is the main focus of this LCA.

This section aims to provide a comparison between conventional techniques and the novel drilling technique ORCHYD develops. Accurate predictions about the carbon emissions are subjected to site specific conditions, material choice, and drilling depth. A precise evaluation can only be made in situ conditions knowing the final consumption of diesel and materials required in specific drilling sites. At this stage, LCA has a preliminary and approximate character based on the evaluation of expected results.

Apart from carbon emissions, which will be expressed in terms of CO_2 equivalent, the present LCA will also cover additionally categories such as ozone depletion; smog; acidification; eutrophication; and fossil fuel depletion (irrespective of whether these impact categories were rated as important in the scoping survey).

- The ozone depletion potential will be calculated in terms of chlorofluorocarbons (CFCs), which are ozone depleting substances that can lead to increased quantity of harmful ultraviolet (UV) radiation for humans as well as terrestrial and aquatic ecosystems.
- Smog, which is a reaction of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) associated with air quality degradation and human health risks, will be expressed in ozone (O_3) equivalent.
- The acidification potential will be expressed in terms of sulfur dioxide (SO_2) equivalent, which can cause damages to the groundwater, the soil, and surface water.

- Eutrophication potential will be expressed in terms of nitrogen (N), and will measure the possibility of dense plant growth, which can threaten animal life in aquatic environments due dissolved oxygen depletion.
- Last but not least, fossil fuel depletion will be measured in terms of energy (MJ) surplus *“which is defined as the total additional future cost to the global society due to the production of one unit of resource”*, as Thomas, Tinjum and Holcomb (2020) explained.

The scenarios developed for this study examine the drilling of a single geothermal well. In the case of doublet or triplet configurations, the results may be doubled or tripled accordingly.

A target depth is 5100 m and full casing throughout the length of the well is assumed. It is based on the well documented GPK-3 geothermal well at Soultz-sous-Forêts, France.

The speed of the drill bit decreases in denser formations. Vidal, Genter and Schmittbuhl (2015) wrote that *“at Soultz, the mean speed is 8 m/h in soft sediments (above 1-km depth), 5 m/h in hard sediments (below 1-km depth) and just 2 m/h in the granite. When the ROP is higher than the mean value, the occurrence is generally interpreted as the effect of a localized fracture zone”.*

A sedimentary rock zone down to 1 km; an intersection zone of 420 m with hard sediments; and a 3680 m zone of granite formation are encountered in GPK-3 (Hooijkaas, Genter & Dezayes, 2006). Given that ORCHYD aims to increase ROP in hard rock formations, the developed scenarios will account for alterations of ROP for the deeper part of the well, which ranges from 1420 to 5100 m.

This section develops seven scenarios with average total ROPs, ROPs in the hard rock zone, and drilling operation lengths for each scenario as shown the following tables.

Table 4.4. Values of LCA characteristics common among scenarios (h: hours, d: days)

Characteristic	*Value*
Total depth (m)	5100
Sedimentary zone length (m)	1000
Sedimentary zone average ROP (m/h)	8
Intermediate zone length (m)	420
Intermediate zone average ROP (m/h)	5
Crystalline zone length (m)	3680

Table 4.5. Values of LCA characteristics for different scenarios (h: hours, d: days)

	Scenarios							
Characteristic	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Crystalline zone average ROP (m/h)	2	4	5	6	7	8	9	10
Average ROP (m/h)	3.42	4.87	5.59	6.31	7.03	7.75	8.47	9.20
Duration of operation (d)	85.38	47.04	39.38	34.26	30.61	27.88	25.74	24.04

This section is based on values found in the literature both for the expression of emission factors as well as material quantities. The Life Cycle Inventory utilized is illustrated in Table 4.6, which includes emission factors presented by Thomas, Tinjum and Holcomb (2020). For the calculation of emissions, a spreadsheet by Tinjum, Thomas and Holcomb (2020) was used as a basis (exact calculations and data are available in an Excel archive).

The usage of diesel for the production of materials; transport of materials and equipment; and usage of equipment during the various construction phases of the well, was conducted. Materials used for the submersible pump, chiller, and surface components were also accounted for. Finally, trenching was also considered. For the sake of analysis, it was assumed that operations run on a 24/7 basis and no accidents were encountered.

Calculations on the size and diameter of the wellbore for concrete and steel use as well as water and diesel consumption, yielded typical values for these materials in all scenarios. More specifically, it was estimated that a total of 357,550.13 kg of steel; 226.29 m^3 of concrete (approximately equal to 543 tons, but intentionally computed as volume); and 29,030.78 kg of water will be used (according to calculations based on the well design). An extra analysis is following concerning the usage of drilling bits made of steel, which slightly alters the steel consumption between scenario 1 and the rest of scenarios. On the other hand, the use of diesel appears to be inversely proportional to the ROP, and its total consumption varies for the developed scenarios. The reference value for diesel consumption was 157.7 L/h (or 49 gallons per hour), as McKay, Feliks and Roberts (2019) suggested.

Other material categories were also examined and presented in the respective parts of the table for each scenario.

Table 4.6. Life Cycle Inventory (process and units data as presented in Thomas, Tinjum & Holcomb, 2020)

Lifecycle Stage, Components & Processes		*Impact Categories*					
Material Production		Impact Inventory					
Production Well (PW)	SimaPro Process and Unit	Total kg CFC eq	Total kg CO_2 eq	Total kg O_3 eq	Total kg SO_2 eq	Total kg N eq	Total MJ surplus
Casing 1 (surface)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Casing 2 (int,)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Casing 3 (long string)	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
Concrete 1 (surface)	1 m³ Concrete, normal {RoW}| market for | Alloc Def, U	1.85E-05	2.24E+02	1.38E+01	7.22E-01	2.68E-01	1.69E+02
Concrete 2 (int,)	1 m³ Concrete, normal {RoW}| market for | Alloc Def, U	1.85E-05	2.24E+02	1.38E+01	7.22E-01	2.68E-01	1.69E+02
Concrete 3 (long string)	1 m³ Concrete, normal {RoW}| market for | Alloc Def, U	1.85E-05	2.24E+02	1.38E+01	7.22E-01	2.68E-01	1.69E+02
Production packer insulation	Polymer foaming {RoW}| processing | Alloc Def, U	4.73E-08	9.51E-01	6.90E-02	5.43E-03	3.27E-03	5.01E-01
Drilling (prod. of fuel)	1 kg Diesel, low-sulfur {RoW}| production	9.20E-07	5.76E-01	4.60E-02	5.53E-03	1.83E-03	8.15E+00
Drilling (water)	1 kg Tap water {RoW}| tap water production, underground water without treatment	1.96E-11	3.07E-04	1.58E-05	1.55E-06	1.28E-06	2.04E-04

Lifecycle Stage, Components & Processes		*Impact Categories*					
Submersible Pump	SimaPro Process and Unit	Total kg CFC eq	Total kg CO_2 eq	Total kg O_3 eq	Total kg SO_2 eq	Total kg N eq	Total MJ surplus
Copper wire	1 kg Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	1.11E-07	7.89E-01	3.89E-02	3.60E-03	2.41E-04	7.48E-01
Steel	1 kg Steel, low-alloyed {GLO}| market for	1.12E-07	1.64E+00	1.02E-01	8.08E-03	1.23E-02	1.04E+00
Lead	1 kg Lead {GLO}| market for | Alloc Def, U	1.27E-07	1.36E+00	1.38E-01	1.90E-02	1.30E-02	1.40E+00
Lubricant oil	1 kg Lubricating oil {RER}| production | Alloc Def, U	1.26E-06	1.00E+00	6.98E-02	8.27E-03	4.09E-03	1.11E+01
Chiller	SimaPro Process and Unit	Total kg CFC eq	Total kg CO_2 eq	Total kg O_3 eq	Total kg SO_2 eq	Total kg N eq	Total MJ surplus
Refrigerant	1 kg Refrigerant R134a {RoW}| production | Alloc Def, U	1.04E-02	1.03E+02	7.87E-01	8.98E-02	2.44E-02	1.53E+01
Steel	1 kg Steel, low-alloyed {GLO}| market for	1.12E-07	1.64E+00	1.02E-01	8.08E-03	1.23E-02	1.04E+00
Copper	1 kg Copper wire, technology mix, consumption mix, at plant, cross section 1 mm² EU-15 S	1.11E-07	7.89E-01	3.89E-02	3.60E-03	2.41E-04	7.48E-01
Surface Components	SimaPro Process and Unit	Total kg CFC eq	Total kg CO_2 eq	Total kg O_3 eq	Total kg SO_2 eq	Total kg N eq	Total MJ surplus
Heat Exchanger	1 kg Steel, unalloyed {RoW}| steel production, converter, unalloyed | Alloc Def, U	9.76E-08	1.82E+00	8.99E-02	7.36E-03	6.23E-03	7.45E-01
HDPE	1 kg HDPE pipes E	0.00E+00	2.48E+00	1.12E-01	9.46E-03	2.16E-04	1.11E+01
Transportation of Materials	SimaPro Process and Unit	Total kg CFC eq	Total kg CO_2 eq	Total kg O_3 eq	Total kg SO_2 eq	Total kg N eq	Total MJ surplus
Transport of concrete	1 tkm Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	2.30E-08	9.13E-02	7.14E-03	3.43E-04	9.74E-05	2.04E-01

Lifecycle Stage, Components & Processes		*Impact Categories*					
Transport of steel	1 tkm Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	2.30E-08	9.13E-02	7.14E-03	3.43E-04	9.74E-05	2.04E-01
Transport of construction equipment	1 tkm Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Alloc Def, U	2.30E-08	9.13E-02	7.14E-03	3.43E-04	9.74E-05	2.04E-01
Construction of Wells	SimaPro Process and Unit	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Drilling PW (comb. of fuel)	1 m Deep well, drilled, for geothermal power {RoW}| deep well drilling, for deep geothermal power | Alloc Def, U	2.51E-04	3.92E+03	2.04E+02	1.89E+01	1.67E+01	2.67E+03
Pumping cement PW (comb. of fuel)	1 hr Machine operation, diesel, < 18,64 kW, generators {GLO}| machine operation, diesel, < 18.64 kW, generators | Alloc Def, U	1.06E-06	4.37E+00	7.25E-01	2.57E-02	4.13E-03	9.35E+00
Pumping water PW (comb. of fuel)	1 hr Machine operation, diesel, < 18,64 kW, generators {GLO}| machine operation, diesel, < 18.64 kW, generators | Alloc Def, U	1.06E-06	4.37E+00	7.25E-01	2.57E-02	4.13E-03	9.35E+00
Trenching	SimaPro Process and Unit	Total kg CFC eq	Total kg CO_2 eq	Total kg O_3 eq	Total kg SO_2 eq	Total kg N eq	Total MJ surplus
Excavating (comb. of fuel)	1 hr Excavator, technology mix, 100 kW, Construction GLO	4.39E-12	2.00E-03	2.00E-04	9.49E-06	5.40E-07	4.02E-03

It is important to note that special calculations are required for the cement and concrete use, as they are highly dependent on the borehole diameter and drilling depth.

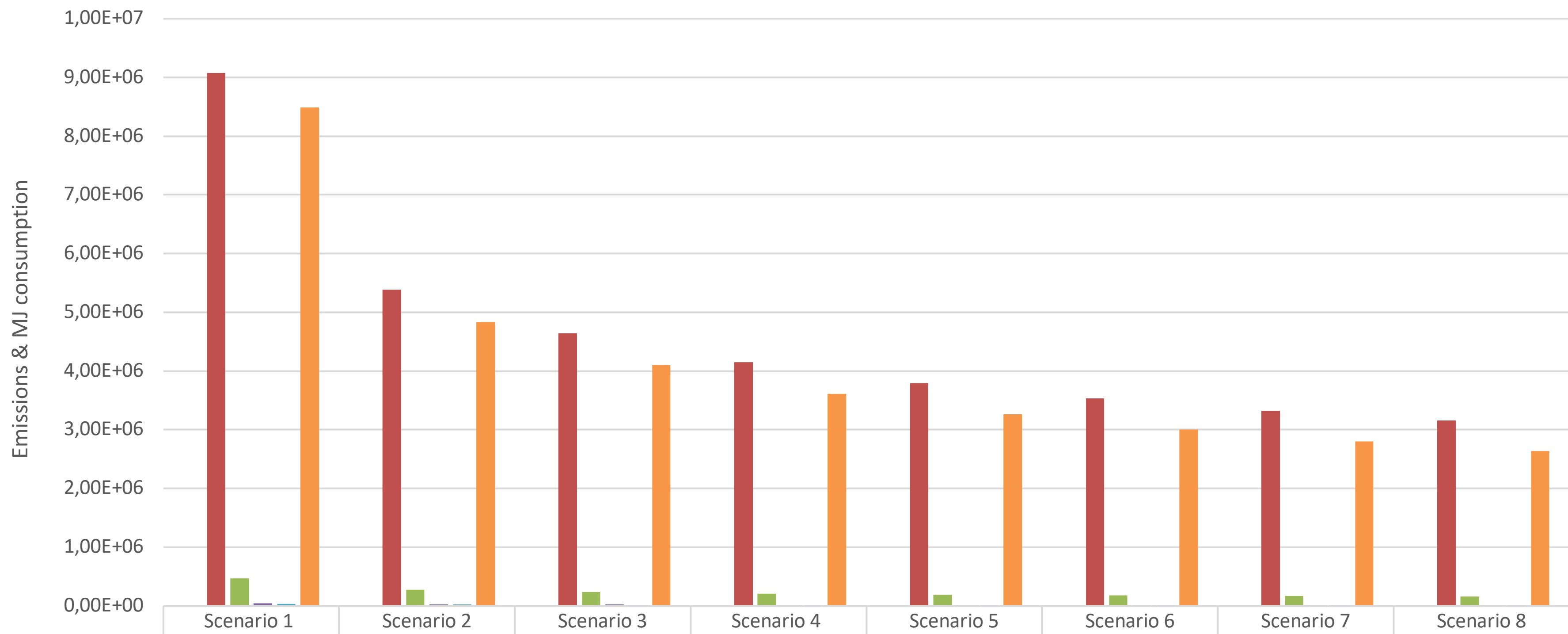
As Kinsang (2013) noted: *“Drilling geothermal wells is carried out in a series of stages with each stage being of smaller diameter than the previous stage, and each being secured by steel casings, which are cemented in place before drilling the subsequent stage”*. The drilling depth is 5100 m and it is divided in four sections, two in sedimentary rock and two in fractured granite formation.

1. The first section from the surface to 574 m was drilled at a 24-inch diameter.
2. The second section between 574 m and 1447 m was drilled at a 17½ inch diameter.
3. The third section between 1447 m and 4580 m was reopened (initially drilled in an 8½ inch diameter) at a 12¼ inch diameter.
4. The final section was drilled at an 8 ½ inch diameter down to 5100 m.

As mentioned in Deliverable 2.1 of ORCHYD (Project Specifications, p. 32), directional drilling was done between 2681 and 3180 m, using a downhole mud motor. A total of 33 tricone bits were used, working an average of 40 hours each. *“It is important to increase drill bit longevity and reduce the drill bit consumption for all drilling projects and, especially, for deep EGS drillings as a step to reduce the total cost. The time to replace a drill bit around, e.g., 3 km depth can take around 18 h and the daily drilling cost can be 30,000 Euros or higher. It is therefore valuable to use experience from other drilling operations in similar geological settings, which in this case is the crystalline basement, when designing the drilling program and selecting the best suited drill bits”*, as Rosberg and Erlstrom (2021) point. In the developed scenarios, an improvement on drill bit consumption based on estimates was considered, as well as the materials used for their production. Based on the aforementioned, it is considered that a conductor casing is used for the first 20 m and a surface casing is used down to 574 m. Intermediate casing is used for the section between 574 m to 1447 m, production casing is used for the section between 1447 m to 5080 m and a slotted liner is used between 5080 m to 5100 m.

4.5.2. Analysis of scenarios

The baseline scenario considers an average ROP of 3.4 m/h, which progressively leads to an average ROP of 9.2 m/h in scenario 8. The total impacts of all scenarios are illustrated in Figure 4.11. The total effects of ROP enhancements on emissions and energy consumption are extensively illustrated in Figures 4.4 to 4.8. The results underscore the favorable environmental impacts of higher ROP and highlight the importance of ORCHYD in the path towards sustainable geothermal drilling.



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8
Total kg CFC eq	1,32E+01	1,29E+01	1,28E+01	1,28E+01	1,27E+01	1,27E+01	1,27E+01	1,27E+01
Total kg CO2 eq	9,08E+06	5,38E+06	4,64E+06	4,15E+06	3,80E+06	3,53E+06	3,33E+06	3,16E+06
Total kg O3 eq	4,73E+05	2,78E+05	2,39E+05	2,13E+05	1,94E+05	1,80E+05	1,69E+05	1,60E+05
Total kg SO2 eq	4,36E+04	2,54E+04	2,17E+04	1,93E+04	1,76E+04	1,63E+04	1,53E+04	1,45E+04
Total kg N eq	3,74E+04	2,17E+04	1,86E+04	1,65E+04	1,50E+04	1,39E+04	1,30E+04	1,23E+04
Total MJ surplus	8,49E+06	4,83E+06	4,10E+06	3,61E+06	3,26E+06	3,00E+06	2,80E+06	2,64E+06

Axis Title

Total kg CFC eq, Total kg CO2 eq, Total kg O3 eq, Total kg SO2 eq, Total kg N eq, Total MJ surplus

Figure 4.11. Total impacts of all scenarios for the six examined categories

The ozone depletion category appears to be the least impacted by the implementation of the ORCHYD drilling technique. In any case, ozone depletion potential is low for deep geothermal drilling. However, small positive changes in the carbon equivalent of ozone are achieved, as illustrated in Figure 4.12.

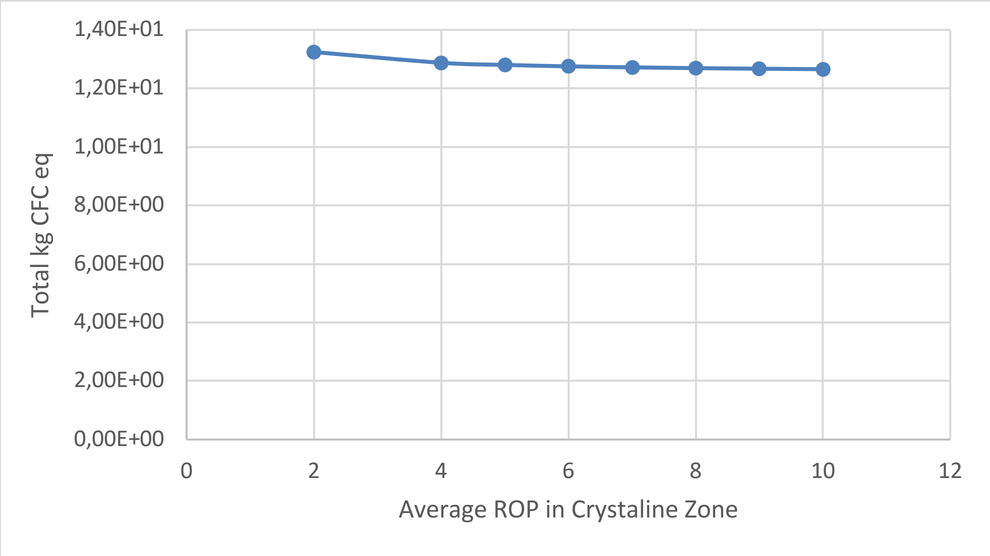


Figure 4.12. ROP effect on ozone depletion emissions

The impact of ORCHYD on the effectiveness of carbon neutral energy strategies is likely to be significant. As illustrated in Figure 4.13, enhancement of ROP rates is estimated lead to reduction of CO_2 equivalent by more than half the amount of emissions produced by conventional drilling techniques. Reduction of the carbon footprint of geothermal will be significant even if only the minimum targeted enhancement of ROP by ORCHYD is achieved.

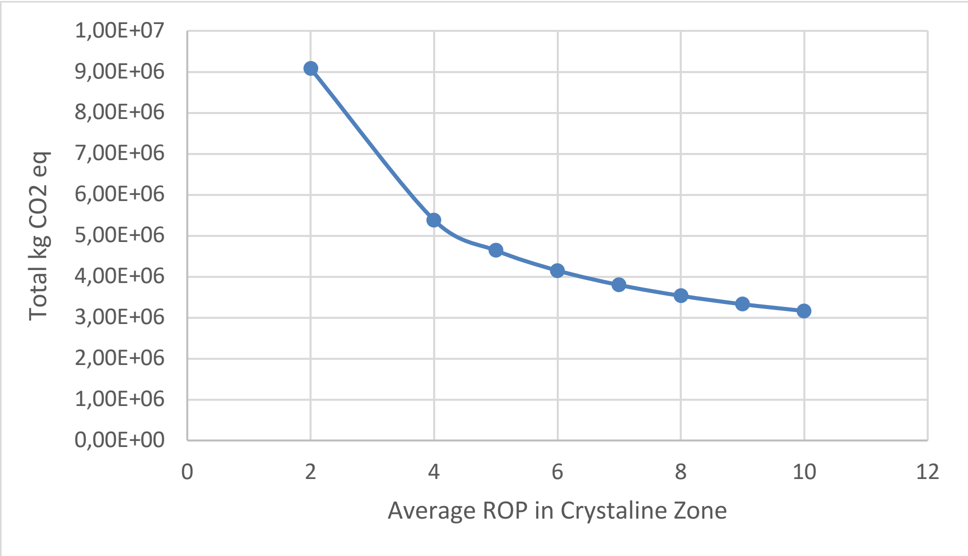


Figure 4.13. ROP effect on carbon footprint emissions

Smog is also significantly reduced by the improvements achieved by ORCHYD. As illustrated in Figure 4.14, enhancement of ROP leads to a reduction of the carbon equivalent of ozone (O_3). This is attributed mainly to the reduction of volatile organic compounds (VOCs), as diesel consumption is reduced.

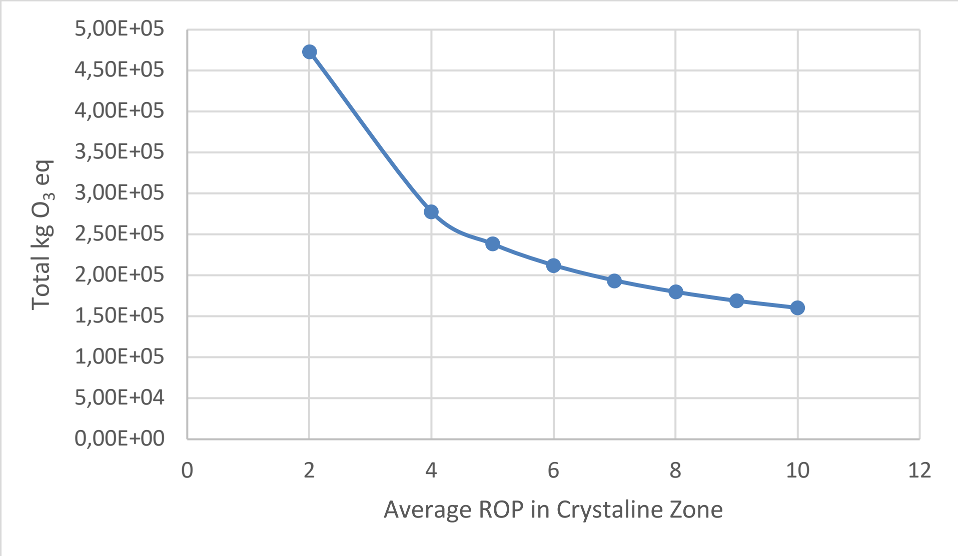


Figure 4.14. ROP effect on smog related emissions

Acidification carbon potential is drastically reduced, as illustrated in Figure 4.15. Potential damages to groundwater, soil, and surface water are also reduced linearly with the reduction of sulfur emissions (SO_2).

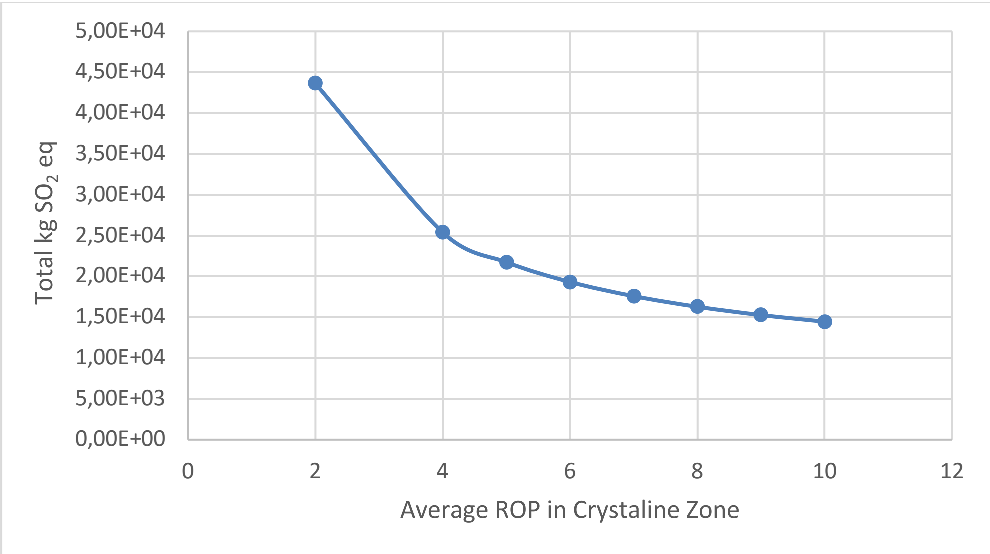


Figure 4.15. ROP effect on acidification potential

Eutrophication potential is drastically reduced as illustrated in Figure 4.16. Nitrogen equivalent production is reduced, leading to a reduction of the likelihood of dense plant growth, which can deplete dissolved oxygen and affect negatively animal life in aquatic environments.

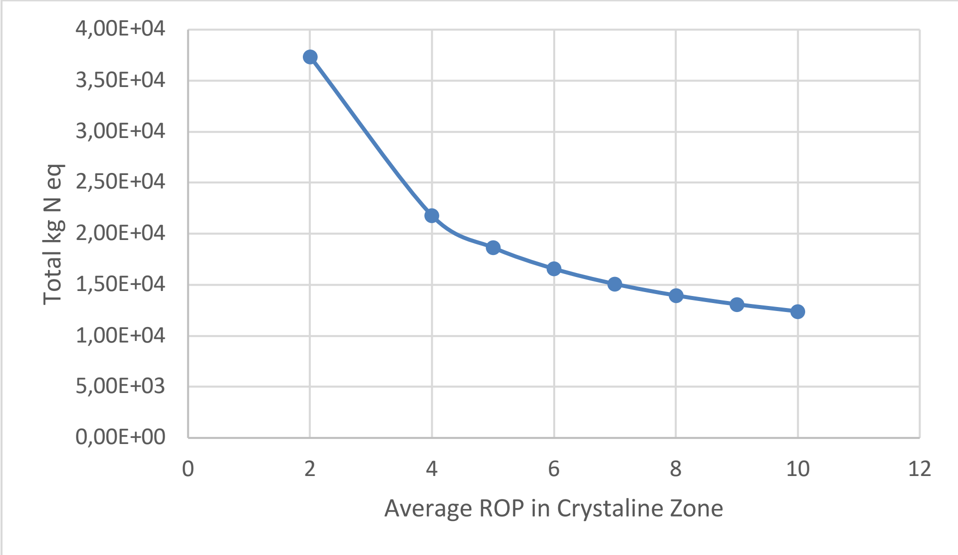


Figure 4.16. ROP effect on eutrophication potential

The second most important category examined is perhaps the potential for fossil fuel depletion, which is measured in terms of MJ surplus. Obviously, whenever energy from renewable energy sources (RES) is available, it should be preferred over hydrocarbon generated energy. As illustrated in Figure 4.17, ROP enhancement can lead to a significant reduction of the demand for fossil fuels. This is attributed to the fact that drilling operations last for a shorter duration, and completion of the drilling stage is achieved faster through the techniques proposed by ORCHYD.

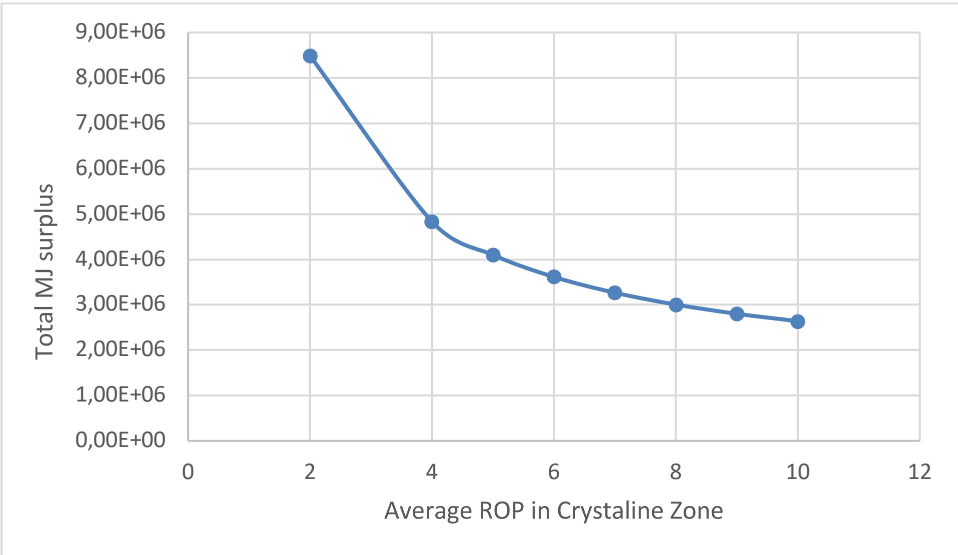
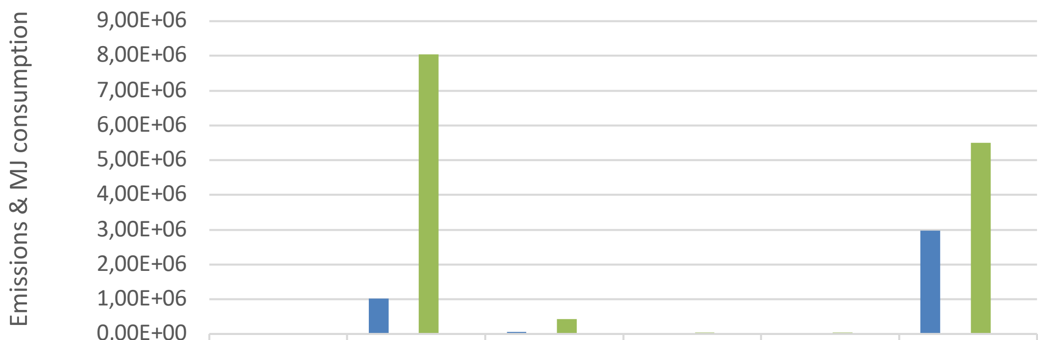


Figure 4.17. Energy consumption vs ROP in crystalline zone

The drilling life cycle approach considers the stages of material production, submersible pump, transportation of materials, construction of wells, and trenching. A comparison of the total impact of all six examined categories among scenarios 1, 2, and 8 is illustrated in Figures 4.18, 4.19, and 4.20 respectively.

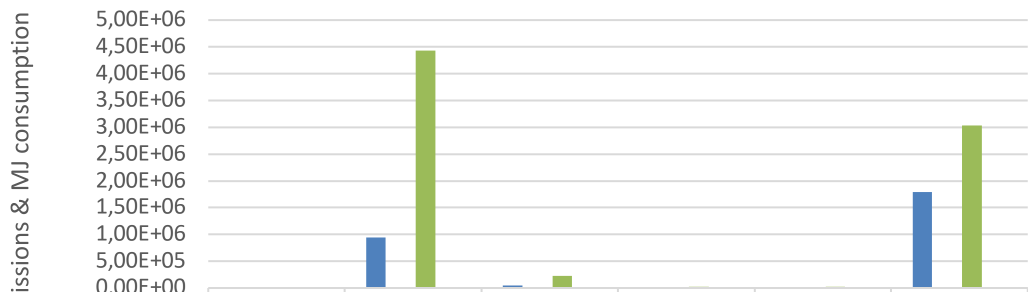
Scenarios 2 and 8 represent the lower and upper expectations for ROP enhancement by ORCHYD, as it is critical to recognize the minimum and maximum possible impacts of the techniques developed by ORCHYD in comparison to the existing ones. The most important impacts appear in the case of carbon footprint and fossil fuel depletion, while impacts on the other four categories are considered minor. Important stages include material production and construction of wells. The stage of well construction yielded the highest values on both carbon footprint and fossil fuel depletion, followed by the material production stage.



	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Material Production	1,27E+01	1,03E+06	5,24E+04	4,80E+03	3,11E+03	2,98E+06
Transportation of Materials	3,44E-04	1,37E+03	1,07E+02	5,13E+00	1,46E+00	3,05E+03
Construction of Wells	5,19E-01	8,05E+06	4,21E+05	3,88E+04	3,42E+04	5,51E+06
Trenching	2,11E-09	9,60E-01	9,60E-02	4,56E-03	2,59E-04	1,93E+00

Material Production Transportation of Materials Construction of Wells Trenching

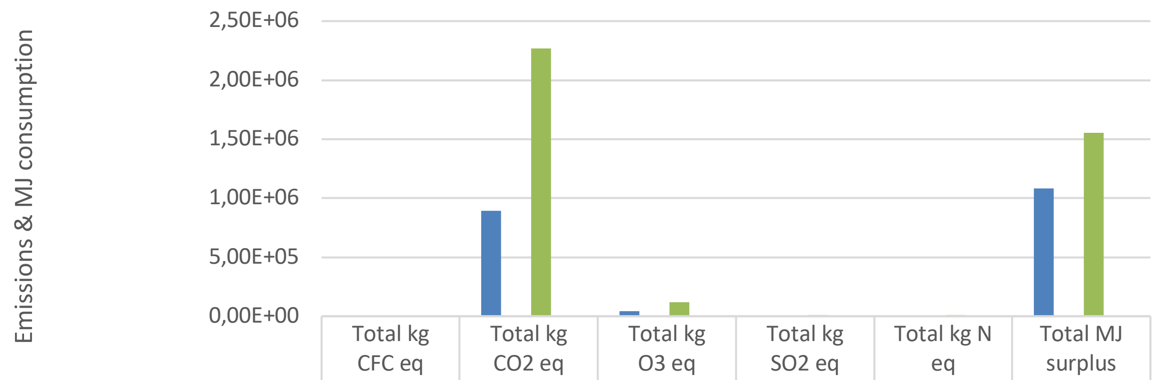
Figure 4.18. Life cycle stages comparison, Scenario 1



	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Material Production	1,26E+01	9,44E+05	4,57E+04	3,99E+03	2,85E+03	1,79E+06
Transportation of Materials	3,44E-04	1,37E+03	1,07E+02	5,13E+00	1,46E+00	3,05E+03
Construction of Wells	2,86E-01	4,44E+06	2,32E+05	2,14E+04	1,89E+04	3,04E+06
Trenching	2,11E-09	9,60E-01	9,60E-02	4,56E-03	2,59E-04	1,93E+00

Material Production Transportation of Materials Construction of Wells Trenching

Figure 4.19. Life cycle stages comparison, Scenario 2



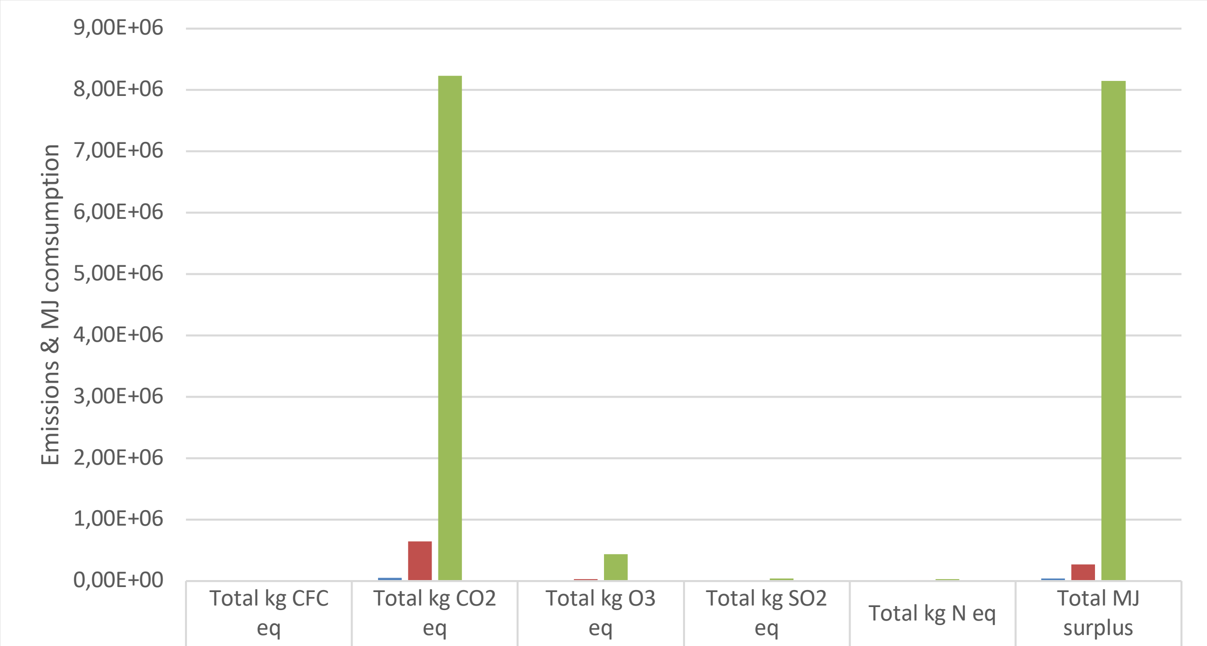
	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Material Production	1,25E+01	8,93E+05	4,17E+04	3,51E+03	2,69E+03	1,08E+06
Transportation of Materials	3,44E-04	1,37E+03	1,07E+02	5,13E+00	1,46E+00	3,05E+03
Construction of Wells	1,46E-01	2,27E+06	1,19E+05	1,09E+04	9,64E+03	1,55E+06
Trenching	2,11E-09	9,60E-01	9,60E-02	4,56E-03	2,59E-04	1,93E+00

Material Production · Transportation of Materials · Construction of Wells · Trenching

Figure 4.20. Life cycle stages comparison, Scenario 8

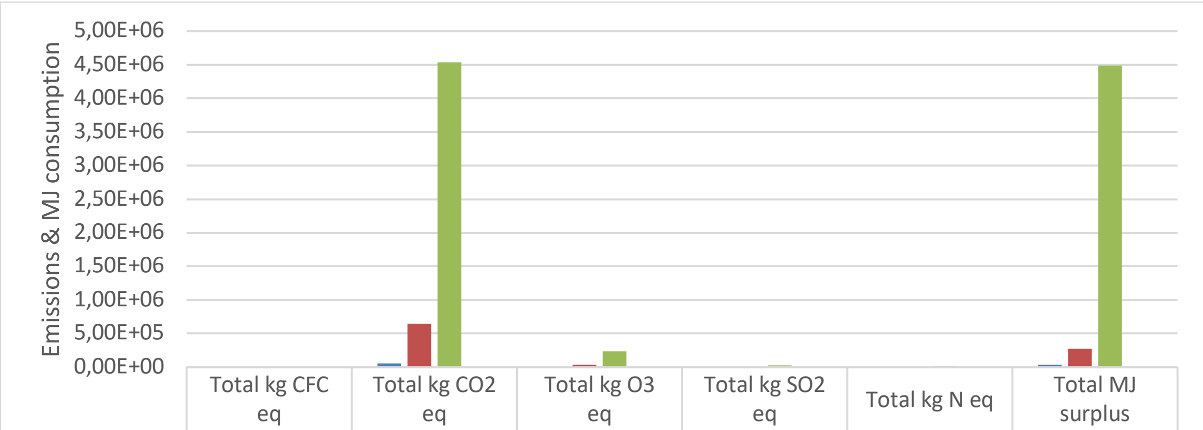
The results show that total carbon footprint and energy consumption is drastically reduced for the well construction stage through enhancement of ROP rates, with smaller positive variations occurring in other stages as well.

Concerning material use, examining scenarios 1, 2 and 8, it appears that the most important material in terms of carbon footprint was diesel followed by steel. The same applies in the case of fossil fuel depletion, as illustrated in Figures 4.21, 4.22, and 4.23 respectively. It should be noted that impacts of steel, water and cement remain constant in all examined scenarios, while the impact of diesel reduces proportionally to the ROP. These results are attributed to the fact that material use remains constant for cement, water, and steel, whereas diesel consumption is significantly reduced.



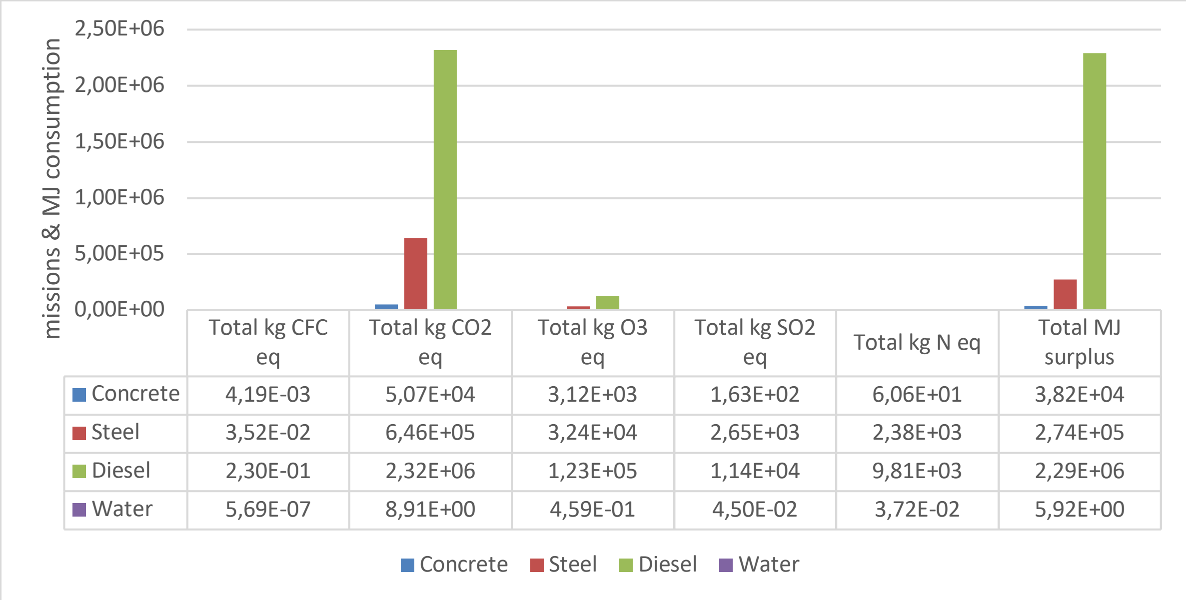
	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Concrete	4,19E-03	5,07E+04	3,12E+03	1,63E+02	6,06E+01	3,82E+04
Steel	3,52E-02	6,46E+05	3,24E+04	2,65E+03	2,38E+03	2,74E+05
Diesel	8,16E-01	8,24E+06	4,36E+05	4,06E+04	3,48E+04	8,14E+06
Water	5,69E-07	8,91E+00	4,59E-01	4,50E-02	3,72E-02	5,92E+00

Figure 4.21. Material use impacts, Scenario 1



	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Concrete	4,19E-03	5,07E+04	3,12E+03	1,63E+02	6,06E+01	3,82E+04
Steel	3,52E-02	6,46E+05	3,24E+04	2,65E+03	2,38E+03	2,74E+05
Diesel	4,50E-01	4,54E+06	2,40E+05	2,24E+04	1,92E+04	4,49E+06
Water	5,69E-07	8,91E+00	4,59E-01	4,50E-02	3,72E-02	5,92E+00

Figure 4.22. Material use impacts, Scenario 2



	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Concrete	4,19E-03	5,07E+04	3,12E+03	1,63E+02	6,06E+01	3,82E+04
Steel	3,52E-02	6,46E+05	3,24E+04	2,65E+03	2,38E+03	2,74E+05
Diesel	2,30E-01	2,32E+06	1,23E+05	1,14E+04	9,81E+03	2,29E+06
Water	5,69E-07	8,91E+00	4,59E-01	4,50E-02	3,72E-02	5,92E+00

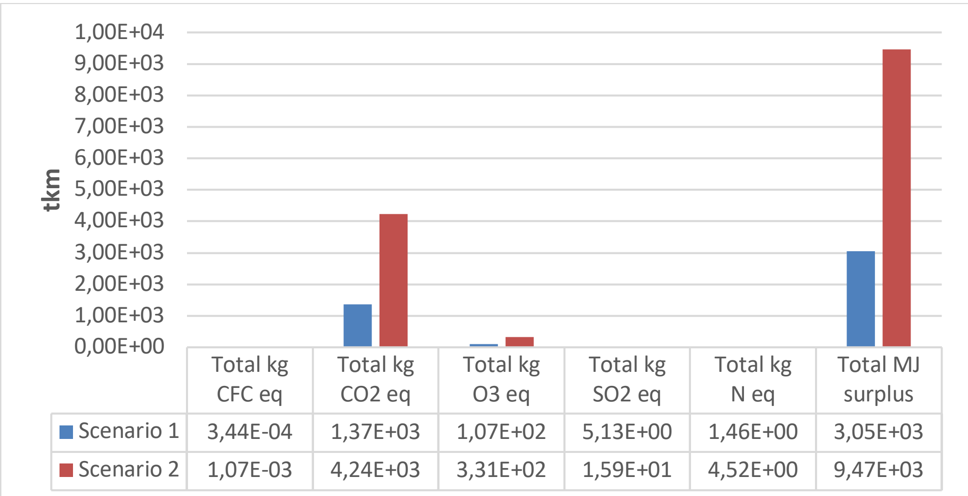
Figure 4.23. Material use impacts, Scenario 8

4.5.2.1. Effect of distance

This section of the LCA covers the effect of distance that is needed to be covered by project developers for the transportation of materials and equipment, on emissions.

ORCHYD is interested in both remote geothermal operations and geothermal operations near cities. For each case, two scenarios, scenario 1 and scenario 2, are developed, assuming a typical near distance of 16 km and a typical far distance of 50 km based on geographic proximity to Soultz-sous-Forêtz. A total of 36 truckloads were assumed for concrete transport, with a maximum load of 15 tons per truck; 10 truckloads with a maximum load of 35 tons for steel transport; and 4 truckloads with a total equipment weight of 40 tons for steel transport. Another assumption was that materials and equipment would be transported using a EURO V category freight truck (over 32 metric tons). For scenario 1 of geothermal drilling operations near an urban area, these data yielded a total of 14,966.86 tkm. The total for Scenario 2, a remote area requiring 50 km of transportation, was 46,397.27 tkm.

Transportation distance, as shown in Figure 4.24, has a significant impact on both the MJ surplus category and the carbon footprint of operations. Other categories are expected to have a smaller impact. When equipment or materials must be transported over longer distances, the effects are expected to be significantly greater (e.g., transcontinental transportation).



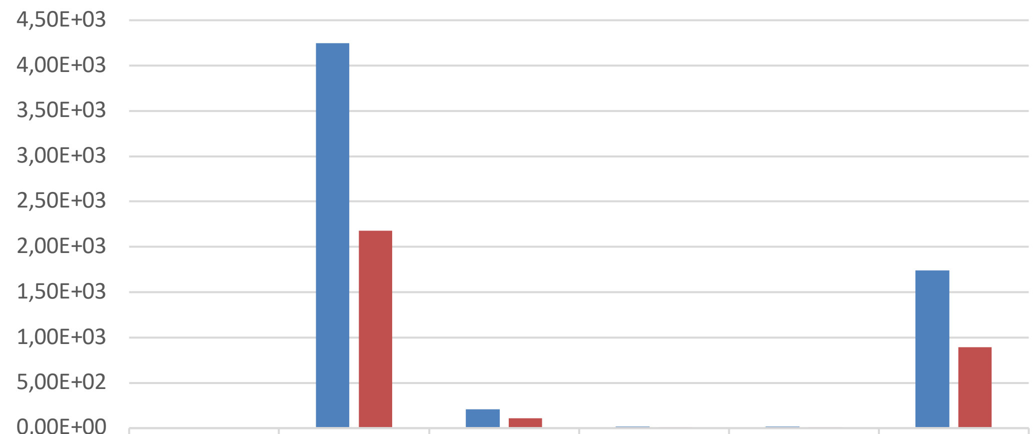
	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Scenario 1	3,44E-04	1,37E+03	1,07E+02	5,13E+00	1,46E+00	3,05E+03
Scenario 2	1,07E-03	4,24E+03	3,31E+02	1,59E+01	4,52E+00	9,47E+03

Figure 4.24. Distance impact on LCA

4.5.2.2. Effect of drill bit usage

ORCHYD focuses on deep geothermal drilling. At depths greater than 3000 m, current drilling techniques have a significantly reduced ROP, and the time required to complete the final drilling phases becomes critical (as costs explode). Given that drill bits have a limited lifetime, when the ROP is very slow, the bit can only drill a short distance before needing to be replaced. The time required to replace a bit (approximately 4 days at 3000 m depth) is added to the delay.

As described in Deliverable 2.1, 33 tricone bits were used for the drilling of GPK-3 well. For the sedimentary and intersection zone, seven tricone bits can be considered as standard both for rotary as well as percussive and HPWJ drilling (that ORCHYD seeks to implement). When the two techniques are compared, it is suggested that 26 drill bits are used with the rotary drilling technique for the crystalline zone, while 13 are used with the percussive and HPWJ techniques for the same zone. In the developed rotary drilling scenario (scenario 1), 23 drill bits of 12 and 1/4 inch and 3 drill bits of 8 and 1/2 inch are used. On the contrary, 12 drill bits of 12 and 1/4 inches and 1 drill bit of 8 and 1/2 inches are used in the developed scenario for percussive and HPWJ drilling (scenario 2). According to Premium Rock Bit. (n.d.), the first scenario requires 2,334.6 kg of steel for the drill bits, while the second scenario requires 1,196.8 kg of steel. Figure 4.25 depicts the life cycle impact of the two techniques on drill bit usage, which is a significant economic component of any geothermal project.



	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Scenario 1	2,28E-04	4,25E+03	2,10E+02	1,72E+01	1,45E+01	1,74E+03
Scenario 2	1,17E-04	2,18E+03	1,08E+02	8,81E+00	7,46E+00	8,92E+02

Figure 4.25. Life cycle emission equivalent and energy surplus vs rotary and percussive/HPWJ of drill bit usage

Drill bit replacement is an expensive and time-consuming process that can take anywhere from one to three days, depending on the depth of the drill bit at the time of replacement. No replacement time was taken into account in the main LCA study developed in this report (section 4.5.1). The aforementioned scenarios 1 and 2 are used as a basis for examining how drill bit replacement time affects the LCA for the granite drill zone. It is assumed that the average time for replacing a drill bit is 48 hours. The only emissions taken into account are those caused by the generators' use of diesel fuel. The same holds true for MJ consumption.

Figure 4.26 shows an LCA comparison between rotary and percussive/HPWJ for the replacement of drill bits.

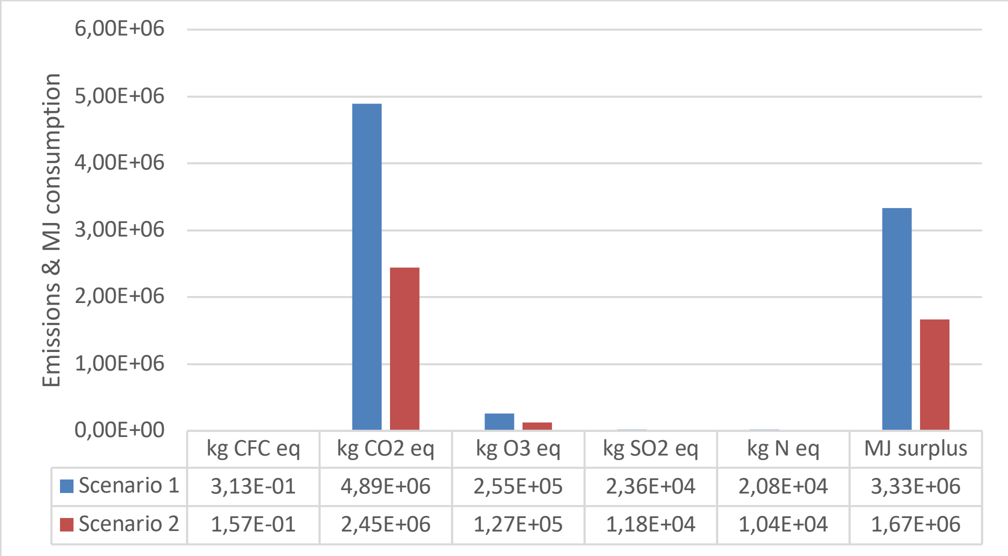


Figure 4.26. Life cycle emission equivalent and energy surplus vs rotary and percussive/HPWJ of drill bit replacement

It is obvious that the new technology that ORCHYD will develop reduces emissions and energy consumption during the bit replacement process.

4.5.2.3. Summary of LCA

The conducted LCA on the different scenarios gave important results concerning the impact of ROP on the emissions and energy consumption of drilling operations. There was an inversely proportional relation between ROP and the categories examined. ROP rates over the 3.5 m/h value of ROP (which was considered in Scenario 1), yielded significantly lower carbon footprint and energy consumption during drilling operations (Scenarios 2 to 8). Furthermore, smog was reduced significantly, while minor reductions occurred in the rest of the examined categories, as well.

It may be concluded that the techniques developed by ORCHYD will lower emissions, reduce energy consumption, and make geothermal drilling operations more sustainable.

4.5.3. Simplified LCA for ORCHYD

Based on the aforementioned presentation of the Simplified LCA (4.3.3 section) proposed by Lacirignola et al. (2014), an attempt to incorporate it in the ORCHYD LCA study on drilling operations is conducted.

The aim is to examine the impact of ORCHYD on the whole life cycle of a geothermal plant, using as basis the 8 different scenarios developed within LCA study (4.5.1). The assumptions are the same as in sections 4.5.1 and 4.5.2. The reference model provided the estimation of GHG emissions for EGS plants with the following equation:

$$GHG_{ref} = \frac{z \times N_w \times (a_1 + a_2 \times d) + LT \times f \times a_3 + P_{ORC} \times LT \times a_4 + Nw \times SF_e \times a_5}{LT \times LF \times \left(P_{ORC} - f \times P_p\right) \times 8{,}760}$$

The values of the parameters and the results for GHG for each scenario are illustrated in Table 4.7. This approach considers one well drilled to a depth of 5100 m. Excluding the drilling stage, all inputs of values related to the rest of stages of geothermal plant are considered to be equal to thosed proposed by Lacirignola et al. (2014). Parameters d, a_1 and a_2 were adjusted to the values of the LCA conducted in section 4.5.1.

Examining the results of the Simplified LCA, it appears that drilling with conventional technology yields a value of 79.57 gCO_{2eq}/kWh for the entire life cycle of a geothermal plant. Drilling with the proposed technique by ORCHYD yields a range between 62.09 gCO_{2eq}/kWh

(Scenario 2) and 42.56 gCO_{2eq}/kWh (Scenario 8), for the minimum and maximum improvement of ROP respectively.

These results underscore the high importance of ROP enhancements that ORCHYD aspires to achieve as regards the environmental impact of deep geothermal drilling and enhanced geothermal systems. Figure 4.27 illustrates the reduction in gCO_{2eq}/kWh for the 8 different scenarios examined within this simplified LCA study.

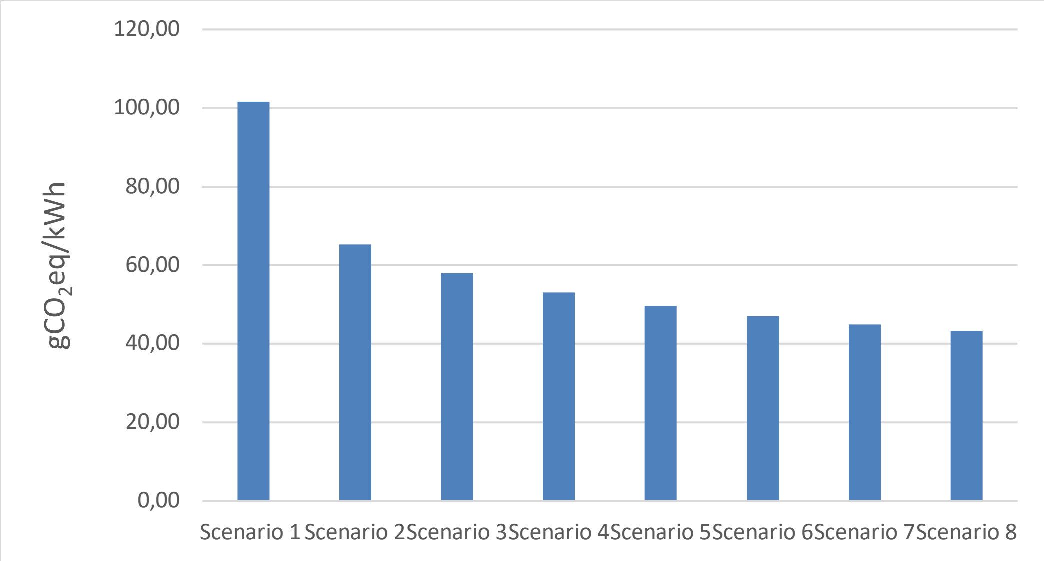


Figure 4.27. Simplified LCA of the whole life cycle of a geothermal plant, for the different scenarios developed within section 4.5.1.

Table 4.7. Parameters, values and results of simplified LCA for ORCHYD

Parameter	*Vari-able*	*Unit*	*Scenario 1*	*Scenario 2*	*Scenario 3*	*Scenario 4*	*Scenario 5*	*Scenario 6*	*Scenario 7*	*Scenario 8*
Depth	z	m	5100	5100	5100	5100	5100	5100	5100	5100
Number of wells	N_w	dimensionless	1	1	1	1	1	1	1	1
Amount of fuel for drilling	d	MJ/m drilled	1,66E+03	9,77E+02	8,34E+02	7,38E+02	6,70E+02	6,19E+02	5,79E+02	5,47E+02
Lifetime	LT	years	30	30	30	30	30	30	30	30
Total produced flow rate	f	kg/s	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5
Load Factor	LF	dimensionless	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
ORC power output	P_{ORC}	kW	1240	1240	1240	1240	1240	1240	1240	1240
Enhancement Factor	SF_e	dimensionless	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Specific power of pumps	P_p	kW/(kg/s)	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Drilling processes	a_1	gCO_{2eq}/m	1.34E+06	9,93E+05	8,86E+05	8,04E+05	7,38E+05	6,85E+05	6,41E+05	6,04E+05
Diesel consumption	a_2	gCO_{2eq}/MJ	1,09E+03	1,12E+03	1,13E+03	1,15E+03	1,16E+03	1,17E+03	1,19E+03	1,20E+03
	a_3	gCO_{2eq}×s/(kg×year)	411384	411384	411384	411384	411384	411384	411384	411384
	a_4	gCO_{2eq}/(kW×year)	43139	43139	43139	43139	43139	43139	43139	43139
	a_5	gCO_{2eq}	65017978.7	65017978.7	65017978.7	65017978.7	65017978.7	65017978.7	65017978.7	65017978.7
GHG Emissions	GHG	gCO_{2eq}/kWh	101,64	65,89	58,61	53,75	50,28	47,68	45,66	44,04

4.6. Induced seismicity

4.6.1. Introduction

The primary physical mechanisms of anthropogenic activity are pore pressure change; earthquake-to-earth interactions; deformation; temperature change; and chemical deformation. Induced seismicity is a term describing earthquakes that are a result of anthropogenic activity. This category of earthquakes maybe *classified "on a physical basis as induced if the human activity causes a stress change that is comparable in magnitude to the shear stress acting on a fault to cause slip, or as triggered should the stress change only be a small fraction of the ambient level"* (Kraft, Roth &Wiemer, 2020).

Critically stressed faults are the most crucial component related to fault reactivation, leading to induced seismicity. Small stress changes can initiate large seismic events, which are characterized as triggered events, while larger changes in stress lead to induced seismicity events (Buijze et al., 2020). No distinction is made between induced and triggered events in this report.

The distinction between hazards and risk is clarified, for a good understanding of how induced seismicity is treated in this section. The hazard of induced seismicity is related to earthquakes that can be generated by geothermal energy. The risk of induced seismicity concerns the injuries, fatalities, and structural damages that can occur. When seismic events occur in remote areas with no human population, the risk is limited to the workers on the ground.

There is no standard method in the literature for the implementation of risk assessment of induced seismicity. To provide a reliable risk assessment of induced seismicity, stratigraphy, structural data, and faulting patterns; petrophysical data; background seismicity data; net pore pressure and stresses; fluid injection and extraction rates must be measured over time. Quantification of both hazard and risk requires probabilistic estimates based on statistics or engineering models. Such assessments are critical for constructing protocols that aim to reduce the possibility of felt seismic events.

Sedimentary basins are usual targets of deep geothermal drilling operations, since they constitute a favorable environment for the formation and accumulation of geo-energy resources (Omodeo-Sale et al., 2020). Moreover, deep geothermal drilling operations usually target tectonically active regions with high-stress levels in the upper crust area (Shortall, Davidsdottir & Axelsson, 2015).

Thus, it is crucial for a geothermal project to consider risks arising from the geological setting of each specific drilling target site. "*Seismic risk can be defined as the likelihood or probability of different levels of undesirable consequences due to the occurrence of earthquakes. Such consequences may include loss of life, injury, damage and collapse of buildings, economic costs, and business interruption, among others,*" as suggested by Bommer, Crowley and Pinho (2015). Induced seismicity can be further connected to public disturbance; non-structural damage to buildings; reputational damage to developers of a geothermal project; and the concept of geothermal energy itself.

At an early stage of geothermal development, it is necessary to reduce risk and uncertainties. Schumacher, Pietrau and Wirth (2020) pointed out that the geological risk of geothermal projects related to induced seismicity cannot be easily assessed due to reservoir heterogeneities and sparse data. Furthermore, due to the lack of data from similar deep geothermal drilling operations and the novelty of the ORCHYD technique, it is challenging to develop informed estimates which may be incorporated into a risk analysis. This is doubled by the fact that a risk analysis should include site-specific data which are subjected to each drilling target location.

4.6.2. Induced seismicity in geothermal systems

Deep geothermal projects into crystalline basements tend to produce seismic events, as in the cases of Upper Rhine Graben, Basel, Soultz-sous-Forets, Landau, Insheim, and Rittershoffen. Usually, seismic events in these cases are of low magnitude, since circulation through sedimentary rocks tends to be less seismogenic.

"Perceptible seismicity is of major concern in the context of public acceptance and may hinder the development of a deep hydro-and petrothermal projects significantly," as Reinecker et al. (2019) pointed out. The majority of microearthquakes caused by geothermal operations are felt by no one. According to the US Geological Survey (2021), the majority of earthquakes felt by humans are greater than 3.0 in magnitude. However, ORCHYD partner experience indicates that earthquakes with a magnitude of 2.5 are also detectable by the general public.

Induced seismicity is one of the primary sources of public opposition against geothermal energy, mainly due to reduced public awareness. Seismic hazards related to geothermal projects can cause damage depending on the geological structure, geothermal system, and local vulnerability (Chen et al., 2020). Seismic hazards resulting from geothermal energy use may cause significant damage.

The risk of induced seismicity appears due to faults that allow vertical penetration of pressure into significant distances down to the crystalline basement. Reinecker et al. (2019) wrote that *"it is, therefore, advisable to keep distance to the crystalline basement, to operate with rather low pressures and explore for faults with very high permeability in sedimentary rocks. Only with high structural permeability, will it be possible to keep pressures low while circulating with high flow rates Mapping critically stressed faults with a potential for perceptible induced seismicity is limited by the resolution of seismic surveys. And even a 3D seismic survey will not necessarily detect all faults of a size that is relevant for the seismic hazard"*. Economic considerations, on the other hand, may necessitate the search for hotter fluids, which may require drilling deeper into or into the basement.

Changes in the pressure and temperature regime of geothermal reservoirs can occur during the development phase of a geothermal project. Ground deformation, subsidence, fault reactivation, and microseismic events are the main impacts of these changes. Ideally, geothermal developers need to have a detailed knowledge of the seismic response of any targeted subsoil before the initiation of operations. However, Kraft, Roth and Wiemer (2020) explain that indicators can only yield a rough estimate of expected induced seismicity.

Reservoir rock type and background seismicity need to be assessed, as well, considering that crystalline basement rocks are more seismogenic (and the natural seismicity of an area should always be accounted for). The injected volume of liquids is critical for induced seismicity, as larger quantities of fluids tend to cause more extensive stress changes to the rocks. Moeck, Kwiatek and Zimmermann (2009) have claimed that fluid pressures above 100 MPa, in depth ranges of approximately 4 km can induce reactivation of normal and strike-slip faults. Furthermore, the temperature differential between water and rock generates stresses that are proportional to the difference and increase in magnitude with time as the rock cools. Thus, thermal shrinkage, in conjunction with the fluid pressure effect, contributes to the initiation of delayed seismic events. The depth of geothermal operations is another factor that needs to be stressed, since it appears to be proportional to induced seismic hazard. Finally, proximity to existing prestressed or extended seismogenic faults should always be investigated as the possibility of inducing earthquakes is always more significant in such areas.

However, induced seismicity is more of a concern during the stimulation stage than during the drilling stage. Beckers et al. (2021) note that "*Stimulation techniques can enhance the reservoir permeability and increase fluid production rates, but may also lead to induced seismicity, causing disturbance and potentially damage at the surface. Minimizing induced seismicity requires evaluation of the uncertainty and impact of several risk factors, such as the rate and volume of fluid injection and withdrawal, injection pressures, depth of disturbance, state of stress in the crust, rock properties, and proximity to seismogenic faults*".

Seismicity tends to level off over time in hydraulically bounded systems, whereas seismicity can fluctuate or increase over time in hydraulically open systems. Seismic events can occur 3 to 5 months after water injection for drilling operations beyond 3 km, according to Chen et al. (2020). This is due to liquid diffusion. Developers frequently choose to halt operations in order to deal with seismic activity. However, this measure is controversial because liquid diffusion continues in the formation, resulting in large earthquakes months later (e.g., Pohang). Beckers et al. (2021) suggest that seismicity risk evaluations need to be communicated openly to stakeholders, government entities, communities, and end-users for this reason.

ORCHYD targets the development of geothermal drilling operations in depths below 5 km, where natural permeability is low and significant contraction can occur due to pressure decline. Injected fluids during drilling operations can reduce rock temperature and rise pore pressure, eventually leading to reactivation of faults. Simultaneously, it is well established that geothermal exploitation in close proximity to large geological faults is generally preferred due to its increased productivity. However, this method of exploitation has the potential to result in larger seismic events. ORCHYD's advanced drilling architectures will enable it to avoid large faults and thus mitigate the risk of large seismic events by drilling deeper (and thus reaching hotter horizons) with advanced drilling architectures.

In 2009 in Switzerland, the *Deep Heat Mining Project* near Basel was abandoned due to issues related to induced seismicity. The target was deep crystalline rocks below the city of Basel. An earthquake of 3.4 mL magnitude provoked damages to buildings and concern to the local population, eventually leading to the termination of the project (Mignan et al., 2015). A seismic hazard map of Europe is illustrated in Figure 4.28. Giardini, Woessner and Danciu (2014) explain: *“European Seismic Hazard Map (ESHM13) displaying the 10% exceedance probability in 50years for peak ground acceleration (PGA) in units of gravity(g). Cold colors indicate comparatively low hazard areas (PGA≤0.1g), yellow and orange indicate moderate-hazard values (0.1g<PGA≤0.25g), and red colors indicate high-hazard areas (PGA≥0.25g)”*.

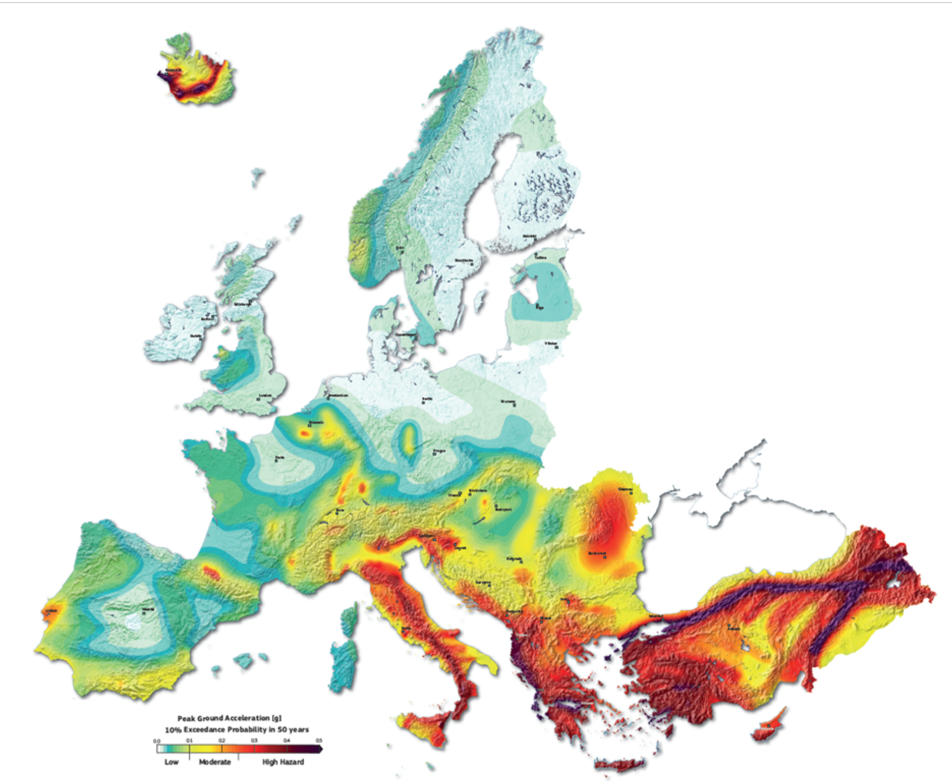


Fig. 4.28. The 2013 Euro-Mediterranean Seismic Hazard Model (Giardini, Woessner & Danciu, 2014)

4.6.3. Risk assessment in induced seismicity

The concepts of risk and uncertainty are related, because risk considers the impact of uncertainties, and can vary during the life cycle of a process, as illustrated in Figure 4.29.

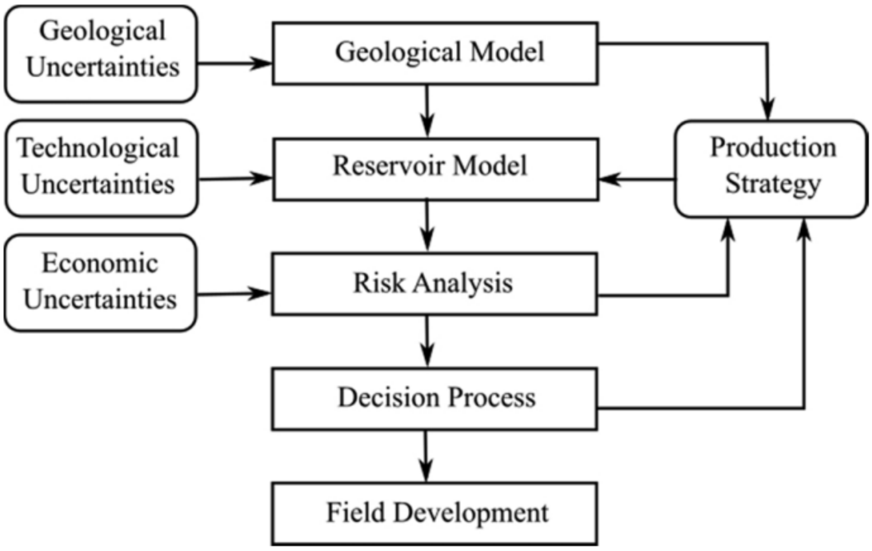


Figure 4.29. Flow chart showing typical geothermal resource development pathways including the relationship between uncertainty and risk (Witter et al., 2019)

Minimizing risks and uncertainties is integral for the geothermal sector and enhancing the success rate of geothermal projects. Risk examines (1) what can occur, (2) with what probability, and (3) with what consequences (Witter et al., 2019).

Risk reduction strategies related to induced seismicity can provide insight to risk management through hazard control, contrary to standard risk mitigation, where only interventions on vulnerability and exposure are feasible (Mignan et al., 2015). A traffic lights system (TFS) is arguably the most common methodology used to assess and determine the risks associated with induced seismicity during geothermal drilling operations, and is later presented in this report. Issues that TFS cannot easily consider, include the diffusion of drilling fluids, which continues after the shut-in of a well; biased decision threshold due to some ambiguity on hazard and risk estimates; and unexpected operational problems (Mignan et al., 2015).

According to Chen et al. (2020), seismic events are classified as primary or induced. The following steps have been proposed for the assessment of risk from induced seismicity include (Majer et al., 2012):

1. Preliminary screening evaluation
2. Implementation of a communication program to the public
3. Seismic monitoring
4. Quantification of seismic hazards
5. Characterization of risk of induced seismic events
6. Development of a mitigation plan

Induced seismicity should always be coupled with assessing natural seismicity in geothermal development areas since the latter is the seismic hazard basis of any given area. As a result, a local, sufficiently sensitive monitoring network for seismic analysis must be put in place well in advance of any industrial activity.

Determination of the magnitude of an earthquake requires the estimation and combination of several quantities (e.g., seismic moment, average fault displacement, total surface area of fault, average rigidity of rocks) but is a mathematically well-defined process. Observable damages are quantified through the Modified Mercalli Intensity (MMI) scale. Magnitude scales, such as body-wave magnitude (M_b), surface-wave magnitude (M_s), and local magnitude (M_L), quantify the energy released by an earthquake. The Richter scale is a local magnitude scale.

Ground shaking is examined in terms of acceleration, velocity, or displacement. Characterization of earthquakes may be implemented based on the intensity of ground shaking; damage invoked; or magnitude of measured physical parameters. However, the impacts of seismic events depend on the duration; distance; depth of hypocenter; terrain characteristics; and structural characteristics of buildings in the vicinity of an earthquake.

Porter et al. (2018) explain that induced earthquakes from a geothermal field development can be more damaging than a naturally occurring earthquake of equivalent magnitude, due to different depths of occurrence. Ground motion at a site may be assessed through the Probabilistic Seismic Hazard Analysis (PSHA) and the Deterministic Seismic Hazard Analysis (DSHA) approaches, involving terms like Peak Ground Acceleration (PGA) and peak ground velocity (PGV). PSHA is more suitable for risk analysis of induced seismicity. In typical PSHAs, the minimum earthquake magnitude considered is 5.0. However, since induced seismicity related to geothermal projects rarely exceeds the magnitude of 4.0, as shown in the following figure, based on the data of recorded induced seismicity events related to geothermal energy and tabulated in Figure 4.30. (HiQuake, 2021), a lower minimum magnitude should be considered.

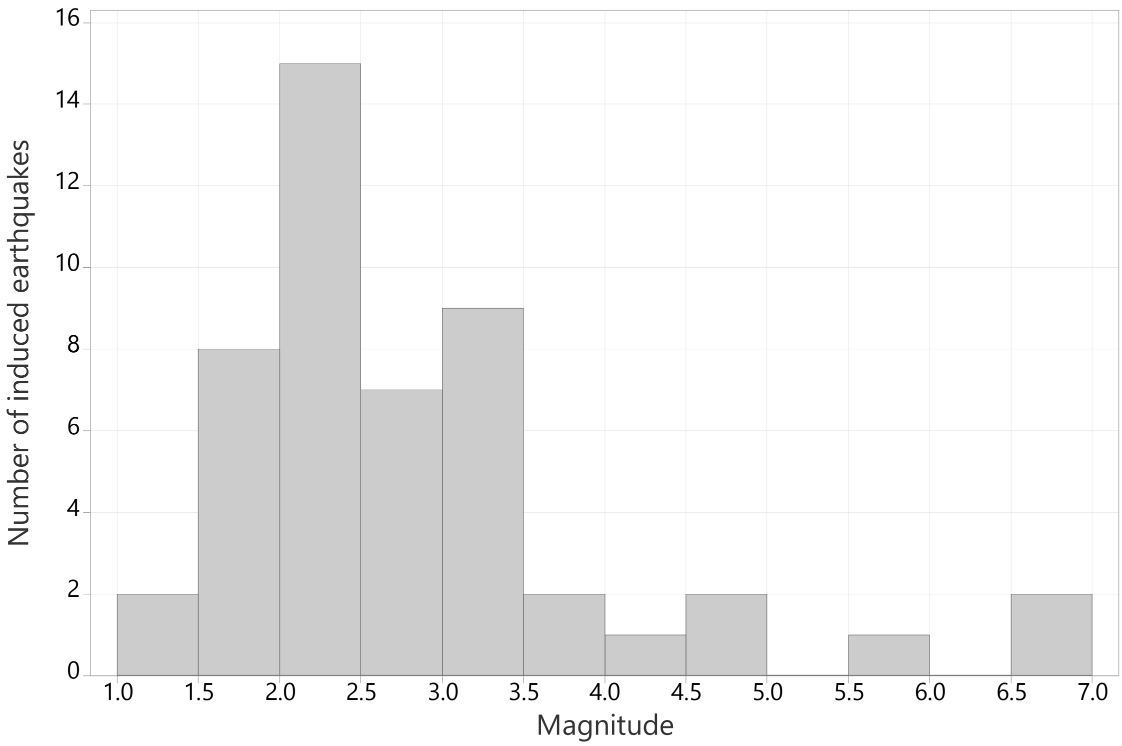


Figure 4.30. Number of induced earthquakes and their magnitude (HiQuake, 2021)

PSHAs should first be conducted for the evaluation of natural seismicity. Estimating the baseline hazard from natural seismicity includes evaluating historical seismicity data, characterizing any active or potentially active faults, evaluating geological site-specific conditions, and utilizing appropriate ground motion prediction models. The second step is the estimation of hazards from induced seismicity. This is achieved by evaluating and characterizing the tectonic stress field based on earthquake focal mechanisms, the structural framework, and seismic monitoring of the target area. A review of comparable cases of induced seismicity and utilization of DSHA for simulation scenarios should be conducted, as well.

4.6.4. Characterization of risk of induced seismicity

Characterization of induced seismicity risk is an integral part of risk analysis, as outlined below:

1. Firstly, the ground motion of any target location needs to be characterized.
2. Secondly, adversely impacted categories need to be identified. This includes physical damage to residential housing, facilities of any kind, human activity interference, and socioeconomic impact.
3. Thirdly the damage potential on any of these categories needs to be characterized to assess their vulnerability.
4. Lastly, risk estimation and its public presentation should take place.

Fluid injection is considered the prime cause of minor seismic events in geothermal reservoirs. The magnitude of seismic events is connected to injection pressure, while their frequency of occurrence is proportional to the injected amount (Shapiro et al., 2010).

The TLS method has been developed and widely applied to predict and manage geological hazards rising from geothermal operations. It makes an educated guess as to the occurrence rate of geological hazards; identifies and classifies their intensity; and defines and describes the scope of the damage they can cause. The use of TLS may be extended to a form of statistical forecasting approach (as categorized by Gaucher et al., 2015), as seismic events are induced by geothermal operations that force fluids to circulate. On this basis, Gaucher et al. (2015) pointed out that it should be possible to prevent significant disturbances on the surface by modifying or suspending some operations at the right moment. "*A suitable reaction scheme is derived from the induced seismic events unfelt by the population and recorded during the operations by a permanent seismic network. Such a traffic-light system can be implemented relatively easily and requires real-time processing of the acquired data*", as Gaucher et al. (2015) further explain.

Chen et al. (2020) presented several factors that impact the extent of damage both to population and buildings. Earthquakes of the same scale can cause more damage in areas with weaker buildings, different population density, occurrence time, and available rescue countermeasures. The damage caused by seismic events is classified into none, minor, moderate, heavy, very heavy, and completely damaged.

Table 4.8. summarizes the classification of damage on buildings and population according to Hassanzadeh et al. (2013).

Table 4.8. Damage classification on buildings and people (modified from Hassanzadeh et al., 2013)

Category	Buildings		Population	
Type of destruction	*Percentage of damage*	*Status*	*Percentage of damage*	*Status*
No destruction	0-2	Damages are underestimate	0	Dead
			0	Hospitalized
			1	Injured and not hospitalized
			99	Not injured
Light destruction	3-10	Very tiny cracks	2	Dead
			5	Hospitalized
			9	Injured and not hospitalized
			84	Not injured
Moderate destruction	11-30	5–20 mm cracks are seen in the building	4	Dead
			9	Hospitalized
			15	Injured and not hospitalized
			72	Not injured
Heavy Destruction	31-60	420 mm cracks are seen and some components of building such as walls are destroyed	13	Dead
			17	Hospitalized
			23	Injured and not hospitalized
			47	Not injured
Very heavy destruction	61-80	A part of roof and one building's wall is destroyed	16	Dead
			22	Hospitalized
			28	Injured and not hospitalized
			34	Not injured
Completely collapsed	81-100	Entire of roof and more than one building's walls are destroyed	41	Dead
			16	Hospitalized
			21	Injured and not hospitalized
			22	Not injured

Various assessment models for estimating damage have been developed, and they are illustrated in Table 4.9.

Table 4.9. Summary of published models for seismic building and population damage assessment (modified from Chen et al., 2020)

Name of model	*Developer*	*Type of analysis*	*Description*
Prompt assessment of global earthquakes for response	U.S. Geological Survey	Deterministic, probabilistic	Assessing potential societal impacts including inferred vulnerability of the regional buildings and population exposed to severe ground shaking.
Quake loss assessment for response and mitigation	International Centre for Earth Simulation	Deterministic, probabilistic near-real-time	Estimation earthquake loss in near real-time and scenario modes based on world data sets of population and building stocks.
Hazard of United State	Federal Emergency Management Agency	Deterministic, probabilistic	Using Geographic Information System (GIS) to visualize spatial relationships between population and geographic assets and to estimate earthquake loss.
Earthquake loss estimation routine	Kandilli Observatory and Earthquake Research Institute	Probabilistic, near-real-time	Incorporating both regional- and urban-scales in real-time estimations of rapid loss of earthquakes.
Seismic loss estimation using a logic tree approach	Norwegian Seismic Array	Deterministic, probabilistic, near-real-time	Implementing a logic tree-computation scheme and allowing users to define weighted input parameters and providing results within a confidence level.
Earthquake risk management	Geoscience, Australia	Deterministic, probabilistic	Focusing on direct financial losses caused by building and contents damage exclude the damage caused by secondary hazards.
Realtime assessment of earthquake disaster in Yokohama	Governments in Japan	Deterministic, real-time	Estimating the distribution of seismic intensity and damage to wooden buildings based on the GIS system, and gathering information of actual damages to roads within 60 min.
Systemic seismic vulnerability and risk analysis	14 countries including USA, Japan, and Europe	Deterministic, probabilistic	Evaluating socio-economic seismic vulnerability, and considering buildings, transportation, utility networks and critical infrastructures in urban and regional scale.
People trapped in earthquakes	China earthquake administration	Deterministic	Estimating the distribution of the trapped population according to actual data of Ludian earthquake-hit areas in 2014.

Name of model	*Developer*	*Type of analysis*	*Description*
Displacement-Based Earthquake Loss Assessment	University of Pavia and Imperial College	Deterministic, probabilistic	Using displacement response spectra to show a correlation between the frequency of the ground motion and fundamental period of the building under uncertainties.

Several models have been proposed in the literature to forecast the occurrence rate of geological hazards (Chen et al., 2020).

- The Shapiro model related the probability of occurrence of an earthquake to injection time and pressure. However, this model does not take into consideration micro-seismicity events or stress drop.
- The Short-Term Earthquake Probabilities (STEP) model, based on the Gutenberg-Richter law, predicts aftershocks.
- Aftershocks are also examined by the Trigger model, which is based on known mainshocks.
- The Epidemic-Type Aftershock Sequence (ETAS) model was developed based on the Trigger model, taking a stationary distribution of mainshocks and occurrence rate of both primary and induced events into account.
- The Extended ETAS model considers a variable background rate, while Chen et al. (2020) noted that the (original) ETAS model assumed a constant background rate of events.
- Based on global data and considering the magnitude and distance of seismic events, intensity prediction equations (IPEs) have been developed by Alvarez-Rubio et al. (2011). Intensity prediction models have also been developed on the basis of ground motion, taking into consideration peak ground acceleration (PGA) and peak ground velocity (PGV). In particular, Atkinson and Kaka (2007) developed empirical relationships between instrumental ground-motion parameters and observed Modified Mercalli Intensity (MMI).

Considering the above, the TLS is a suitable tool for decision making during in the context of risk analysis of geothermal well development.

As illustrated in Figure 4.31., the forecast of occurrence of seismic events in combination with hazard intensity and damage assessment, leads to three options for decision making. As in a road traffic light, green means that the operations may proceed; amber that caution is needed; and red that operations must stop.

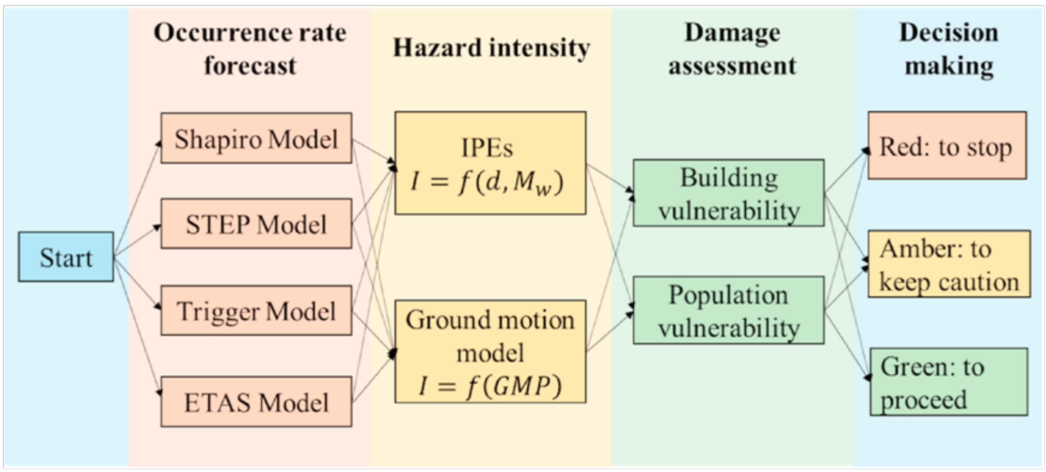


Figure 4.31.The logical structure of traffic-light system in seismic hazard assessment (Chen et al., 2020)

TLS may be modified to site-specific conditions. Different thresholds may be set up for different locations, while, in certain cases, the entire system may encompass more than three categories for decision making. Such an alternative example of TLS, including five decision making categories, is the one implemented in the Geldinganes project in Iceland (http://www.destress-h2020.eu/en/demonstration-sites/Geldinganes/), and is illustrated in Figure 4.32.

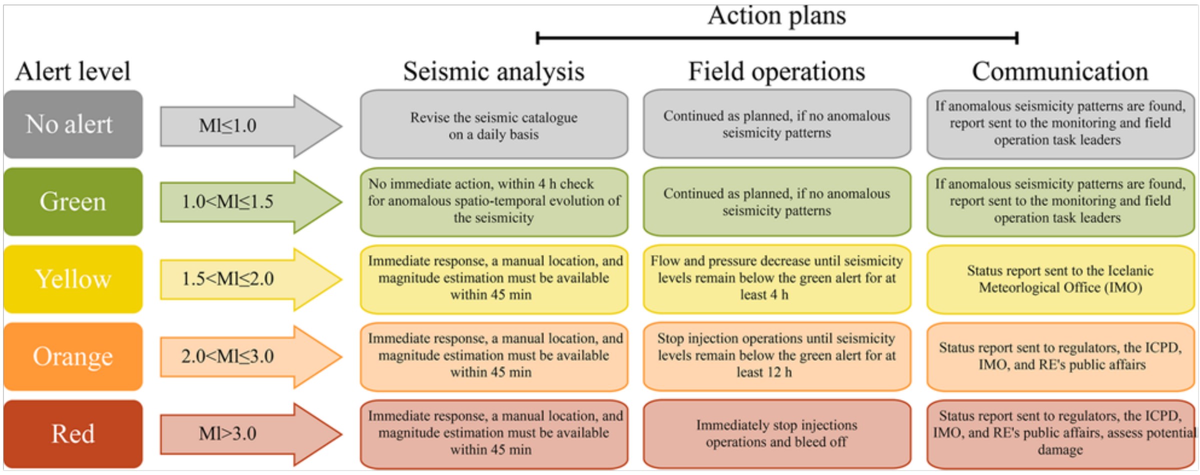


Figure 4.32. The classic traffic light scheme adopted in the Geldinganes project (Broccardo et al., 2020)

4.6.5. Risk calculation

Risk maybe defined as the multiplication of the probability of an event with the loss resulting from it. In the case of induced seismicity, *"risk (R) is defined as the product of the frequency of an event (f) and the severity of the resulting consequences (S)"* (Spada, Sutra & Burgherr, 2021). The frequency is the number of events during a year, and severity is the extent of consequences of each accident. The aforementioned is illustrated in the following equation of induced seismicity risk, modified from Spada, Sutra and Burgherr (2021)

$$R = \frac{N_e \times M_a}{T_w}$$

where

R: induced seismicity risk

N_e: number of recorded induced seismicity events

M_a: average magnitude of induced seismicity events

T_w: number of active geothermal wells.

Using this equation, this report models the risk of induced seismicity (per geothermal well), with example data taken from Table 4.10, which lists seismic event data from the Human-Induced Earthquake Database (HiQuake, 2021).

Table 4.10. Induced seismicity events related to geothermal energy recorded in the Human-Induced Earthquake Database (HiQuake, 2021)

Name of project	*Country*	*Lithology*	*Stage*	*Depth(m)*	*Magnitude*	*M_{max}*	*Previous seismicity*
Cooper Basin (Habanero 3)	Australia	Granite	Injection		1.70	ML	
Paralana 2 (Diagnostic Fracture Injection Test)	Australia		Injection		1.40	ML	
Well Paralana 2	Australia		Injection	3645	2.5	Mw	
Cooper Basin (Habanero 4)	Australia	Granite	Injection	4160	3.90	ML	
Cooper Basin (Habanero 1 restimulation)	Australia	Granite	Injection	4250	2.90	ML	
Cooper Basin (Habanero 1)	Australia	Granite	Injection	4254	3.7	Mw	
Cooper Basin (Jolokia 1)	Australia	Granite	Injection	4852	1.60	ML	
Balmatt (MOL-GT-02)	Belgium		Reinjection	3300	2.10	ML	
Berlín (Well TR8A)	El Salvador	Volcanics	Injection		4.40	ML	El Salvador very active due to subduction and volcanoes
Ahuachapan	El Salvador		Injection	1400	3.00	ML	
OTN3 well, St1 Geothermal Project, Otaniemi, Espoo	Finland	Granite	Stimulation	6100	1.90	ML	
Soultz (GPK-3)	France	Granite	Injection	5000	2.90	ML	
Soultz (GPK-2)	France	Granite	Injection	5084	2.4	Mw	
Landau	Germany	Granite and others	Circulation	3000	2.70	ML	
Unterhaching	Germany	Carbonate	Circulation	3600	2.40	ML	

Name of project	*Country*	*Lithology*	*Stage*	*Depth(m)*	*Magnitude*	*M_{max}*	*Previous seismicity*
Insheim	Germany	Granite and others	Injection	3800	2.40	ML	
Bad Urach	Germany	Gneiss	Injection	4300	1.8	Mw	
Nesjavellir	Iceland		Reinjection	550	3.20	ML	
Hellisheiði (Gráuhnjúkar reinjection site)	Iceland	Basalt	Reinjection	800	2.00	ML	
Laugaland (Holtum) and Kaldárholt	Iceland	Basalt	Reinjection	1000	6.60	ML	
Reykjanes	Iceland	Volcanics	Reinjection	1000	3.00	ML	
Svartsengi	Iceland	Basalt	Reinjection	1200	3.20	ML	
Krafla	Iceland	Basalt	Reinjection	2100	2.20	ML	
Hellisheiði (Well HE-8)	Iceland	Basalt	Drilling	2500	2.40	ML	
Torre Alfina	Italy	Carbonate	Injection	2000	3.00	ML	
Latera	Italy	Carbonate	Injection	2000	2.90	ML	
Cesano	Italy	Carbonate	Injection	2000	2.00	ML	Dispersed low level seismic activity 6000-12000 m
Larderello-Travale	Italy	Carbonate	Circulation	2000	3.20	ML	
Monte Amiata	Italy	Metamorphics	Circulation	3000	4.5	Mw	High levels of background seismicity
Ogachi (OGC-1)	Japan	Granodiorite	Injection	1000	2	Mw	
Olkaria	Kenya	Volcanics	Extraction		2.5	Md	
Curonian Lagoon	Lithuania		Extraction		2.60	ML	
Los Azufres	Mexico		Injection		1.9	Md	
Cerro Prieto (Imperial Valley)	Mexico	Volcanics	Extraction	3000	6.60	ML	Tectonically active area - seismic swarms and eqs>6M
Los Humeros	Mexico		Circulation	3250	4.6	Md	

Name of project	*Country*	*Lithology*	*Stage*	*Depth(m)*	*Magnitude*	*M_{max}*	*Previous seismicity*
Puhagan	Philippines		Reinjection	2500	2.40	ML	
Pohang (PX-1)	South Korea	Granodiorite and Granitic Gneiss	Injection		2.30	ML	
Pohang (PX-2)	South Korea	Granodiorite and Granitic Gneiss	Stimulation	4382	5.5	Mw	
St, Gallen	Switzerland	Carbonate	Injection	4253	3.3	Mw	
Basel	Switzerland	Granite	Injection	5000	3.40	ML	>6,5M in 1356 destroyed the city
Kemaliye	Turkey		Reinjection		1.40	ML	
Çeşneli-Şahyar	Turkey		Reinjection	1900	2.20	ML	
Örnekköy	Turkey		Reinjection	2500	1.60	ML	
Alkan-Piyadeler	Turkey		Reinjection	2700	2.10	ML	
Soğukyurt	Turkey		Reinjection	3700	3.40	ML	
Rosemanowes	United Kingdom	Granite	Circulation	2000	2.00	ML	
United Downs Deep Geothermal Power Project	United Kingdom	Granite		4000	1.5	ML	
Desert Peak, Nevada	United States	Volcanics	Injection	1771	1.70	ML	
Newberry	United States	Volcanics	Injection	3066	2.39	Mw	

Risk assessments for individual wells should take exposure into consideration, as well. Exposure is a critical factor, since ORCHYD targets both remote areas, where exposure can be considered zero, and urban areas, where exposure can be very high. In remote areas, the only risk of induced seismicity concerns the equipment and infrastructure of the project development.

It is important to underline that "*no single aspect or indicator can provide a full risk picture,"* as Spada, Sutra & Burgherr (2021) point out. Bommer, Crowley and Pinho (2015) further suggested the integration of fragility as a measure of the probability of damages under certain motions within the model. Even though fragility will not be integrated into the chosen model for assessing the risk of induced seismicity, the sequence of steps involved in estimating induced seismic risk proposed by Bommer, Crowley and Pinho (2015) is illustrated in Figure 4.33.

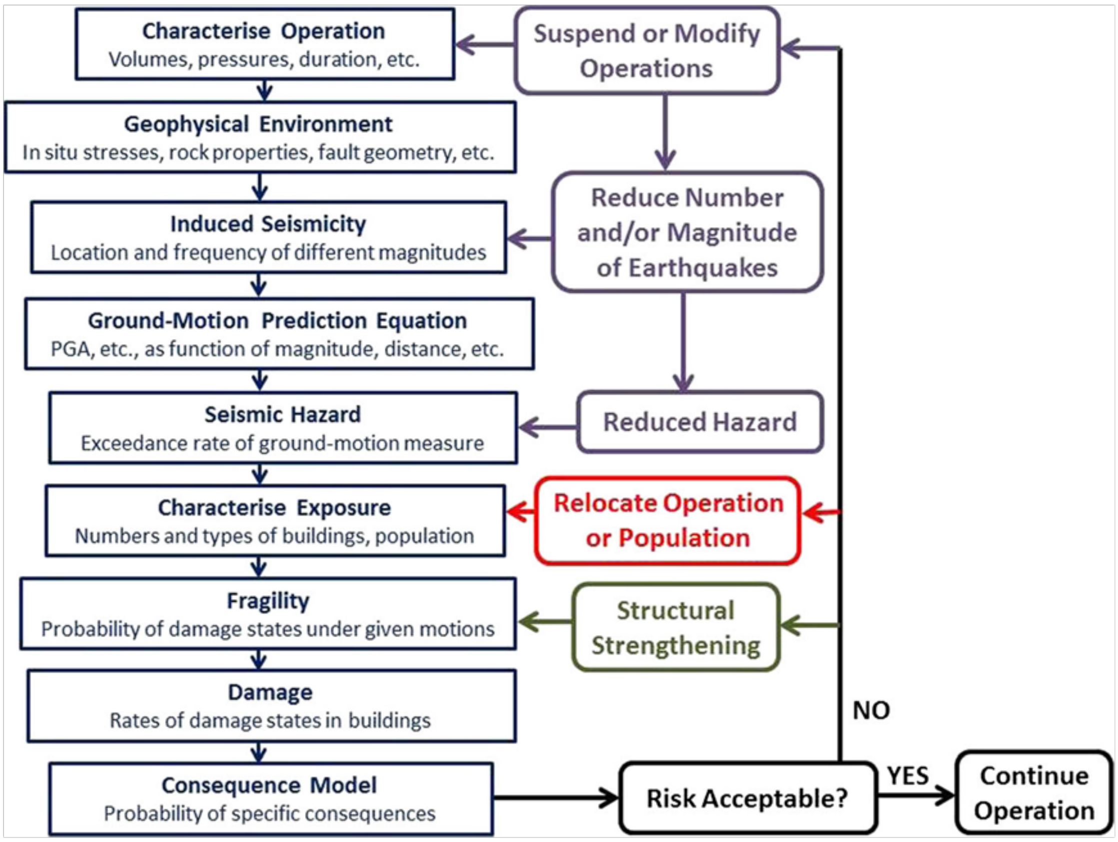


Figure 4.33. Step sequence for the estimation of induced seismic risk (Bommer, Crowley &Pinho, 2015)

Therefore, a variety of risk factors should always be considered. In risk assessment proposed in this section, the risk is examined using a historical-based approach on deep geothermal drilling, relative to the depth of each project and the rock formation that operations took place.

A total of 3200 active geothermal wells as of 2020 has been documented by Smith (2020). There were 49 recorded induced seismicity events that exceeded the magnitude threshold of 1.5, as illustrated in Table 4.10. For a geothermal well, this yields a probability of 0.015 of an event with seismicity levels at least in the yellow category of TLS. The average magnitude of these events is 2.78. Implementing these values in the aforementioned equation for risk calculation, risk is calculated as:

$$R = \frac{N_e \times M_a}{T_w}$$

$$R = \frac{49 \times 2.78}{3200}$$

$$R = 0.04$$

It is seen that the risk of induced seismicity is 0.04, which is quite a low value. It is useful to also examine the recorded events qualitatively, to get an insight into induced seismicity in certain lithologies and depths. Given the fact that ORCHYD focuses on the drilling stage of a geothermal well life cycle, a calculation of risk related to this stage should be implemented as well. Out of 49 recorded induced seismicity events, there is only 1 case in Iceland (Hellisheiði, Well HE-8) where a seismic event of 2.4 ML was recorded. Implementing the given equation, the risk of induced seismicity during drilling operations is calculated as:

$$R = \frac{1 \times 2.4}{3200}$$

$$R = 0.00075$$

Thus, the risk for an induced seismicity event during geothermal drilling operations can be characterized as minimum. Taking into consideration the fact that Iceland is a region with high natural seismicity, the actual risk of induced seismicity during drilling operations can be even lower for areas with lower natural seismicity. Figure 4.34. Illustrates the share of seismic events per geothermal well life cycle stages. It is obvious that drilling stage shares a minimum percentage.

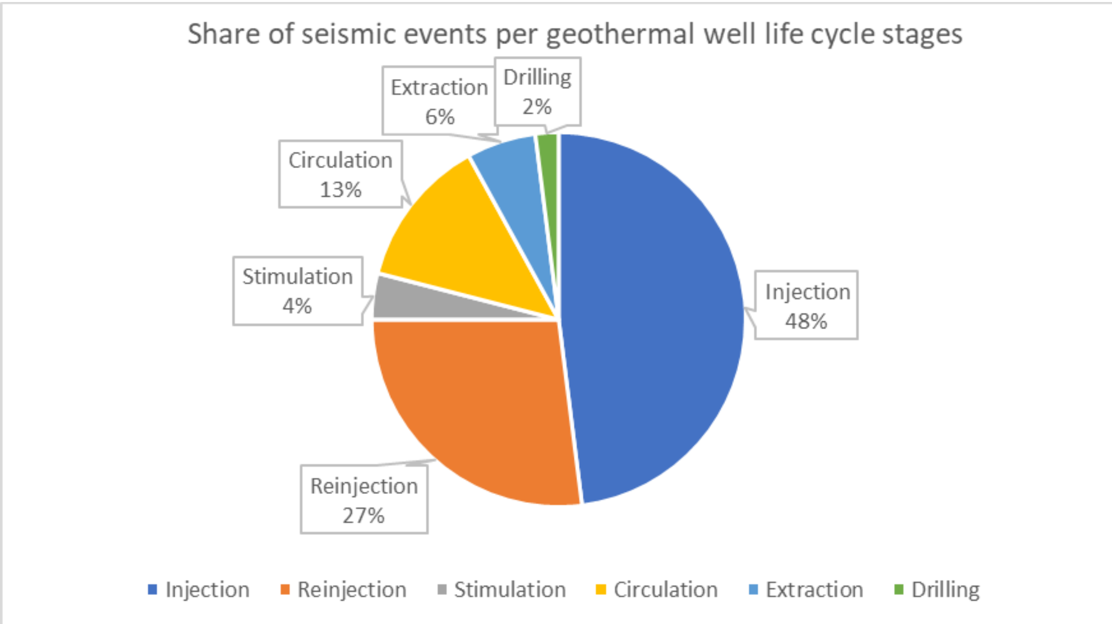


Figure 4.34. Share of seismic events per geothermal well cycle stages

Based on the data of the previous table, the following figure plots the log magnitude of an event of induced seismicity against depth, with data point labels indicating the type of rock (i.e., lithology). Although the association between these two variables is weak and the dispersion of the points quite loose, it may be argued that deeper wells (which were predominantly in granite) are characterized by lower seismic magnitudes. However, dispersion of the points cannot yield to support this claim.

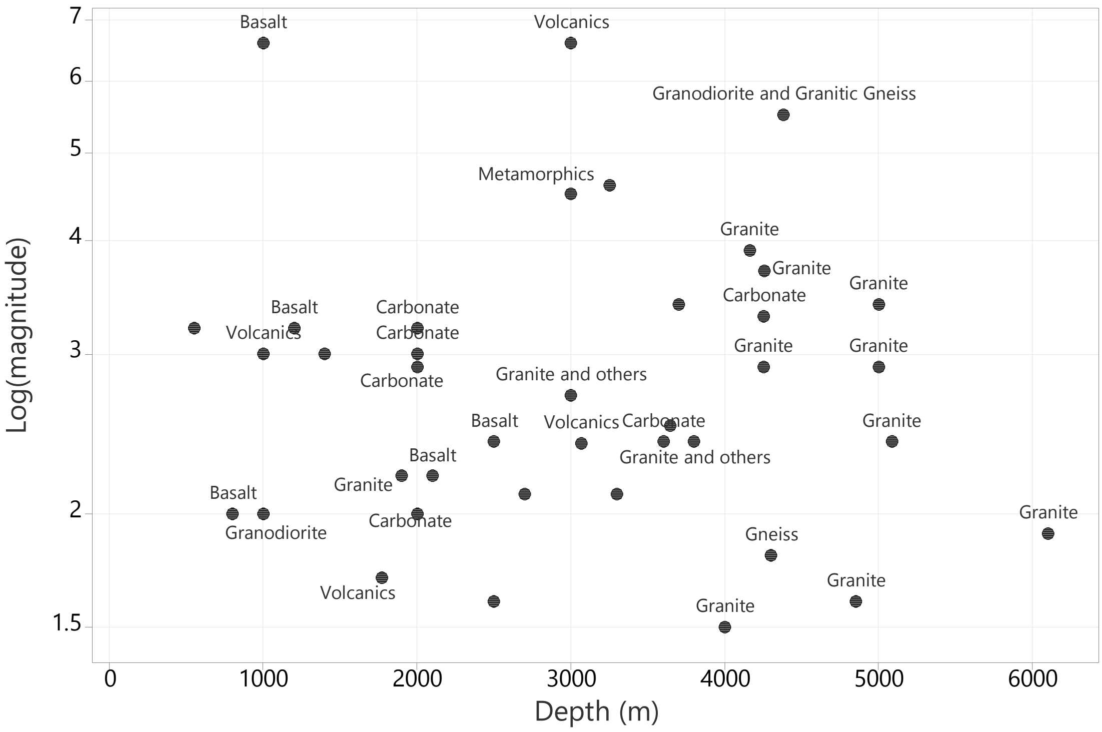


Figure 4.35. Log magnitude of an event of induced seismicity against depth of geothermal well with labels indicating lithology (data from HiQuake, 2021)

Similarly, the next figure plots the log magnitude of an event of induced seismicity against depth, with data point labels indicating the stage of the geothermal process. It appears that induced seismic events in deeper wells were predominantly caused by injection (with some by stimulation).

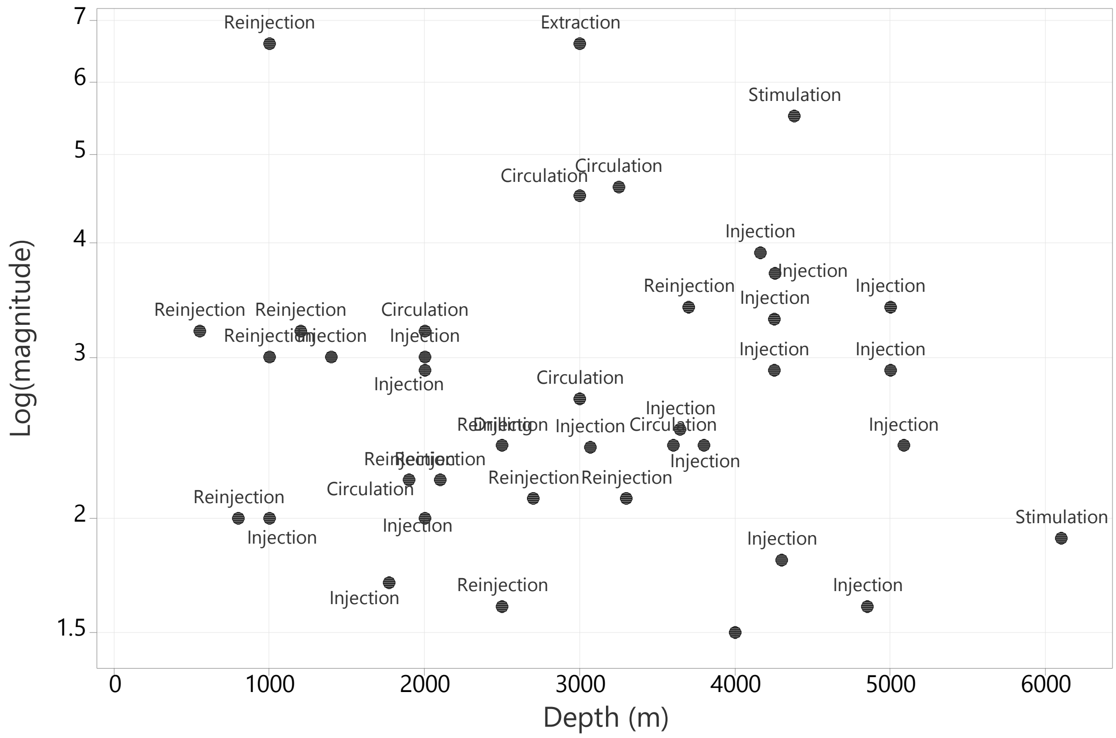


Figure 4.36. Log magnitude of an event of induced seismicity against depth of geothermal well with labels indicating process stage (data from HiQuake, 2021)

Our simple risk model and qualification of the association among induced seismicity and characteristics of a geothermal well and process stage concludes our effort to formulate a framework for risk assessment of induced seismicity in the case of deep geothermal drilling.

4.7. Noise risk assessment

The noise risk assessment considers the noise produced by (1) the operation of drilling equipment at the site and (2) the movement of trucks to and from the site.

4.7.1. Noise from road traffic

Road transportation contributes significantly to environmental noise (Skrúcaný et al., 2017). Traffic noise emitted by motor vehicles is difficult to eliminate and may lower property values (Kulauzović et al., 2020).

The noise emitted by a vehicle is influenced by two types of factors (Skrúcaný et al., 2017). The first group includes engine noise and air flowing around and through the vehicle's cooling and ventilating system as it moves. The engine's construction; engine rotations; the vehicle's technical condition; and the exhaust manifold's tightness all contribute to this type of noise. The second group includes noise generated by the movement of the tires across the road surface (pavement). The intensity of this type of noise is affected by the make (size, type, pattern condition) of the tires, the materials used to construct the road pavement, and the vehicle speed. The level and frequency of the noise signal emitted by a highway are affected by weather conditions, with wet asphalt pavements amplifying higher frequencies (demo provided at https://mynoise.net/NoiseMachines/trafficNoiseGenerator.php).

The noise generated by traffic is between 50 and 95 decibels (Kulauzović et al., 2020). On heavily traveled roads, the equivalent sound pressure level may reach 75 to 80 dB over a 24-hour period. Vehicle noise is produced by the engine, the exhaust system, aerodynamic friction, vehicle-to-road interaction, and vehicle-to-vehicle interaction. Noise levels can also be raised by defective mufflers or other faulty equipment. With increased traffic volume, higher speeds, and more heavy trucks, traffic noise increases exponentially. A steep incline or overloading causes vehicle engines to work hard and raises traffic noise levels. Other more complex factors that influence traffic noise include lateral distance from the road, terrain, vegetation, texture of the (road) pavement, and man-made obstacles.

Skrúcaný et al. (2017) measured exterior noise levels for moving passenger vehicles and found that they ranged from a maximum of 77 dB to a minimum of 69.2 dB. The noise increased from about 69 to about 77.5 dBA as the vehicle speed increased from slightly more than 50 to slightly less than 100 km/h. The maximum sound level recorded on a cement concrete surface varied greatly depending on vehicle speed, ranging from 74.4 dB at 52 km/h to 79.5 dB at 75 km/h and up to 84.8 dB at 98 km/h. An increase in traffic speed of approximately 23 km/h resulted in an increase of approximately 5 dB in the maximum traffic noise level near the road. A change in road surface and a simultaneous reduction in vehicle speed from 98 to 75 km/h could reduce traffic noise by up to 7.6 decibels. Only at a traffic speed of 52 km/h was the sound level less than 70 dB at a distance of 50 m from the measurement point. At higher traffic speeds, the sound level at 50 m exceeded 70 dB, peaking at 77.4 dB for a road with a concrete cement pavement. Overall, Skrúcaný et al. (2017) discovered that measured sound levels were higher than the values declared in the vehicle's technical specifications.

In the EU, approximately 40% of the population is exposed to daytime road traffic noise with an equivalent sound pressure level greater than 55 dB, and 20% are exposed to daytime noise levels greater than 65 dB (Kulauzović et al., 2020). Over 30% of people are exposed to equivalent sound pressure levels greater than 55 dB at night, which disrupts sleep.

Kulauzović et al. (2020) measured traffic volume (i.e., traffic counts), vehicle classification, and noise on a straight section of road that was devoid of obstructions or inclinations and in which vehicles traveled at a constant speed. Vehicle detectors classified vehicles as bicycles, motorcycles, compact cars, passenger vehicles, delivery vans, cars with trailers, trucks, trucks with trailers, tractor trailers, and buses. The measurements lasted 21 days and tallied 33,005 vehicles, of which 5553 (16.8%) were trucks. Heavy vehicles were found to emit noise ranging from 80 to 110 dB, but on average well above dB. The following table shows the average noise values for legally loaded and overloaded trucks.

Table 4.11. Average noise levels for trucks (Kulauzović et al., 2020)

Type of truck	*Noise for legally loaded trucks (dB)*	*Noise for overloaded trucks (dB)*
Rigid truck	93.3	93.7
Truck with trailer	96	97.4
Truck with semi-trailer	95.8	96.9

The noise (dB) emitted by each type of truck as a function of its weight (in tons) was estimated using the linear regressions shown below (Kulauzović et al., 2020):

$$\text{Noise of truck} = 92.805 + 0.0413 \times \text{Weight of truck}$$

$$\text{Noise of truck with trailer} = 93.206 + 0.1245 \times \text{Weight of truck with trailer}$$

$$\text{Noise of truck with semi-trailer} = 94.367 + 0.0602 \times \text{Weight of truck with semi-trailer}$$

These findings are consistent with the maximum noise values (in A-weighted decibels or dBA) obtained from pass-by measurements performed by the Swedish National Testing and Research Institute (Jonasson, 1999) for various axle and wheel truck configurations. Maximum values exceeded 95 dBA and reached 98 dBA when a truck traveled at 81 km/h. Trucks that were overloaded generated an average of 1.5 decibels more noise than those that were legally loaded (Kulauzović et al., 2020). Overloaded trucks with trailers or semi-trailers were found to generate the most traffic noise.

4.7.1.1. Calculations for low traffic flow

The UK Department of Transport (1988) provides a correction for traffic flows of 50 to 200 vehicles per hour, but the traffic volume at a typical geothermal drilling site is likely to be even lower.

An instance of noise calculation at a hypothetical distance of 10 m from a road, with traffic flow of 60 heavy trucks per hour (i.e. one per minute), assuming a single road segment with no gradient, is shown below.

$$\begin{aligned} &\text{Basic noise level } L_{10} \text{ in dBA} \\ &= 42.2 + 10 \times \log_{10}(Q) \\ &= 42.2 + 10 \times \log_{10}(60) \\ &= 60 \text{ dBA} \end{aligned}$$

$$\begin{aligned} &\text{Correction for a mean traffic speed of 60 km/h and 80\% heavy vehicles} \\ &= 33 \times \log_{10}(V + 40 + 500/V) + 10 \times \log_{10}(1+5\times P/V) - 68.8 \\ &= 33 \times \log_{10}(60 + 40 + 500/60) + 10 \times \log_{10}(1 + 5 \times 80/60) - 68.8 \\ &= 7.2 \text{ dBA} \end{aligned}$$

$$\begin{aligned} &\text{Correction for low traffic volume} \\ &= -16.6 \times \log_{10}(D) \times \log_{10}(C)^2 \\ &= -16.6 \times \log_{10}(3) \times \log_{10}(0.3)^2 \\ &= -2.2 \text{ dBA} \end{aligned}$$

$$\text{Sound pressure level (at 10 m from the road)} = 60 + 7.2 - 2.2 = 65 \text{ dBA}$$

Symbols and values are as follows:

Q: traffic flow = 60 vehicles/h
V: velocity = 60 km/h
P: percentage of heavy vehicles = 80%
D: dimensionless correction = 30/shortest slant distance (i.e. connecting line)

between reception and source = 30/(10 m) = 3
C: dimensionless correction for 60 vehicles/h = Q/200
= (60 vehicles/h) / 200 = 0.3

Using the UK Department of Transportation's methodology, the noise level at 10 meters away from the road is predicted to be 65 dBA. That is a much lower level of noise than what is produced by the operation of machinery at the drilling site.

4.7.1.2. Calculations for stationary trucks

There are over ten guides for modeling road traffic noise (WRA, 2019). Unfortunately, no traffic noise modeling procedure, including those recommended by the French noise guide (AFNOR, 2011), can be used to estimate the noise generated by trucks at extremely low traffic volumes, such as those found near geothermal drilling sites.

Assuming a truck weight of 10 t, the noise for each type of truck, according to the previous equations, is:

$$\text{Noise of truck} = 92.805 + 0.0413 \times 10 = 93.2 \text{ dB}$$

$$\text{Noise of truck with trailer} = 93.206 + 0.1245 \times 10 = 94.5 \text{ dB}$$

$$\text{Noise of truck with semi-trailer} = 94.367 + 0.0602 \times 10 = 95 \text{ dB}$$

As a result, a (legally loaded) truck is assumed to emit a sound pressure level of 95 dB. This will be included as a stationary noise source in the noise model (since no traffic noise models may be used for very low traffic volumes).

4.7.2. Noise model

The following equipment is assumed to operate at the specified noise levels in order to obtain a quantitative estimate of the maximum noise generated during the operation of a single (typical) geothermal well. During calculations, decibel (dB) values are converted to dBA.

Table 4.12. Noise levels for indicative equipment and operations in the vicinity of a drilling well

Operation/ equipment	*Height (m)*	*Noise level (dB or dBA)*	*Comments*
Diesel generator (with silencer)	2	55 dB	Four (4) per well were assumed
Pneumatic drill	2	130 dB	Two (2) per well were assumed
Flame torch	2	120 dB	Two (2) per well were assumed
Mud drilling	0	85 dBA	Noise source is underground
Air drilling	0	85 dB to 120 dB	Two noise levels correspond to scenarios with or without suitable silencers; noise source is underground
Changing wellhead master valves	0	125 dBA	Not operating concurrently with drilling; noise source is underground
Discharging well	0	120 dB	Assumed to operate at end of drilling; noise source is underground
Operation of (other) heavy machinery	3	90 dBA	Assumed to operate during all phases

The above noise sources are assumed to be operating in an area of approximately 15×15 m. Noise calculations were performed using the dBmap.net Noise Mapping Tool (https://noisetools.net/dbmap), which adheres to ISO-9613 for noise propagation outdoors.

Due to the fact that the two pneumatic drills (at 130 dB) produce more noise than changing the wellhead master valves or discharging the well, these two operations are disregarded in favor of the drilling phase. The following figure depicts the approximate layout of noise-generating machinery, as well as the noise levels (in dBA) near a hypothetical geothermal well. The observed levels, ranging from 95 to more than 110 dBA, necessitate protection even for brief exposure.

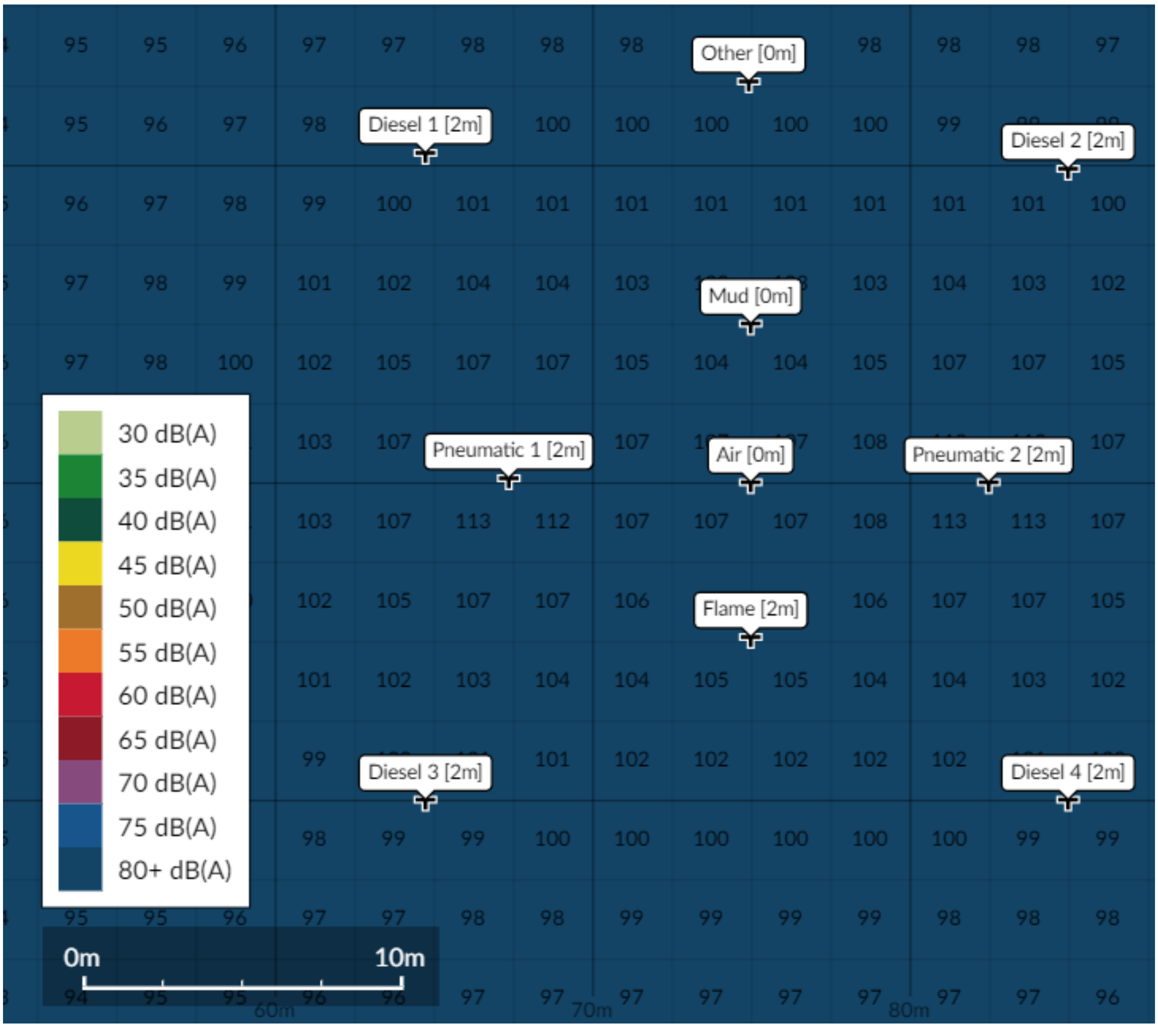


Figure 4.37. Layout and noise levels in the immediate vicinity of the geothermal well

The following figure depicts the noise levels at a greater distance from the drilling well (without any buildings nor any noise barriers). At a distance of about 1 km from the well, it is observed that around 60 dBA are reached, which is a level compatible with normal daytime noise levels.

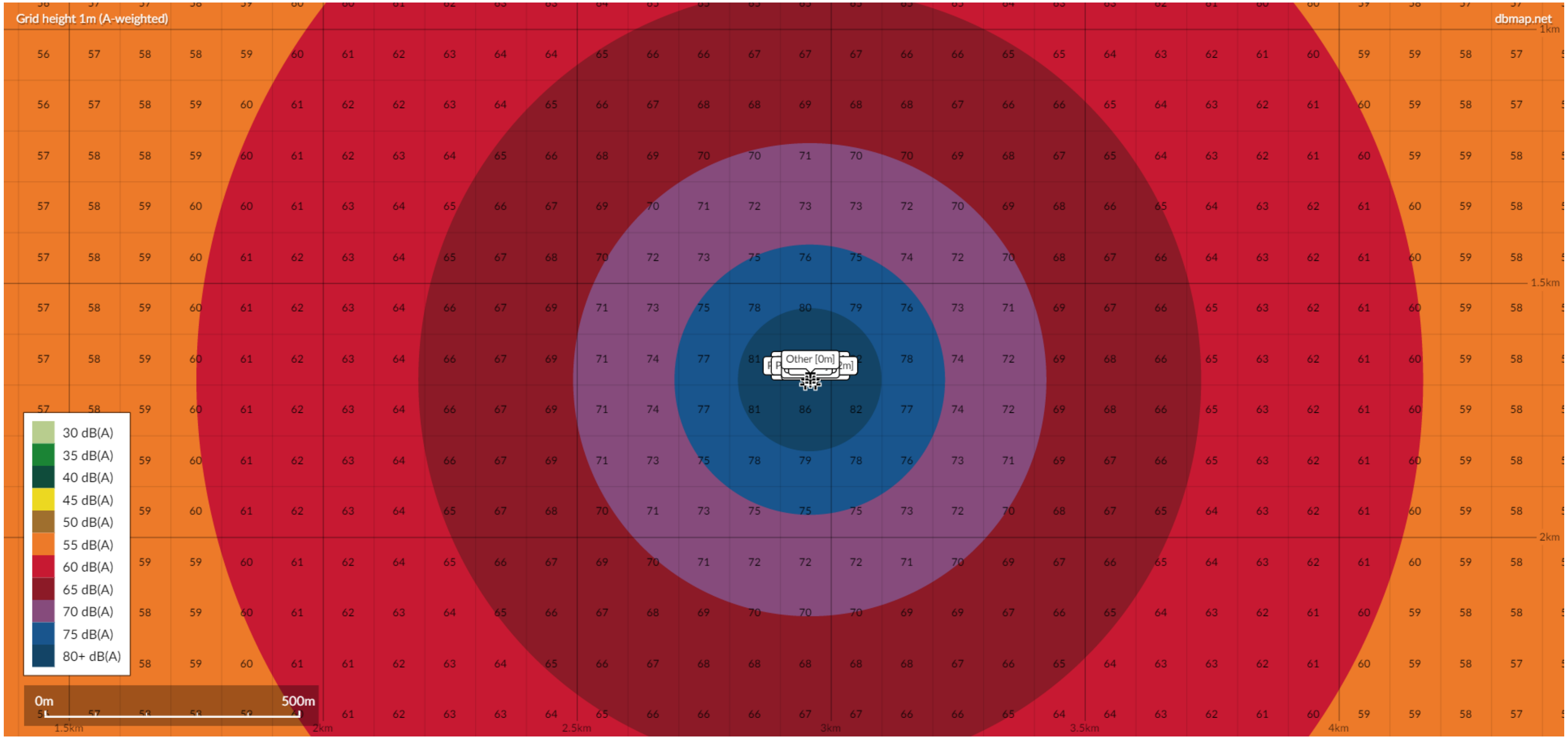


Figure 4.38. Layout and noise levels at greater distances from the geothermal well

In the following figure, a 35×15 m, 4 m high structure is placed approximately 20 m from the drilling well.

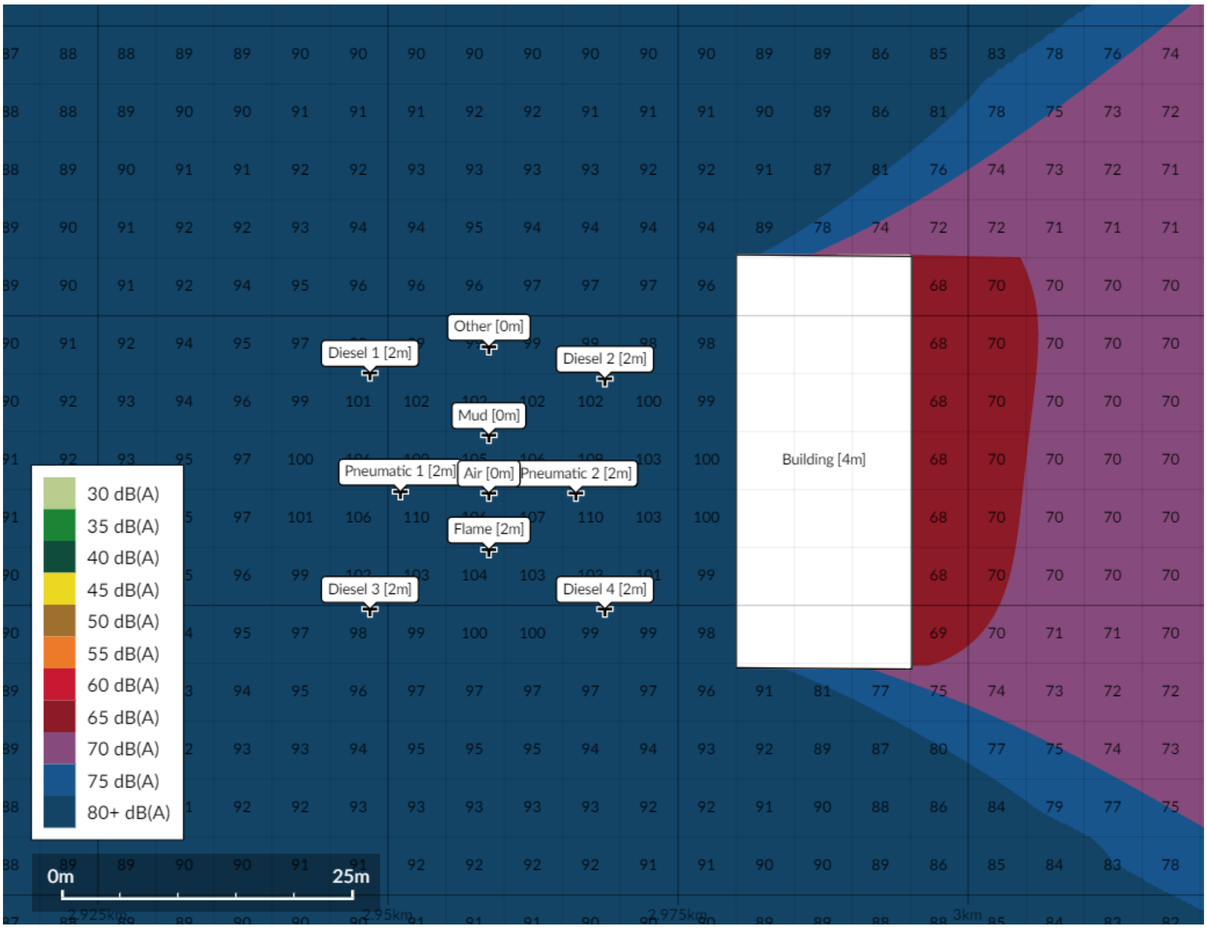


Figure 4.39. Placement of a building near the geothermal well

As illustrated in the following figure, such a structure would dampen noise levels behind it to around 60 dBA at approximately 300 meters. At a distance of more than 2 km from the geothermal well, a level comparable to the noise expected at night (below 50 dBA) would be observed. If the drilling site is close to a populated area, this may not be enough attenuation.

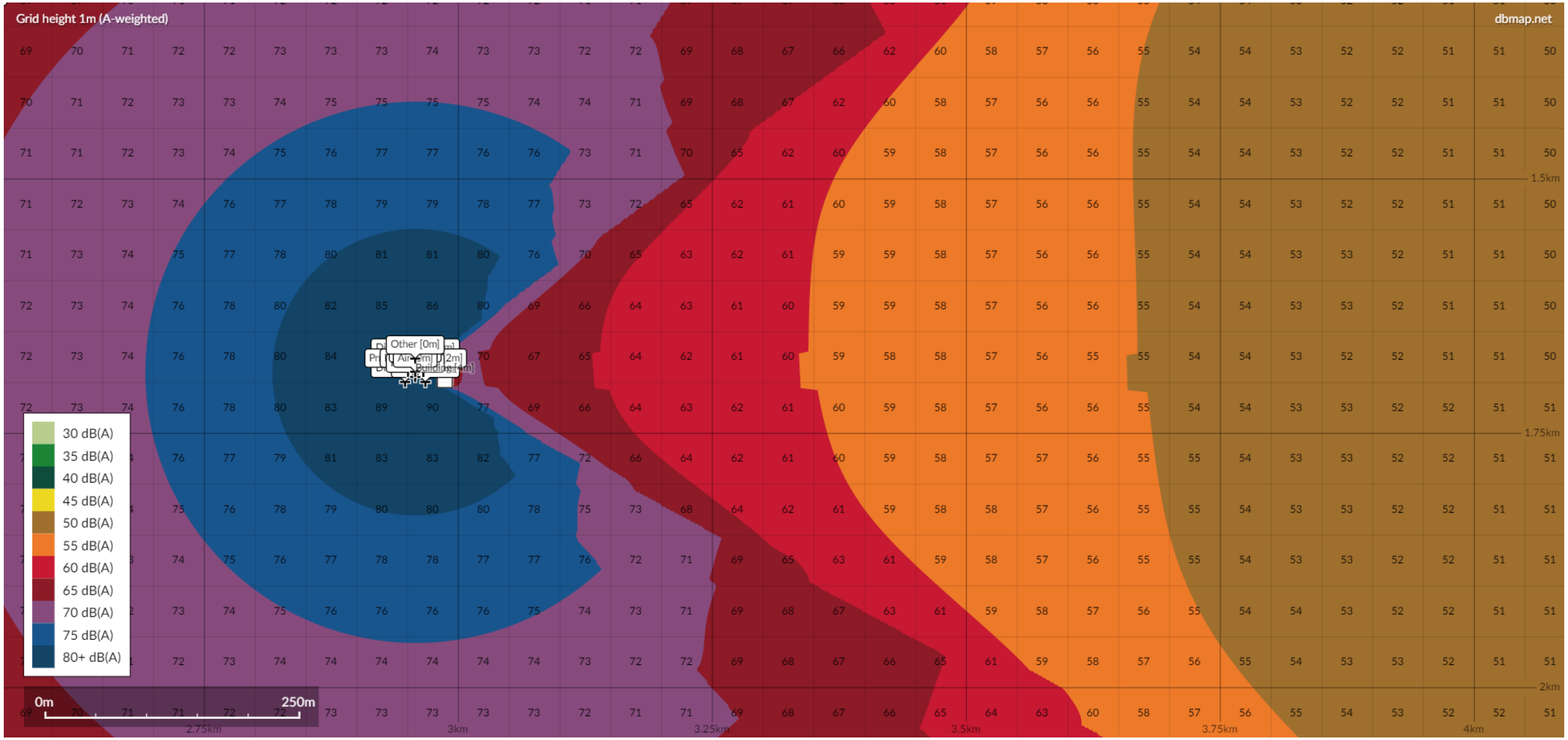


Figure 4.40. Noise levels behind the building

In the following figure, a 6 m high noise barrier (sound wall) is added about 5 m behind the building.

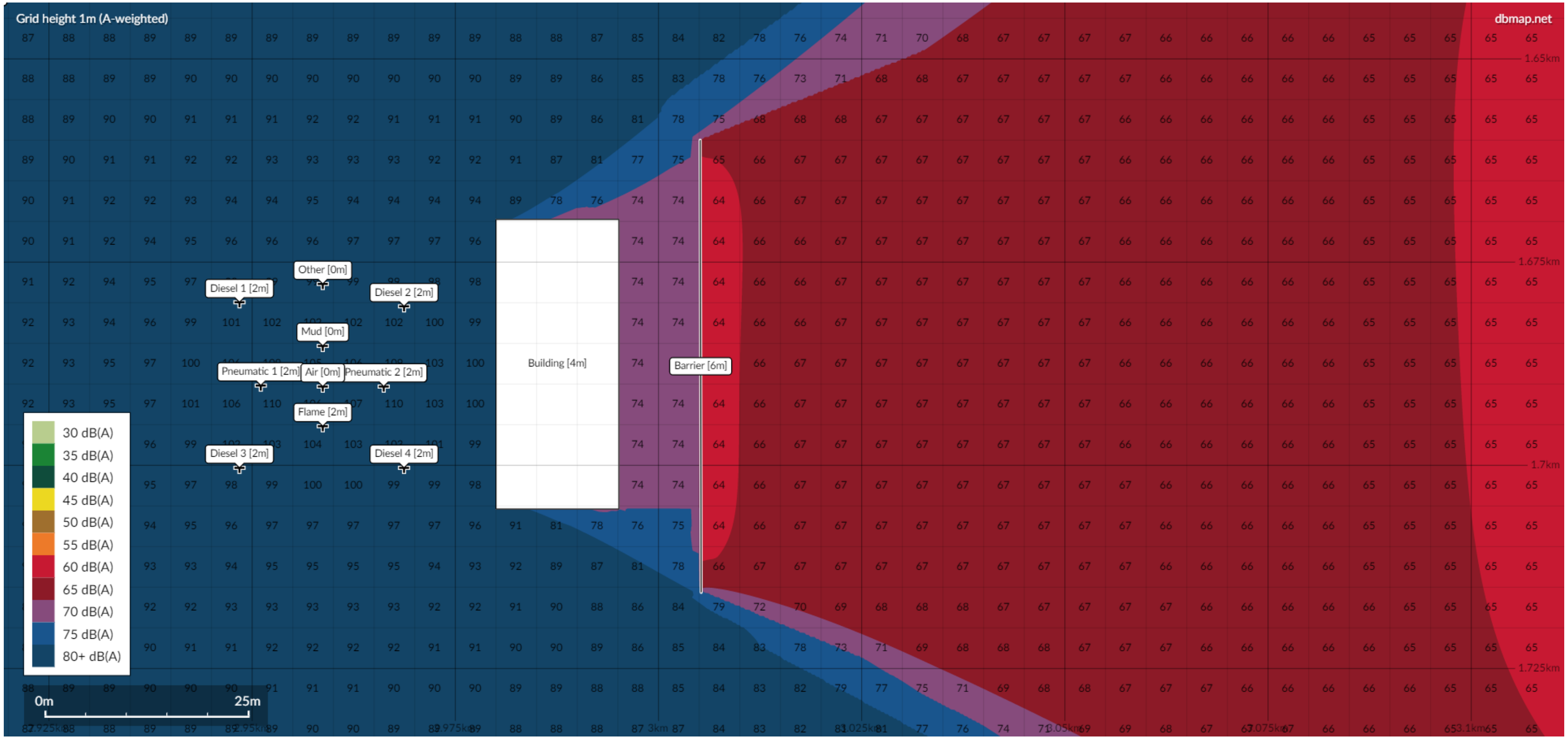


Figure 4.41. Addition of a sound barrier behind the building

As illustrated in the following figure, placing such a noise barrier behind the building would significantly reduce noise levels behind it, reaching levels below 55 dBA beyond 500 m.

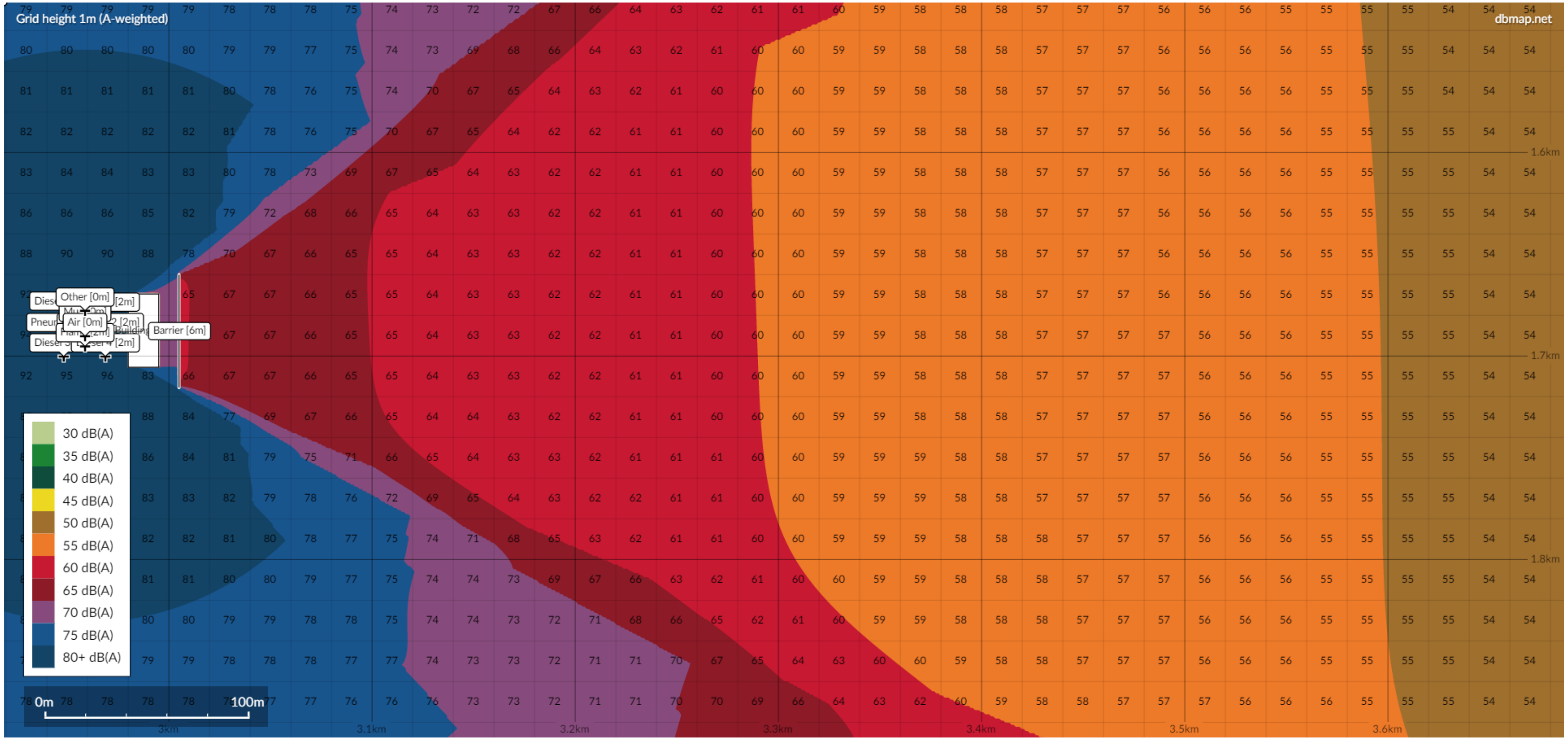


Figure 4.42. Noise levels behind the building and the sound barrier

A sound barrier alone (without the building) would reduce noise levels to 50 dBA at a distance of 1 km (simulation not shown). Although higher (and wider) noise barriers could produce better results, the construction of sound barriers taller than 6 m is unusual and technically more challenging.

A final simulation is run with the addition of a truck modeled as a stationary source emitting 95 dB approximately 30 m behind the sound barrier, as illustrated in the following figure.

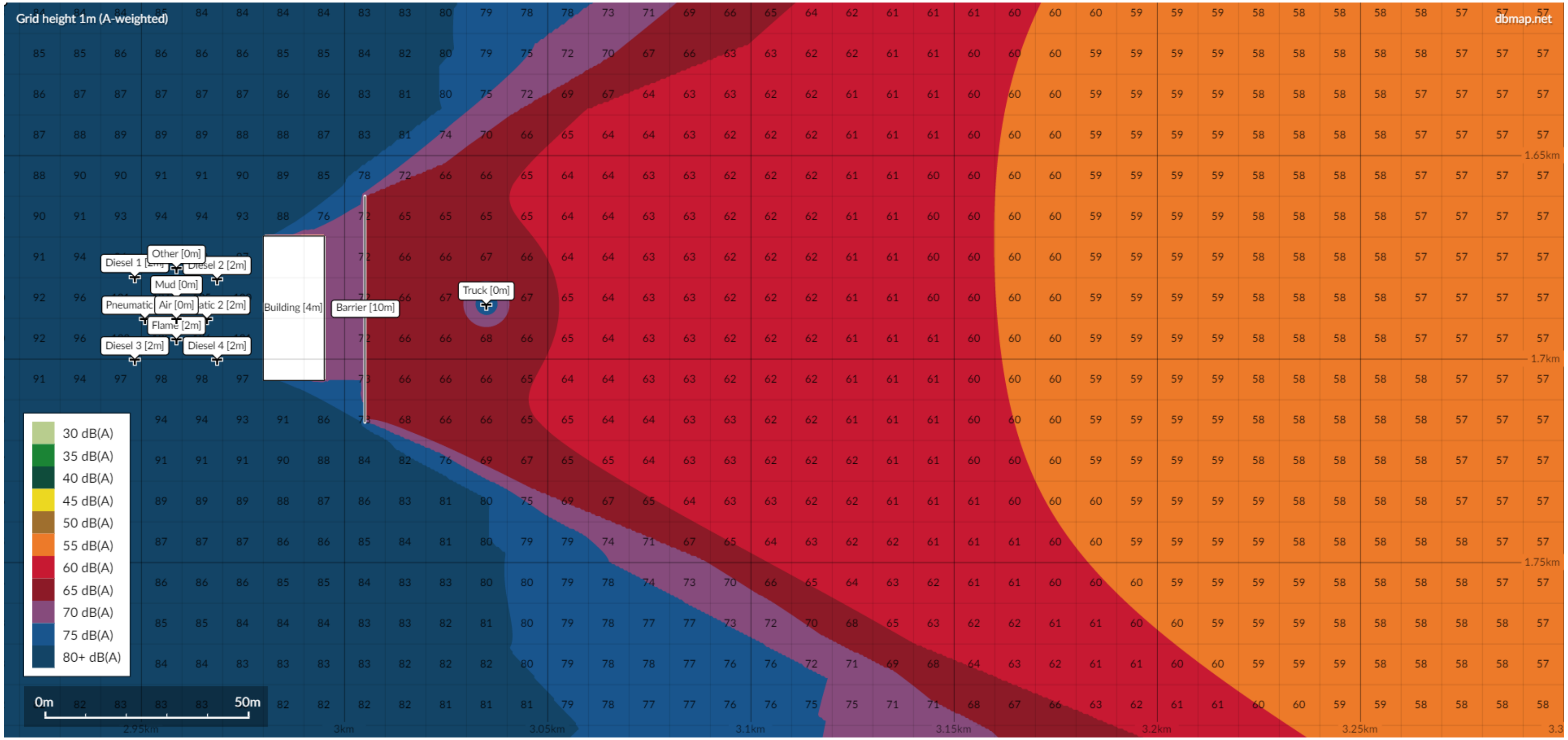


Figure 4.43. Noise levels behind the building, the sound barrier, and the truck

The truck has no effect on the simulated noise levels at longer distances, but it is a (relatively minor) annoyance in its immediate vicinity.

4.7.3. Summary

The following table summarizes the results of the noise model simulations.

Table 4.13. Summary of results of noise model

Distance	*Noise (dBA) without structures*	*Noise (dBA) behind building*	*Noise (dBA) behind building & sound barrier*	*Noise (dBA) with truck behind building & sound barrier*
10 m	107	–	–	–
100 m	84	67	62	62
500 m	70	58	55	55
1 km	62	52	51	51

The following conclusions are drawn from these simulation results:

- The presence of buildings and sound barriers is likely to reduce noise levels by more than 20 decibels (dBA) at a distance of 100 meters. This represents a significant reduction in noise levels, bringing them closer to those experienced during a busy day in a city center.
- At a distance of 1 km, noise barriers are unlikely to contribute significantly to noise reduction as long as buildings are located near the well.

Low volume truck traffic will generate some noise in the vicinity of the road, but will have no effect on noise levels further away.

4.8. Ecological Footprint Assessment

Ecological Footprint Assessment (EFA) is a scalable accounting system with a wide range of applications regarding resource consumption. It can be applied to individuals, cities, regions, countries or the global population, as Wackernagel, Beyers and Rout (2019) explain. EFA complements the LCA study from a biocapacity perspective expressed in global hectares.

EFA was developed during the 1990s by Wackernagel and Rees in Columbia University. It is a tool that aims to quantify in ecological terms the human activity in the biosphere. It determines the extent of land required for the production of all raw materials that are needed for human activities, including waste production and treatment. The biocapacity of an area is always to be accounted for the development of better environmental management policies. The biocapacity of ecosystems varies according to site type and specific conditions. The metric unit used for calculations is the global hectare (gha) which equals to a hectare of land with the average biocapacity factor.

EFA is based in six assumptions, as Wackernagel et al. (2002) explain:

a. “It is possible to keep track of most of the resources humanity consumes and the wastes humanity generates.

b. Most of these resource and waste flows can be measured in terms of the biologically productive area necessary to maintain these flows (those resource and waste flows that cannot are excluded from the assessment).

c. By weighting each area in proportion to its usable biomass productivity (that is, its potential production of biomass that is of economic interest to people), the different areas can be expressed in standardized hectares. These standardized hectares, which we call ‘‘global hectares,’’ represent hectares with biomass productivity equal to the world average productivity that year.

d. Because these areas stand for mutually exclusive uses, and each global hectare represents the same amount of usable biomass production for a given year, they can be added up to a total representing the aggregate human demand.

e. Nature’s supply of ecological services can also be expressed in global hectares of biologically productive space.

f. Area demand can exceed area supply. For example, a forest harvested at twice its regeneration rate appears in our accounts at twice its area. This phenomenon is called ‘‘ecological overshoot’’.

EFA’s pillar is the sentence that adequate resources should be left for the future generations. Sustainable development attempts to change the present unsustainable trend in the consumption of resources. The aim of this section is to measure and determine the material flow and operations ecological footprint during the drilling stage of geothermal well development.

In calculating the ecological footprint of an individual geothermal well drilling stage, it is possible to determine the amount of the land that it is required to provide it with natural resources. These resources are needed for certain activities and absorption of all the waste and emissions that are produced during drilling operations. By calculating the ecological footprint of geothermal drilling operations, it is possible to determine the extent that ORCHYD can be environmentally sustainable.

For the implementation of EFA in a geothermal drilling operation, metrics and methodology of quantification are required. In this section, the carbon footprint results of the LCA will be used for the determination of the ecological footprint of drilling operations using the proposed technique by ORCHYD. All calculations are based on carbon sequestration of forest areas. Different forest areas present different carbon absorption values.

For this assessment, values proposed by EPA Victoria (2005) are used. It is important to note that, in the developed scenario, a similar to GPK-3 well examined in LCA is developed in Australia. A weighted average world carbon absorption value has been calculated to be 1.3 tons of carbon per hectare. The percentage of carbon absorbed by the oceans is considered 30.8%. The footprint of 1 ton of CO_2 in global hectares is 3.737929 tCO_2/gha/yr.

For all the 8 scenarios developed within the LCA, the ecological footprint is illustrated in Table. 4.14. A comparison between the examined 8 scenarios is illustrated in Fig. 4.42.

Table 4.14. Total ecological footprint of the examined LCA scenarios

Scenarios	*Total kg CO_2 eq*	*Footprint of total CO_2 in global hectares*
1	9078519.47	33934.86
2	5380467.89	20111.81
3	4640857.58	17347.20
4	4147784.03	15504.12
5	3795588.65	14187.64
6	3531442.10	13200.28
7	3325994.79	12432.33
8	3161636.95	11817.97

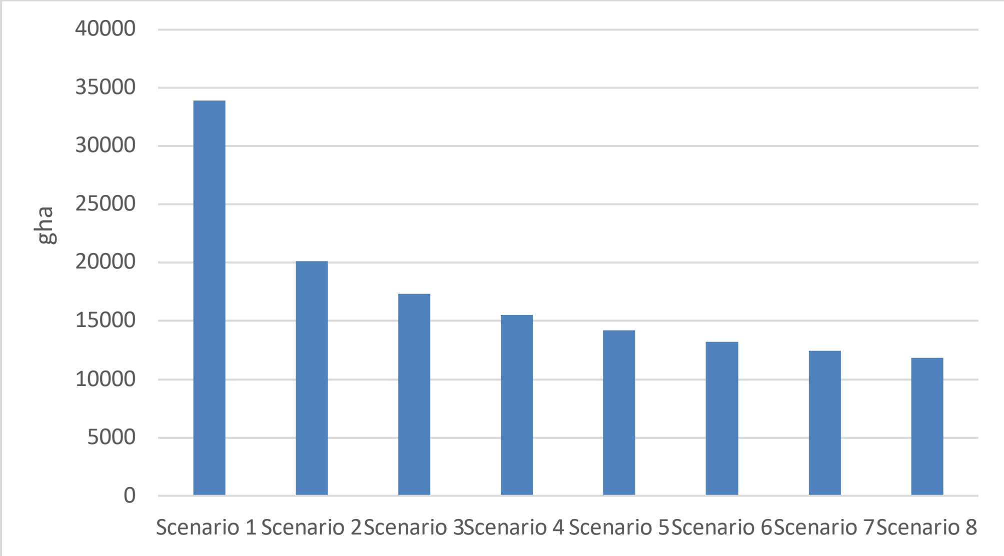


Figure 4.41. Footprint of total CO_2 eq emission in global hectares for all 8 scenarios examined in LCA

Examining the results of EFA for all 8 scenarios developed within LCA study, it is shown that the ecological footprint declines linearly with the CO_2 eq. emission. This yields a total footprint of 33,934.86 global hectares using conventional technology and a range between 20,111.81 and 11,817.97 global hectares respectively for the minimum and maximum ROP enhancement aimed by ORCHYD.

This allows the conclusion that the implementation of ORCHYD can lead to a drastic reduction of the ecologic impacts produced by conventional drilling technologies.

5. Proposed mitigation measures

This concluding section of the report focuses on prevention and mitigation measures. The proposed measures are based on the literature and aim to reduce (the probability and magnitude) of negative (adverse) impacts while increasing (the probability and magnitude) of favorable (positive) impacts.

The proposed mitigation measures (covering monitoring and control) are categorized per the conceptual model of the environment presented in Section 1.1 and followed in Section 3. Such a conceptual approach agrees with the published literature, e.g., based on previous studies, Dhar et al. (2020) confirmed that the significant environmental effects of geothermal energy development and use are divided into the three abiotic spheres (atmosphere, lithosphere, and hydrosphere) and the biosphere.

The proposed mitigation measures are tabulated in Table 5.1 that appears towards the end of this section.

5.1. Lithosphere

5.1.1. Soil subsidence

Previous studies by Kagel, Bates and Gawell (2007) and Shortall, Davidsdottir and Axelsson (2015) mentioned that soil subsidence may result from geothermal plants, when the reservoir pressure declines after fluid withdrawal, which results in a slow, downward sinking of the soil surface.

The (re)injection of fluids in the geothermal reservoir is an efficient way of mitigating soil subsidence in geothermal systems, compensating for mass deficit and pressure decline induced by fluid extraction. A properly placed reinjection well can reduce potential subsidence by maintaining reservoir pressures (Kagel, Bates and Gawell, 2007). Incorporating reinjection into reservoir management from the start can minimize the risk and prolong reservoir life.

If the prevention by reinjection is not enough and ground deformation appears, the best recovery measure is to reduce the rate of geothermal fluid extraction or raise the re-injection temperature. Compliance with regulations for site selection and improvements in construction methods can reduce potential landslide risks.

5.1.2. Induced seismicity

Although induced seismicity in geothermal drilling is related to small-magnitude earthquakes, which pose zero to minor threat of physical damage to infrastructure. such earthquakes shape a negative public perception. Quantifying public tolerance to such events is a challenging issue that we assess as part of the D.3.2. Engaging with the local population and securing its support, based on benefits for communities and the environment, would benefit any geothermal drilling project. The implementation of a (widely publicized) in-situ traffic lights system (TLS) for the quantification of risk may help assure local communities for the safety of operations.

The development of systems capable of controlling seismicity has not yielded solutions that can be applied in most cases. Furthermore, the numerical quantification of induced seismicity risk is challenging, and it includes a wide range of subjective factors. When risk to humans and infrastructure is identified, strengthening measures are preferred to attempting to ensure that some threshold on earthquake magnitude or ground-shaking amplitude is not exceeded (Bommer, Crowley & Pinho, 2015). Mitigation measures for induced seismicity are categorized into direct and indirect:

- Direct mitigation measures refer to direct technological intervention, such as adjusting the injection or production rates (based on TLS, as explained in the corresponding section).
- Indirect mitigation measures may refer to incentives for the communities in the proximity of drilling operations, such as increased outreach concerning seismic monitoring, attracting community support, and development of compensation schemes.

Mitigation measures are connected to seismicity risk, which was described in the previous section. Bommer, Crowley & Pinho (2015) developed three different mitigation measures scenarios, which are discussed in the following subsections.

5.1.2.1. Scenario 1 – Risk of public disturbance by the seismic events

In this scenario, induced seismicity by geothermal drilling is assumed to pose the risk of public disturbance due to small-magnitude earthquakes. There is no risk of damages, injuries, or fatalities.

As a first step, the developers should communicate the benefits of the development of a geothermal plant. If local communities can accept the risk, a monitoring network and a TLS should provide adequate protection for the local population and operations.

However, if permissible thresholds are exceeded during drilling operations, the developers may be forced to terminate the project and suffer critical economic losses. If the local community is not willing to accept the risk, then relocation or termination of the project may need to be considered.

5.1.2.2. Scenario 2 – Risk of minor damages

In this scenario, induced seismicity by geothermal drilling is assumed to pose the risk of non-structural damage to a community's infrastructure. There is no risk of injuries or fatalities.

To set up a publicly acceptable compensation scheme, the project developers should conduct a baseline building survey in the area doubled by a feasibility study. A monitoring network and TLS should protect the local population and operations if the project can proceed with public acceptance.

Again, if permissible thresholds are exceeded during drilling operations, the developers may be forced to relocate or terminate the project.

5.1.2.3. Scenario 3 – Risk of structural damage and injuries

In this scenario, induced seismicity by geothermal drilling is assumed to pose the risk of structural damage and injuries to a community.

Developers should consider relocating the project. If this is not feasible, then they should consider relocating the population. If this is not feasible, relocating only the people at greater risk, and making global and element-type structural interventions in (selected) buildings should be conducted.

In any other case, geothermal drilling should be terminated.

5.1.3. Groundwater contamination

Preventive and corrective measures should be considered related to the risk of aquifer contamination.

Preventive measures include the following:

- Optimal well design is fundamental for minimizing adverse effects on groundwater aquifers. A first step would be the choice of appropriate drilling muds which will limit losses of fluids and materials into the formation. Extensive discussion concerning the drilling fluids is conducted in the corresponding chapter. Secondly, an appropriate cementation program should ensure that the borehole is isolated from the surrounding formations during the drilling and construction of the well. Cementation should be planned and executed according to site specific conditions, such as temperature and pressure regime, wellbore geometry and formation characteristics. This would minimize the possibility of groundwater contamination at first place.
- This should be coupled with monitoring of the cementation and tubing processes; control of casing and tubing conditions; monitoring of reservoir behavior; and maintenance operations, which will contribute to preventing and mitigating aquifer interconnection and contamination.
- Injection of an anticorrosion inhibitor is also a prevention method done at the surface and downhole production wells.
- The sealing of the well through its entire life cycle can be ensured by appropriate drilling work (cementation and casing).

Corrective actions intended to confine or stop potential leakages are implemented through direct well operations and work-over, using a patch or new casing.

Regarding well decommissioning (although not directly related to the work carried out in ORCHYD), any aquifer contamination risks relate to the conception and implementation of plugs. Casing and cementing processes need to correspond to the characteristics of the fluid as well as the thermal and mechanical constraints encountered.

Working with qualified professionals (driller, manufacturer, etc.) and understanding the local geological and hydrogeological context are critical elements for the mitigation of environmental risks during geothermal operations.

5.1.4. Generation and management of liquid and solid wastes

Liquid wastes (i.e., wastewater) from drilling operations may be either collected (in basins, tanks, and areas segregated from other materials and equipment) for further processing or connected to sewage (to avoid dumping into the natural environment). Reserve pits are usually excavated adjacent to the well site for the disposal of liquid wastes. Solids within liquid wastes settle fast, permitting the implementation of accelerated drying methods for the reclamation of the open reserve pits sites for further use. Management of drilling mud wastes is extensively presented in the corresponding chapter.

As regards solid wastes, Kagel, Bates, and Gawell (2007) and Bayer et al. (2013) have argued that the total amount of solid wastes from geothermal plants is minor and, as a result, is not of environmental concern.

Wastes (inert, wood, metal, cartons, plastic, etc.) are collected and placed in appropriate containers and/or bins. Selective collection is mandatory in several countries of Europe for industrial working sites. Storage units are labeled and placed over containment basins or slabs before being disposed from the site, to avoid leakage and contamination of the soil.

Depending on the waste type (e.g., packaging, rubber, lubricant oil, chemicals, scrap metal, timber), the site contractor will manage waste recycling or disposal towards the appropriate treatment plant or landfilling site, to limit the impact on the environment and humans.

According to the European Directive on waste and repealing certain Directives (Directive 2008/98/EC), waste producers are responsible for their waste from production to recycling and/or disposal. They must ensure that contractors for cleaning and disposal are certified and able to do the job correctly.

Hazardous wastes (such as oils and batteries) are stored in segregated and labeled containers. There must be a specific storage area at a site, and licensed waste management plants and carriers must be appointed.

5.1.5. Land use

Land use is influenced by the type and extent of development and original use. The planning phase of geothermal development should consider the related characteristics (national parks, site productivity, forest conservation areas, tourist areas, cultural value) of geothermal sites.

Combining geothermal systems with other renewable resources (if possible) is one way of reducing the land footprint and allow energy production, which could be utilized for different purposes. Solar and wind energy (in particular) can be co-located with geothermal plants to enhance geothermal reservoirs by supplying heat (solar) or power for pumping (wind) to the fluid injection system that replenishes the reservoir (Cardemil et al., 2016; McTigue et al., 2018).

5.1.6. Visual intrusion

Starting from the drilling phase, geothermal development brings about some damages to the landscape, caused by (unpaved and paved) roads; well pads; pipe routes; separator stations; holding ponds; the powerhouse, and associated facilities.

The visual footprint, especially during the initial stages of geothermal development and operation, mainly consists of imposing drilling machines, with fences around the site, and (movement of) different types of trucks and other vehicles. The construction of roads and civil works should be carefully organized to minimize adverse visual effects as well as avoid accelerated erosion and minimize landslide risks (e.g.by reducing the number of steeply sloping exposed banks or planting fast-growing trees that bind the soil). Commonly, companies utilize the same drilling site for several (deviated) wells, a practice that tends to lessen visual intrusion. In the same spirit, it is advantageous to locate drilling sites as close as possible to the power plant.

Drilling sites operate 24 hours/day for at least 4 to 6 months. The sites are brightly lit and visible during the night, so light pollution could conceivably impact humans especially if they are located relatively close to a housing estate. Reduction of the brightness of lights at a site during the night; choosing the type, direction, and location of lamps (so that they project less light outside the drilling sites without compromising safety); and using temporary screens around the drilling sites should also be considered. The wellheads (“Christmas Trees”) may be masked with a suitably designed cover (provided it allows better maintenance and provides for the security of the structure).

However, visual intrusion is mostly temporary, depending on the duration of drilling operations. An increased ROP will shorten the time it takes to drill to the depth of the geothermal resource, leading (among other favorable impacts) to a reduction of the duration of visual intrusion.

5.2. Hydrosphere

5.2.1. Water consumption

A standard method to reduce water consumption during drilling is the recirculation of drilling mud and the quick plugging of mud losses zones. A successful drilling mud program also minimizes loss of water in the formation.

Freshwater consumption may also be reduced by using meteoric water collected and stored in containers (and used to prepare mud and cement slurry during drilling).

Discharged geothermal fluids or low-quality water may be used to support cooling as well as make-up fluid. In some projects, surface water (like canal water) may be used for drilling, after checking its quality to avoid the risk of polluting drinking water aquifers.

Another way to reduce water consumption could be a dry cooling system. Adding a dry cooling tower can minimize the water consumption by over 75%, compared with a wet recirculation cooling system (Bosnjakovic, Stojko & Jurjevic, 2019).

5.2.2. Water pollution

Simple measures to reduce water pollution include controlling water spills to the soil and local aquatic systems; and preventing the connection of contaminated zones and aquifers.

5.3. Atmosphere

5.3.1. Greenhouse gas emissions

Emissions from fossil-fueled engines, regulated by the European Directive 2010/75/EU on emissions of carbon dioxide for industrial activities, are strictly controlled and monitored.

As shown by the LCA carried out in this report (Section 4.5), ROP enhancements shorten the length of drilling operations, yielding a reduction in diesel consumption. This has a direct positive effect on greenhouse gas emissions.

Connection to the local electrical grid and/or alternative power supply (produced from local renewable electricity or nuclear electricity) improves the environmental performances of a geothermal system.

The use of modern techniques and tools can reduce negative environmental impacts associated with the release of chemical effluents from geothermal operations, some of which may contribute to climate change. Standard practices (like installing drift eliminators, filters, and blowout preventers) have been used in geothermal facilities worldwide (Kagel, Bates, & Gawell, 2007). Binary and flash binary geothermal plants exhibit significant potential of reducing emission, oftentimes emitting no non-condensable gas, and negligible amounts of particulate matter (Kagel, Bates, & Gawell, 2007; Glassley, 2015; Shortall, Davidsdottir, & Axelsson, 2015).

5.3.2. Local air pollution

Local air pollution refers to the smog produced by the transport of equipment and materials, and any other operations of vehicles, and it is examined within the LCA (Section 4.5).

Enhancement of ROP affect positively the local air pollution, which reduces with the shortening of the duration of drilling operations and corresponding energy consumption.

For a further reduction in local air pollution, it is proposed that vehicles of the EURO VI category (Regulation [EC] No. 595/2009) should be utilized. Euro VI standards have been applied to all new diesel and gas engines since 2013. The emission limits have been changed, the durability provisions have been expanded, and several significant new elements have been added.

5.3.3. Odors (degassing)

Preventive and mitigation measures for degassing consist of adopting technologies to avoid the release of gases into the atmosphere.

Accidental emissions during the drilling phase maybe prevented by installing blowout preventers and expansion vessels. Expansion vessels are tanks used for the maintenance of pressure within permissible limits, so that evaporation of the liquid system within the circuit is prevented.

5.3.4. Noise

Noise is a peculiar environmental concern, in the sense that as soon as a source stops emitting noise, most of its impacts also disappear (with the exception of, e.g. long-term health impacts).

Directive 2002/49/EC (https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2002:189:0012:0025:EN:PDF) regulates the assessment and management of environmental noise, and provides a basis for the development of short, medium, and long term measures concerning noise emitted by industrial and other activities and equipment. Selected common noise indicators are L_{den} (to assess annoyance) and L_{night} (to assess sleep disturbance). Strategic noise mapping and action plans are proposed as a basis for the development of measures for the mitigation of noise.

The quantification of noise levels around a drilling well showed that workers need protection near the well. Without any interventions, noise levels are expected to fall to those expected during the daytime in an urban area (around 55 to 60 dBA) at a distance of at least 600 m from the borehole.

If inhabited areas are near a drilling well, the existence of buildings will likely attenuate noise levels to those tolerated during the nighttime (around 45 dBA, to allow around the clock operation) at the distance of approximately 500 m. If more attenuation is desired, sound barriers must be located near the well. Ideally, drilling (and related mechanical equipment) should be distant from dwellings and related human activities.

Other mitigation measures to reduce the unfavorable effects of noise on human population and ecosystems may concern many aspects of geothermal drilling include the following:

- Noisy activities near dwellings should be restricted (during the daytime) and banned (during the nighttime), unless safety constraints dictate otherwise.
- Good design and layout of facilities should provide for the placement of noisy equipment in soundproof encasings or buildings. The use of muffled or sound absorption panels around motors, drill pads, vents, and pumps could be an option too.
- Electrically driven motors should be preferred to diesel engines, when possible. The use of hydraulic rigs that produce less noise should be preferred.

Finally, sound levels should be monitored (using offline dB meters on an occasional basis should be enough). In case it is desired that sound levels be used to create a map and test alternative sound barrier schemes, the online tool (dBmap.net) used in this report, should be adequate.

5.4. Biosphere

5.4.1. Ecosystem disturbances

Geothermal drilling sites (and geothermal plants) must comply with regulations that protect ecosystems. While many ecosystem disturbances are inevitable, they may be mitigated by proper planning and restorative actions.

An environmental study (in the form of an Environmental Impacts Assessment) should be undertaken before drilling, as it would allow defining the background level, establishing the impacts, and delineating mitigating measures.

When geothermal drilling is completed, an effort to replant native trees and vegetation (with a focus on endangered species) should be made, with the objective of restoring the original ecosystems and facilitate the repopulation of local flora and fauna.

Care should be taken when the geothermal development areas include areas with natural foliage, woods, and meadowland. Birds and invertebrates in particular are often linked to the vegetation.

In particular, geothermal operations in a forested area require caution to protect the forest around the boreholes, as healthy forests promote rainwater infiltration and help them reach geothermal reservoirs (Shortall, Davidsdottir & Axelsson, 2015).

5.4.2. Biodiversity

Measures to prevent or mitigate soil disturbances and erosion could lead to the loss of native vegetation species or even decreases in biodiversity (Dhar et al., 2018).

In the case of pipelines (connected to drilling sites), thermal insulation prevents thermal losses in the surroundings, which could interact with biodiversity.

5.4.3. Effects on wildlife

It has been argued that geothermal development poses only minor impacts to wildlife in the surrounding area compared to other energy extraction methods (Kagel, Bates & Gawell, 2007).

Geothermal development sites should be fenced to prevent wildlife access (if their location dictates such a measure).

Furthermore, drilling and seismic surveys may result in erosion, runoff, and noise, disturbing wildlife or affecting breeding, foraging, and migrating of certain species. To this end, areas with high wildlife concentrations, specific vegetation, and sensitive sites should be avoided.

In particular, compliance with regulatory requirements addressing endangered species is essential.

5.4.4. Health impacts

Regarding pollutants having toxic effects, workers should be skilled and trained in compliance with health, safety, and environment (HSE) programs, such as the ISO certification 14001.

Apart from standard protection measures for personnel working at the site, mitigation measures for human exposure will apply to visitors of the geothermal installations.

Further than that, it is not expected that reference levels pollutants threatening human health will be exceeded for the population outside geothermal installations.

5.4.5. Risk from radioactive deposits

Directive 2013/59/Euratom (https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:PDF) lays down basic safety standards (BSS) for protection against dangers arising from exposure to ionizing radiation. Basic safety standards consider the recommendations of the International Commission on Radiological Protection (ICRP).

The basic principle of radiation protection is the ALARA principle: received dose should be "As Low As Reasonably Achievable" by adopting radiation protection measures to ensure that employees and visitors do not receive a cumulative dose larger than the threshold established by regulation, and guarantee a minimum level of exposure.

Adopting technological solutions to prevent or reduce scaling is an important mitigation measure for reducing radioactive material. Total reinjection of fluids, and prevention of scales (deposit) formation is a way to decrease or even avoid the radioactivity related to geothermal fluid production.

Employees and visitors of geothermal plants should only be allowed in public zones and be equipped with protective equipment. Protective clothing and organic filter materials should be recycled thermally – only specialized companies can manage these residues.

The management of radioactive waste may represents a high cost for operators, so it is best to minimize or avoid it (if possible). Potential NORM (Naturally Occurring Radioactive Material) residue is treated following radioactive waste management rules, which regulated differently from one country to the other.

5.4.6. Energy consumption

Most of the energy consumption related to surface operations is usually contained within the life cycle of a geothermal plant. Energy consumption is also limited in time during the development phase of a project.

Increasing the ROP reduces the time required to complete drilling and, therefore, energy consumption. It would be preferable for the energy used for drilling to come from RES rather than diesel.

5.4.7. Use of materials

As the geothermal industry is evolving, the need for materials with better mechanical, chemical and thermal properties, as well as cost effective and environmentally friendly is becoming more critical. Diesel is the most important material in terms of environmental footprint used during drilling operations. ORCHYD technique minimizes energy consumption by enhancement of ROP, leading to a drastic reduction of diesel and its environmental footprint, as analyzed, and presented in chapter 4.5. In cases where this is possible, energy produced by RES or other conventional sources should be preferred over diesel for the minimization of carbon footprint. Steel used for casing and equipment of geothermal drilling operations is the second most important material in terms of environmental footprint (as diesel use is examined within the scope of energy consumption), and its impact is extensively analyzed and presented in chapter 4.5. In order to mitigate its effects in the environment, operators should consider the use of applicable alloys with the smallest possible environmental footprint. In cases where formation characteristics and pressure and temperature regime are favorable, partial casing of the well should be considered as well, minimizing the steel use and reducing the environmental impact. Material use by the workers during drilling operations should be considered and recycle bins should be located in the project site for paper, plastic, metals and glass. Recycling processes should be designed and executed when possible for recyclable parts of the equipment, as well.

5.5. Summary of proposed measures

In general, prevention and mitigation measures are typically very broad as they seek to take a wide range of factors into account. Table 5.1 depicts a summary of mitigation measures customized to the needs of ORCHYD project. Many of them are based on the assessed research of previous sections of the report.

Table 5.1. Summary of main prevention and mitigation measures

Impact	*Main prevention and mitigation measures*
Soil subsidence	• Incorporate reinjection into reservoir management from the start • Reduce the rate of geothermal fluid extraction • Raise the re-injection temperature
Induced seismicity	• Engage with the local population and secure its support • Benefits for communities • Implementation of a (widely publicized) in-situ traffic lights system (TLS) • Adjust the injection or production rates • Increased outreach concerning seismic monitoring • Attract community support • Development of compensation schemes • Communicate the benefits • Monitoring network and a TLS • Baseline building survey • Relocation of the project • Relocation of the population • Interventions in (selected) buildings • Termination of the project
Groundwater contamination	• Choice of appropriate drilling muds • Cementation program • Monitoring of the cementation and tubing processes • Control of casing and tubing conditions • Monitoring of reservoir behavior • Maintenance • Injection of an anticorrosion inhibitor • Conception and implementation of plugs • Casing and cementing processes • Working with qualified professionals
Generation and management of liquid and solid wastes	• Appropriate containers and/or bins • Storage units are labeled and placed over containment basins or slabs • Waste recycling or disposal towards the appropriate treatment plant or landfilling site • Hazardous wastes stored in segregated and labeled containers
Land use	• Combining geothermal systems with other renewable resources • Solar and wind energy (in particular) can be co-located with geothermal plants
Visual intrusion	• Construction of roads and civil works • Utilization of the same drilling site for several (deviated) wells • Location of drilling sites as close as possible to the power plant. • Reduction of the brightness of lights at a site during the night • Choosing the type, direction, and location of lamps (so that they project less light outside the drilling sites without compromising safety) • Use of temporary screens around the drilling sites • Suitably designed cover for the wellheads
Water consumption	• Recirculation of drilling mud • Quick plugging of mud losses zones • Use of meteoric water

Impact	*Main prevention and mitigation measures*
	• Surface water (like canal water) may be used for drilling • Dry cooling system
Water pollution	• Control of water spills to the soil and local aquatic systems • Prevent of the connection of contaminated zones and aquifers
Greenhouse gas emissions	• Connection to the local electrical grid • Alternative power supply (produced from local renewable electricity)
Local air pollution	• Vehicles of the EURO VI category
Odors/Degassing	• Blowout preventers
Noise	• Strategic noise mapping • Action plans • Distant from dwellings and related human activities • Noisy activities near dwellings should be restricted (during the daytime) and banned (during the nighttime) • Noisy equipment in soundproof encasings or buildings • Use of muffled or sound absorption panels • Preference of electrically driven motors • Use of hydraulic rigs that produce less noise • Monitoring of sound levels (using offline dB meters)
Ecosystem disturbances	• Environmental study • Replant native trees and vegetation
Biodiversity	• Measures to prevent or mitigate soil disturbances and erosion • Thermal insulation
Effects on wildlife	• Geothermal development sites should be fenced to prevent wildlife access • Areas with high wildlife concentrations, specific vegetation, and sensitive sites should be avoided • Compliance with regulatory requirements addressing endangered species
Health impacts	• Regarding pollutants having toxic effects, workers should be skilled and trained • Mitigation measures for human exposure will apply to visitors of the geothermal installations
Risk from radioactive deposits	• Radiation protection measures • Total reinjection of fluids • Prevention of scales (deposit) formation • Employees and visitors of geothermal plants should only be allowed in public zones and be equipped with protective equipment • Potential NORM (Naturally Occurring Radioactive Material) residue is treated following radioactive waste management rules
Energy consumption	• RES rather than diesel
Use of materials	• Enhancement of ROP minimizes diesel use and its environmental footprint • More carbon effective energy sources than diesel should be preferred for energy source of geothermal drilling operations when this is possible • Operators should consider the use of applicable alloys with the smallest possible environmental footprint • In cases where formation characteristics and pressure and temperature regime are favorable, partial casing of the well should

Impact	*Main prevention and mitigation measures*
	be considered for the minimization of steel use and reduction of the environmental footprint • A recycle program for metal, plastic, glass, and paper used by workers during operations, as well as a recycling program for recyclable parts of the equipment should be implemented

6. References

[1] Abdou, M. I., Al-Sabagh, A. M., Ahmed, H. E.-S., & Fadl, A. M. (2018). Impact of barite and ilmenite mixture on enhancing the drilling mud weight. *Egyptian Journal of Petroleum*, 27(4), 955-967. http://doi.org/10.1016/j.ejpe.2018.02.004

[2] Adiansyah, J. S., Biswas, W., & Haque, N. (2021). Life cycle based carbon footprint assessment of Indonesia's geothermal energy exploration project. *Chemical Engineering Transactions*, (83), 61-66. https://doi.org/10.3303/CET2183011

[3] AFNOR (2011). *Acoustique - Bruit dans l'environnement - Calcul de niveaux sonores* (Acoustics - Outdoor-noise - Calculation-of-Sound-Levels). NF S31-133, Association Française de Normalisation, Paris, France. https://www.boutique.afnor.org/standard/nf-s31-133/acoustics-outdoor-noise-calculation-of-sound-levels/article/678966/fa169343

[4] Ahmad, R., & Mirza, A. (2018). Adsorptive removal of heavy metals and anionic dye from aqueous solution using novel Xanthan gum-Glutathione/Zeolite bionanocomposite. *Groundwater for Sustainable Development*, 7, 305-312. https://doi.org/10.1016/j.gsd.2018.07.002

[5] Ali, M., Jarni, H. H., Aftab, A., Ismail, A. R., Saady, N. M., Sahito, M. F., Keshavarz, A., Iglauer, S., & Sarmadivaleh, M. (2020). Nanomaterial-based drilling fluids for exploitation of unconventional reservoirs: A review. *Energies*, 13(13), 3417. http://doi.org/10.3390/en13133417

[6] Alvarez-Rubio, S., Kästli, P., Fäh, D., Sellami, S., & Giardini, D. (2011). Parameterization of historical earthquakes in Switzerland. *Journal of Seismology*, 16(1), 1–24. https://doi.org/10.1007/s10950-011-9245-8

[7] Anthony, A. A., Esther, O. C., Chris, D. O., & Oni, B. A. (2020). Assessment of clay materials for suitability in drilling mud formulation from part of Ondo State, South-West Nigeria. *Journal of Petroleum Exploration and Production Technology*, 10(7), 2815-2828. https://doi.org/10.1007/s13202-020-00947-9

[8] Atkinson, G. M., & Kaka, S. I. (2007). Relationships between felt intensity and instrumental ground motion in the Central United States and California. *Bulletin of the Seismological Society of America*, *97*(2), 497–510. https://doi.org/10.1785/0120060154

[9] Avci, E., & Mert, B. A. (2019). The rheology and performance of geothermal spring water-based drilling fluids. *Geofluids*, 2019, 1-8. http://doi.org/10.1155/2019/3786293

[10] Bayer, P., Rybach, L., Blum, P., & Brauchler, R. (2013). Review on life cycle environmental effects of geothermal power generation. *Renewable and Sustainable Energy Reviews*, 26, 446-463. https://doi.org/10.1016/j.rser.2013.05.039

[11] Beckers, K. F., Kolker, A., Pauling, H., McTigue, J. D., &Kesseli, D. (2021). Evaluating the feasibility of geothermal deep direct-use in the United States. *Energy Conversion and Management*, *243*, 114335. https://doi.org/10.1016/j.enconman.2021.114335

[12] Begum, P., Ikhtiari, R., & Fugetsu, B. (2011). Graphene phytotoxicity in the seedling stage of cabbage, tomato, red spinach, and lettuce. *Carbon*, 49(12), 3907-3919. http://doi.org/10.1016/j.carbon.2011.05.029

[13] Bommer, J. J., Crowley, H., & Pinho, R. (2015). A risk-mitigation approach to the management of induced seismicity. *Journal of Seismology*, *19*(2), 623–646. https://doi.org/10.1007/s10950-015-9478-z

[14] Bošnjaković, M., Stojkov, M., & Jurjević, M. (2019). Environmental impact of geothermal power plants. *Tehnički Vjesnik*, 26(5), 1515-1522. https://doi.org/10.17559/TV-20180829122640

[15] Breede, K., Dzebisashvili, K., Liu, X., & Falcone, G. (2013). A systematic review of enhanced (or engineered) geothermal systems: Past, present, and future. *Geothermal Energy*, 1(4). https://doi.org/10.1186/2195-9706-1-4

[16] Broccardo, M., Mignan, A., Grigoli, F., Karvounis, D., Rinaldi, A. P., Danciu, L., Hofmann, H., Milkereit, C., Dahm, T., Zimmermann, G., Hjörleifsdóttir, V., & Wiemer, S. (2020). Induced seismicity risk analysis of the hydraulic stimulation of a geothermal well on geldinganes, Iceland. *Natural Hazards and Earth System Sciences*, *20*(6), 1573–1593. https://doi.org/10.5194/nhess-20-1573-2020

[17] Buijze, L., van Bijsterveldt, L., Cremer, H., Paap, B., Veldkamp, H., Wassing, B. B. T., van Wees, J.-D., van Yperen, G. C. N., Jaarsma, B., & ter Heege, J. H. (2020). Review of induced seismicity in geothermal systems worldwide and implications for geothermal systems in the Netherlands – CORRIGENDUM. Netherlands Journal of Geosciences, 99, e10. https://doi.org/10.1017/njg.2020.9

[18] Burden, P., Dimitriadis, K., Clements, K., Nguyen, C., Staples, T., & Thomas, S. (2013, March 5-7). *Drilling Fluid Selection Methodology for Environmentally Sensitive Areas* [Conference Presentation Abstract]. SPE/IADC Drilling Conference, Amsterdam, The Netherlands. https://doi.org/10.2118/163508-MS

[19] Bustaffa, E., Cori, L., Manzella, A., Nuvolone, D., Minichilli, F., Bianchi, F., & Gorini, F. (2020). The health of communities living in proximity of geothermal plants generating heat and electricity: A review. Science of The Total Environment, 706, 135998. https://doi.org/10.1016/j.scitotenv.2019.135998

[20] CAGE (n.d.). http://www.geothermica.eu/projects/cage/

[21] Capuano, L. E. (2016). Geothermal well drilling. In R. DiPippo (Ed.), *Geothermal Power Generation* (pp. 107–139). Woodhead Publishing. ISBN: 9780081003442

[22] Cardemil, M., Cortés, J.F., Díaz, A., & Escobar, R. (2016). Thermodynamic evaluation of solar-geothermal hybrid power plants in northern Chile. *Energy Conversion and Management,*123, 348–61. doi:https://doi.org/10.1016/j.enconman.2016.06.032

[23] Cardiff, M., Lim, D. D., Patterson, J. R., Akerley, J., Spielman, P., Lopeman, J., Walsh, P., Singh, A., Foxall, W., Wang, H. F., Lord, N. E., Thurber, C. H., Fratta, D., Mellors, R. J., Davatzes, N. C., & Feigl, K. L. (2018). Geothermal production and reduced seismicity: Correlation and proposed mechanism. *Earth and Planetary Science Letters*, 482, 470-477. https://doi.org/10.1016/j.epsl.2017.11.037

[24] CEFAS (2019). New PLONOR list issued. https://www.cefas.co.uk/data-and-publications/ocns/ocns-bulletin-board/new-plonor-list-issued

[25] Cheap-GSHPs (n.d.). Cheap and efficient application of reliable ground source heat exchangers and pumps. https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/geothermal/cheap-gshps

[26] Chen, S., Zhang, Q., Andrews-Speed, P., & Mclellan, B. (2020). Quantitative assessment of the environmental risks of geothermal energy: A Review. *Journal of Environmental Management*, *276*, 111287. https://doi.org/10.1016/j.jenvman.2020.111287

[27] Cheraghian, G. (2021). Nanoparticles in drilling fluid: A review of the state-of-the-art. *Journal of Materials Research and Technology*, 13, 737-753. http://doi.org/10.1016/j.jmrt.2021.04.089

[28] Clark, C. E., Harto, C. B., Sullivan, J. L., & Wang, M. Q. (2011). *Water use in the development and operation of geothermal power plants* [Technical report]. Argonne, Illinois: U.S. Department of Energy. https://doi.org/10.2172/1013997

[29] Clark, C., Sullivan, J., Harto, C., Han, J., & Wang, M. (2012, January 30-February 1). *Life cycle environmental impacts of geothermal systems*. Thirty-Seventh Workshop on Geothermal Reservoir Engineering, Stanford, California. https://geothermalcommunities.eu/assets/elearning/8.11.Clark.pdf

[30] COSEISMIQ (n.d.). http://www.geothermica.eu/projects/coseismiq/

[31] CROWDTHERMAL (n.d.). Crowdfunding our way to a geothermal future. https://www.crowdthermalproject.eu

[32] Dankwa, O. K., Appau, P. O., & Broni-Bediako, E. (2018). Evaluating the effects of monovalent and divalent salts on the rheological properties of water based mud. *The Open Petroleum Engineering Journal*, 11(1), 98-106. http://doi.org/10.2174/1874834101811010098

[33] Davraz, A., Afsin, M., Aksever, F., Karakaş, Z., & Ali Hınıs, M. (2016). The interference of a deep thermal system with a shallow aquifer and health risk assessment: The case of sandıklı (afyonkarahisar) basin, Turkey. *Environmental Earth Sciences*, 75(4). https://doi.org/10.1007/s12665-015-5144-6

[34] DEEP (n.d.). Innovation for de-risking enhanced geothermal energy projects. http://www.geothermica.eu/projects/call-2/deep/

[35] DEEPEGS (n.d.). Deployment of deep enhanced geothermal systems for sustainable energy business. https://deepegs.eu

[36] DEEPEN (n.d.). Derisking exploration for geothermal plays in magmatic environments. http://www.geothermica.eu/projects/call-2/deepen/

[37] Department for Business, Energy & Industrial Strategy(2021). Greenhouse gas reporting: Conversion factors 2021. GOV.UK. https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

[38] Department of Transport (1988). *Calculator of road traffic noise*. Welsh Office, 17978m, London: Her Majesty's Stationery Office. https://www.bradford.gov.uk/Documents/Hard%20Ings%20Road%20improvement%20scheme/2b%20Compulsory%20Purchase%20Order%20and%20Side%20Road%20Order/5%20Supporting%20documents/Calculation%20of%20Road%20Traffic%20Noise%201988.pdf

[39] DESCRAMBLE (n.d.). Drilling in dEep, Super-CRiticalAMBient of continentaL Europe. http://www.descramble-h2020.eu

[40] DESTRESS (n.d.). Demonstration of soft stimulation treatments of geothermal reservoirs. http://www.destress-h2020.eu/en/home/

[41] Dhar, A., Comeau, P.G., Karst, J., Pinno, B., Chang, S., Naeth, M.A., Vassov, R., and Bampfylde, C. (2018). Plant community development following reclamation of oil sands mine sites in the boreal forest: a review. *Environmental Reviews*, 26 (3), 286–298. https://doi.org/10.1139/er-2017-0091

[42] Dhar, A., Naeth, M. A., Jennings, P. D., & Gamal El-Din, M. (2020). Geothermal energy resources: Potential environmental impact and land reclamation. *Environmental Reviews*, 28(4), 415-427. https://doi.org/10.1139/er-2019-0069

[43] Duque, M. R. (2013). Geothermal reservoirs: From vapour dominated to conductive systems. *Renewable Energy and Power Quality Journal*, 1(11), 310–313. https://doi.org/10.24084/repqj11.286

[44] Echt, T., & Plank, J. (2019). An improved test protocol for high temperature carrying capacity of drilling fluids exemplified on a sepiolite mud. *Journal of Natural Gas Science and Engineering*, 70, 102964. http://doi.org/10.1016/j.jngse.2019.102964

[45] Ecoinvent. (n.d.). Ecoinvent - The world's most consistent & transparent cycle inventory database. https://www.ecoinvent.org/.

[46] Environmental Protection Agency (EPA) (2006). *Reregistration eligibility decision for sodium carbonate; weak mineral bases*. United States Environmental Protection Agency, Washington, D.C., 20460. https://nepis.epa.gov/Exe/ZyPDF.cgi/P100B5W6.PDF?Dockey=P100B5W6.PDF

[47] EPA Victoria. (2005). (tech.). *EPA Ecological Footprint Calculators: Technical Background Paper*. Environment Protection Authority Victoria. https://www.epa.vic.gov.au/about-epa/publications/972

[48] European Technology & Innovation Platform on Deep Geothermal (ETIP-DG) (2018). *Strategic research and innovation agenda for deep geothermal*. http://www.etip-dg.eu/front/wp-content/uploads/AB_AC_ETIP-DG_SRA_v3.3_web.pdf

[49] Feng, Y., Li, X., & Gray, K. E. (2018). Mudcake effects on wellbore stress and fracture initiation pressure and implications for wellbore strengthening. *Petroleum Science*, 15(2), 319-334. http://doi.org/10.1007/s12182-018-0218-1

[50] Ferrara, N., Basosi, R., & Parisi, M. L. (2019). Data analysis of atmospheric emission from geothermal power plants in Italy. *Data in Brief*, 25, 104339. https://doi.org/10.1016/j.dib.2019.104339

[51] Finger, J., & Blankenship, D. (2010). *Handbook of best practices for geothermal drilling*. Sandia National Laboratories. U.S. Department of Commerce, National Technical Information Service. https://www1.eere.energy.gov/geothermal/pdfs/drillinghandbook.pdf

[52] Finster, M., Clark, C., Schroeder, J., & Martino, L. (2015). Geothermal produced fluids: Characteristics, treatment technologies, and management options. Renewable and Sustainable Energy Reviews, 50, 952-966. https://doi.org/10.1016/j.rser.2015.05.059

[53] Frick, S., Kaltschmitt, M., & Schröder, G. (2010). Life cycle assessment of geothermal binary power plants using enhanced low-temperature reservoirs. *Energy*, 35(5), 2281-2294. https://doi.org/10.1016/j.energy.2010.02.016

[54] Fridriksson, T., Mateos, A., Audinet, P., & Orucu, Y. (2016). *Greenhouse gases from geothermal power production* [Report]. World Bank, Washington, D.C. https://openknowledge.worldbank.org/handle/10986/24691

[55] Fu, L., Liao, K., Tang, B., Jiang, L., & Huang, W. (2020). Applications of graphene and its derivatives in the upstream oil and gas industry: A systematic review. *Nanomaterials*, 10(6), 1013. http://doi.org/10.3390/nano10061013

[56] GaBi (n.d.). Life Cycle Assessment LCA Software. GaBi Solutions. https://gabi.sphera.com/international/index/

[57] García-Gil, A., Garrido Schneider, E., Mejías, M., Barceló, D., Vázquez-Suñé, E., & Díaz-Cruz, S. (2018). Occurrence of pharmaceuticals and personal care products in the URBAN aquifer of Zaragoza (Spain) and its relationship with INTENSIVE SHALLOW geothermal Energy exploitation. Journal of Hydrology, 566, 629-642. https://doi.org/10.1016/j.jhydrol.2018.09.066

[58] Gaucher, E., Schoenball, M., Heidbach, O., Zang, A., Fokker, P. A., van Wees, J.-D., & Kohl, T. (2015). Induced seismicity in geothermal reservoirs: A review of forecasting approaches. *Renewable and Sustainable Energy Reviews*, *52*, 1473–1490. https://doi.org/10.1016/j.rser.2015.08.026

[59] GECO (n.d.). Geothermal emission control. https://geco-h2020.eu

[60] GECONNECT (2018). Tight geothermal casing connections for axial stress mitigation. https://www.geothermalresearch.eu/geconnect/

[61] GEMex (n.d.). Cooperation in geothermal energy research Europe-Mexico for development of enhanced geothermal systems and superhot geothermal systems. http://www.gemex-h2020.eu/index.php?lang=en

[62] GEO4CIVHIC (n.d.). Most easy, efficient and low cost geothermal systems for retrofitting civil and historical buildings. https://geo4civhic.eu

[63] GEOCOND. (2021). Advanced materials and processes to improve performance and cost-efficiency of shallow geothermal systems and underground thermal storage. CORDIS. https://cordis.europa.eu/project/id/727583

[64] GEODEPower (2018). Cutting-edge deep geothermal system and drilling technology suitable for all users and locations. CORDIS. https://cordis.europa.eu/project/id/807809

[65] Geo-Drill (2020). Development of novel and cost-effective drilling technology for geothermal systems. CORDIS. https://cordis.europa.eu/project/id/815319

[66] GEOENVI (n.d.). Tackling the environmental concerns for deploying geothermal energy in Europe. https://www.geoenvi.eu/about-us/

[67] Geofit (n.d). Geothermal systems, technologies, and tools for energy efficient building retrofitting. https://geofit-project.eu

[68] GEOFOOD (n.d.). Greener way to a better world. https://geofoodproject.eu/

[69] GEORISK (2021). Developing geothermal and renewable energy projects by mitigating their risks. CORDIS. https://cordis.europa.eu/project/id/818232

[70] GeoSmart (2020). Technologies for geothermal to enhance competitiveness in smart and flexible operation. CORDIS. https://cordis.europa.eu/project/id/818576

[71] GEOTech (2020). Geothermal technology for €conomic cooling and heating. CORDIS. https://cordis.europa.eu/project/id/656889

[72] GeoTherm SWS (2019). The first truly mobile geothermal drilling rig. CORDIS. https://cordis.europa.eu/project/id/855257

[73] GEOTHERMICA (2021). Geothermica - ERA NET cofund geothermal. CORDIS. https://cordis.europa.eu/project/id/731117

[74] GEO-URBAN (n.d.). http://www.geothermica.eu/projects/geo-urban

[75] GeoWell (n.d.). The first truly mobile geothermal drilling rig. https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/geothermal/geowell

[76] Giardini, D., Wössner, J., & Danciu, L. (2014). Mapping Europe's seismic hazard. Eos, Transactions American Geophysical Union, 95(29), 261–262. https://doi.org/10.1002/2014eo290001

[77] Glassley, W.E. (2015). Geothermal energy: renewable energy and the environment. (2nd ed.). CRC Press.

[78] Goff, S. J., Bussod, G. Y., Wohletz, K., Cort, E. G., Dreesen, D. S., & Rowley, J. C. (1995). *Rock melting: A specialty drilling system for improved hole stability in geothermal wells*. World geothermal congress: Worldwide utilization of geothermal energy, Florence, Italy. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/1995/2-GoffS.pdf

[79] Goldstein, B., Hiriart, G., Bertani, R., Bromley, C., Gutierrez-Negrin, L., Huenges, E., Muraoka, H., Ragnarsson, A., Tester, J., & Zui, V. (2011). Geothermal Energy. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer & C. von Stechow (Eds.), IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (pp. 401-436). Cambridge University Press. https://doi.org/10.1017/CBO9781139151153.008

[80] Gooday, A. J., Jorissen, F., Jorissen F., Levin, L. A., Middleburg, J. J., Navqi, S. W. A., Rabalais, N. N., Scranton, M., & Zhang, J. (2009). Historical records of coastal eutrophication-induced hypoxia. *Biogeosciences*, 6, 1-39. https://doi.org/10.5194/bg-6-1707-2009

[81] Gowida, A., Elkatatny, S., Ramadan, E., & Abdulraheem, A. (2019). Data-driven framework to predict the rheological properties of $CaCl_2$ brine-based drill-in fluid using artificial neural network. *Energies*, 12(10), 1880. http://doi.org/10.3390/en12101880

[82] GRE-GEO (n.d.). Glass fibre reinforced epoxy casing system for geothermal application.http://www.geothermica.eu/projects/call-2/gre-geo/

[83] Hassanzadeh, R., Nedović- Budić, Z., Alavi Razavi, A., Norouzzadeh, M., &Hodhodkian, H. (2013). Interactive approach for GIS-based earthquake scenario development and resource estimation (karmania hazard model). *Computers & Geosciences*, *51*, 324–338. https://doi.org/10.1016/j.cageo.2012.08.016

[84] HEATSTORE (2021). High temperature underground, thermal energy storage. https://www.heatstore.eu/

[85] Homewood, P. (2018, November 6). *Environmental impacts of drilling for geothermal energy*. https://notalotofpeopleknowthat.wordpress.com/2018/11/09/environmental-impacts-of-drilling-for-geothermal-energy/

[86] Hooijkaas, G. R., Genter, A., & Dezayes, C. (2006). Deep-seated geology of the granite intrusions at the Soultz Egs site based on data from 5km-deep boreholes. *Geothermics*, *35*(5-6), 484–506.https://doi.org/10.1016/j.geothermics.2006.03.003

[87] Hu, W., Peng, C., Luo, W., Lv, M., Li, X., Li, D., Huang, Q., & Fan, C. (2010). Graphene-based antibacterial paper. *ACS Nano*, 4(7), 4317-4323. http://doi.org/10.1021/nn101097v

[88] Huang, S., Li, S., Villalobos, L. F., Dakhchoune, M., Micari, M., Babu, D. J., Vahdat, M. T., Mensi, M., Oveisi, E., & Agrawal, K. V. (2021). Millisecond lattice gasification for high-density CO_2- and O_2-sieving nanopores in single-layer graphene. *Science Advances*, 7(9), eabf0116. https://doi.org/ 10.1126/sciadv.abf0116

[89] Husin, H., Elraies, K. A., Choi, H. J., & Aman, Z. (2018). Influence of graphene nanoplatelet and silver nanoparticle on the rheological properties of water-based mud. *Applied Sciences*, 8(8), 1386. http://doi.org/10.3390/app8081386

[90] Ibrahim, D. S., Sami, N. A., & Balasubramanian, N. (2016). Effect of barite and gas oil drilling fluid additives on the reservoir rock characteristics. *Journal of Petroleum Exploration and Production Technology*, 7(1), 281-292. http://doi.org/10.1007/s13202-016-0258-2

[91] Ikram, R., Mohamed Jan, B., Vejpravova, J., Choudhary, M. I., & Zaman Chowdhury, Z. (2020). Recent advances of graphene-derived nanocomposites in water-based drilling fluids. *Nanomaterials*, 10(10), 2004. http://doi.org/10.3390/nano10102004

[92] International Organization for Standardization. (2006). *Environmental management − life cycle assessment − prinicples and framework* (ISO Standard No.14040:2006). https://www.iso.org/standard/37456.html

[93] Jamrozik, A. (2017). Graphene and graphene oxide in the oil and gas industry. *AGH Drilling, Oil, Gas*, 34(3), 731-743. http://doi.org/10.7494/drill.2017.34.3.731

[94] Jarosz, A., Skoda, M., Dudek, I., & Szukiewicz, D. (2016). Oxidative stress and mitochondrial activation as the main mechanisms underlying graphene toxicity against human cancer cells. *Oxidative Medicine and Cellular Longevity*, 2016, 1-14. http://doi.org/10.1155/2016/5851035

[95] Jassim, L., Yunus, R., & Rashid, U. (2020). Utilization of nano and micro particles to enhance drilling mud rheology. *Materials Science Forum*, 1002, 435-447. http://doi.org/10.4028/www.scientific.net/msf.1002.435

[96] Jiang, G., Li, X., Zhu, H., Yang, L., Li, Y., Wang, T., & Wu, X. (2019). Improved shale hydration inhibition with combination of gelatin and KCl or EPTAC, an environmentally friendly inhibitor for water-based drilling fluids. *Journal of Applied Polymer Science*, 136, 47585. http://doi.org/10.1002/app.47585

[97] Jiang, M., Hendrickson, C. T., & van Briesen, J. M. (2013). Life cycle water consumption and wastewater generation impacts of a Marcellus shale gas well. *Environmental Science & Technology*, 48(3), 1911-1920. https://doi.org/10.1021/es4047654

[98] Jonasson, H. G. (1999). *Measurement and modeling of noise emissions or road vehicles for use in prediction models*. Nordtest project 1452-99, KFN project 1998-0659/1997-0223, SP Report 1999:35, Swedish National Testing and Research Institute (1999). https://www.osti.gov/etdeweb/servlets/purl/20138118

[99] Kabay, N., Sözal, P. Y., Yavuz, E., Yüksel, M., & Yüksel, Ü. (2017). Treatment of geothermal waters for industrial and agricultural purposes. In J. Bundschuh & B. Tomaszewska (Eds.), Geothermal water management (Vol. 6, Ser. Sustainable Water Developments, pp. 113-134). CRC Press. ISBN9781315734972

[100] Kagel, A., Bates, D., & Gawell, K. (2007). A guide to geothermal energy and the environment. Geothermal Energy Association, Washington, District of Columbia. Retrieved from: https://digital.library.unt.edu/ark:/67531/metadc890065/m2/1/high_res_d/897425.pdf

[101] Karlsdóttir, M. R., Pálsson, Ó. P., Pálsson, H., & Maya-Drysdale, L. (2015). Life cycle inventory of a Flash geothermal combined heat and power plant located in Iceland. *The International Journal of Life Cycle Assessment*, 20(4), 503-519. https://doi.org/10.1007/s11367-014-0842-y

[102] Katende, A., Boyou, N. V., Ismail, I., Chung, D. Z., Sagala, F., Hussein, N., & Ismail, M. S. (2019). Improving the performance of oil based mud and water based mud in a high temperature hole using nanosilica nanoparticles. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 577, 645–673. http://doi.org/10.1016/j.colsurfa.2019.05.088

[103] Kipsang, C. (2013). *Cost Model for Geothermal Wells. Reykjavik*, Iceland: United Nations University.

[104] Kolawole, O., Ispas, I., Kolawole, F., Germay, C., & McLennan, J. D. (2021). Mechanical zonation of rock properties and the development of fluid migration pathways: Implications for enhanced geothermal systems in sedimentary-hosted geothermal reservoirs. *Geothermal Energy*, 9(14). https://doi.org/10.1186/s40517-021-00195-y

[105] Kosynkin, D. V., Ceriotti, G., Wilson, K. C., Lomeda, J. R., Scorsone, J. T., Patel, A. D., Friendheim, J.E., & Tour, J. M. (2011). Graphene oxide as a high-performancefluid-loss-control additive in water-based drilling fluids. *ACS Applied Materials & Interfaces*, 4(1), 222-227. http://doi.org/10.1021/am2012799

[106] Kraft, T., Roth, P., & Wiemer, S. (2020). (rep.). Good-Practice Guide for Managing In-duced Seismicity in Deep Geothermal Energy Projects in Switzerland. Zurich: Swiss Seismological Service (SED).

[107] Kulauzović. B., Pejanović Nosaka, T., Jamnik, J. (2020). Relationship between weight of the heavy trucks and traffic noise pollution in the viewpoint of feasibility of fines for exceeded noise – a case study. Proceedings of the *8th Transport Research Arena (TRA 2020)*, April 27-30, 2020, Helsinki, Finland.

[108] Kuo, S., Lai, M. S., & Lin, C. W. (2006). Influence of solution acidity and $CaCl_2$ concentration on the removal of heavy metals from metal-contaminated rice soils. *Environmental Pollution*, 144(3), 918-25. https://doi.org/10.1016/j.envpol.2006.02.001

[109] Kusrini, E., Suseno, B., Khalil, M., Nasruddin, & Usman, A. (2018). Study of the use of nanomaterials as drilling mud additives. *E3S Web of Conferences*, 67, 02007. http://doi.org/10.1051/e3sconf/20186702007

[110] Kwast-Kotlarek, U., Hełdak, M., & Szczepański, J. (2018). Introducing bentonite into the environment in the construction stage of linear underground investment using the HDD method. *Applied Sciences*, 8(11), 2210. http://doi.org/10.3390/app8112210

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

[112] Lacirignola, M., Meany, B. H., Padey, P., & Blanc, I. (2014). A simplified model for the estimation of life-cycle greenhouse gas emissions of enhanced geothermal systems. *Geotherm Energy*, 2(8). https://doi.org/10.1186/s40517-014-0008-y

[113] Langbauer, C., Schwarzenegger, C., & Fruhwirth, R. K. (2020). Subsurface located geothermal well – case study. *Reasearch Square*. https://doi.org/10.21203/rs.3.rs-59570/v1

[114] Legarth, B. A., & Saadat, A. (2005, April 24-29). *Energy consumption for geothermal wells*. In World Geothermal Congress 2005. Antalya, Turkey. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/1002.pdf

[115] Lewis, Sr., R. J. (1993). Hawley's condensed chemical dictionary. 12th edition, New York: Van Nostrand Reinhold.

[116] Li, M., & Lior, N. (2015). Energy analysis for guiding the design of well systems of deep enhanced geothermal systems. *Energy*, 93, 1173-1188. https://doi.org/10.1016/j.energy.2015.09.113

[117] Lizhong, Z., & Baoliang, C. (2009). Use of bentonite-based sorbents in organic pollutant abatements. *Progress in Chemistry*, 21(0203), 420-429. http://manu56.magtech.com.cn/progchem/EN/abstract/abstract9935.shtml

[118] Ma, J., Pang, S., Zhang, Z., Xia, B., & An, Y. (2021). Experimental study on the polymer/graphene oxide composite as a fluid loss agent for water-based drilling fluids. *ACS Omega*, 6(14), 9750-9763. http://doi.org/10.1021/acsomega.1c00374

[119] Ma, Q., Li, J., Lee, C. C. C., Long, X., Liu, Y., & Wu, Q-T. (2019). Combining potassium chloride leaching with vertical electrokinetics to remediate cadmium-contaminated soils. *Environmental Geochemistry and Health*, 41, 2081-2091. https://doi.org/10.1007/s10653-019-00259-w

[120] Mady, A., Mahmoud, O., & Dahab, A. S. (2020). Nanoparticle-based drilling fluids as promising solutions to enhance drilling performance in Egyptian oil and gas fields. *International Journal of Industry and Sustainable Development*, 1(1), 24-38. http://doi.org/10.21608/ijisd.2020.73471

[121] Mahmoud, M., Ramadan, M., Pullen, K., Abdelkareem, M. A., Wilberforce, T., Olabi, A.-G., & Naher, S. (2021). A review of grout materials in geothermal energy applications. *International Journal of Thermofluids*, 10, 100070. http://doi.org/10.1016/j.ijft.2021.100070

[122] Mahmud, H. B., Mahmud, W. M., Ayanarappan, R., & Elmabrouk, S. (2020). Effect of sodium carbonate and bicarbonate contamination on the rheological properties of water based mud. *International Journal of Engineering Research and Technology*, 13(5), 1019. https://doi.org/10.37624/ijert/13.5.2020.1019-1029

[123] Majer, E., Nelson, J., Robertson-Tait, A., Savy, J., & Wong, I. (2012). Protocol for addressing induced seismicity associated with enhanced geothermal systems. *U.S. Department of Energy*. https://doi.org/10.2172/1219482

[124] Malek, A., Adams, B., Rossi, E., Schiegg, H., & Saar, M. (2021). Electric Power Generation, Specific Capital Cost, and Specific Power for Advanced Geothermal Systems (AGS). 46th Annual Stanford Geothermal Workshop (SGW 2021), Online, February 16-18. https://doi.org/https://doi.org/10.3929/ethz-b-000467172

[125] Manzella, A., Bonciani, R., Allansdottir, A., Botteghi, S., Donato, A., Giamberini, S., Lenzi, A., Paci, M., Pellizzone, A., & Scrocca, D. (2018). Environmental and social aspects of geothermal energy in Italy. Geothermics, 72, 232–248. https://doi.org/10.1016/j.geothermics.2017.11.015

[126] Marchand, M., Blanc, I., Marquand, A., Beylot, A., Bezelgues-Courtade, S., & Traineau, H. (2015, April). Life cycle assessment of high temperature geothermal energy systems. In R. Horne and T. Boyd (eds), Proceedings of the *World Geothermal Congress*, article 02028, Melbourne, Australia. https://extranet.isige.mines-paristech.fr/masteres/ige/2015/les-energies-renouvelables/acv-geothermie-hte-tdegc_marchand-wfc2015.pdf

[127] Martín-Gamboa, M., Iribarren, D., & Dufour, J. (2015). On the environmental suitability of high- and low-enthalpy geothermal systems. Geothermics, 53, 27–37. https://doi.org/10.1016/j.geothermics.2014.03.012

[128] MATChING (2020). Materials technologies for performance improvement of cooling systems in power plants. CORDIS. https://cordis.europa.eu/project/id/686031

[129] McCay, A. T., Feliks, M. E. J., & Roberts, J. J. (2019). Life cycle assessment of the carbon intensity of deep geothermal heat systems: A case study from Scotland. *Science of The Total Environment*, 685, 208-219. https://doi.org/10.1016/j.scitotenv.2019.05.311

[130] McTigue, J.D., Zhu,G., Turchi, C., Mungas, G., Kramer, N., King, J., & Castro, J. (2018). Hybridizing a geothermal plant with solar and thermal energy storage to enhance power generation. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-70862. Retrieved from: https://www.nrel.gov/docs/fy18osti/70862.pdf

[131] MEET (n.d.). Multidisciplinary and multi-context demonstration of EGS exploration and exploitation techniques and potentials. https://www.meet-h2020.com

[132] Menberg, K., Heberle, F., Bott, C., Brüggemann, D., & Bayer, P. (2021). Environmental performance of a geothermal power plant using a hydrothermal resource in the Southern German Molasse Basin. *Renewable Energy*, 167, 20-31. https://doi.org/10.1016/j.renene.2020.11.028

[133] Menberg, K., Pfister, S., Blum, P., & Bayer, P. (2016). A matter of meters: State of the art in the life cycle assessment of enhanced geothermal systems. *Energy & Environmental Science*, 9(9), 2720-2743. https://doi.org/10.1039/c6ee01043a

[134] Mignan, A., Landtwing, D., Kästli, P., Mena, B., & Wiemer, S. (2015). Induced seismicity risk analysis of the 2006 Basel, Switzerland, Enhanced Geothermal System Project: Influence of uncertainties on risk mitigation. *Geothermics*, *53*, 133–146. https://doi.org/10.1016/j.geothermics.2014.05.007

[135] Minetto, R., Montanari, D., Planès, T., Bonini, M., Del Ventisette, C., Antunes, V., & Lupi, M. (2020). Tectonic and anthropogenic microseismic activity while drilling toward supercritical conditions in the Larderello-Travale geothermal field, Italy. *Journal of Geophysical Research: Solid Earth*, 125(2). https://doi.org/10.1029/2019jb018618

[136] Moeck, I., Kwiatek, G., & Zimmermann, G. (2009). Slip tendency analysis, fault reactivation potential, and induced seismicity in a Deep Geothermal Reservoir. *Journal of Structural Geology*, *31*(10), 1174–1182. https://doi.org/10.1016/j.jsg.2009.06.012

[137] Mohamed, A., Basfar, S., Elkatatny, S., & Bageri, B. (2020). Impact of perlite on the properties and stability of water-based mud in elevated-temperature applications. *ACS Omega*, 5(50), 32573-32582. http://doi.org/10.1021/acsomega.0c04853

[138] Moriya, H. (2021). Identification of similar seismic waves using the phase-only correlation function and wavelet transform. *Energies*, 14(15), 4527. https://doi.org/10.3390/en14154527

[139] Murtaza, M., Kamal, M. S., & Mahmoud, M. (2020). Application of a novel and sustainable silicate solution as an alternative to sodium silicate for clay swelling inhibition. *ACS Omega*, 5(28), 17405-17415. http://doi.org/10.1021/acsomega.0c01777

[140] Naeimavi, M., Khazali, F., Abdideh, M., & Saadati, Z. (2019). Potassium sorbate as substitute for KCl to shale inhibition in water-base drilling fluids. *Energy Sources, Part A: Recovery, utilization, and environmental effects*, 43(14), 1691-1705. http://doi.org/10.1080/15567036.2019.1663303

[141] Neff, J. M. (2008). Estimation of bioavailability of metals from drilling mud barite. *Integrated Environmental Assessment and Management*, 4(2), 184-93. http://doi.org10.1897/ieam_2007-037.1

[142] Nogueira, P. F. M., Nakabayashi, D., & Zucolotto, V. (2015). The effects of graphene oxide on green algae Raphidocelis subcapitata. *Aquatic Toxicology*, 166, 29-35. http://doi.org/10.1016/j.aquatox.2015.07.001

[143] Noorollahi, Y., & Sahzabi, H. Y. (2005, April 24-29). *Monitoring of surface and ground water quality in geothermal exploration drilling of Meshkinshahr geothermal field, NW-Iran*. Proceedings World Geothermal Congress 2005, Antalya, Turkey. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2005/0210.pdf

[144] Noorollahi, Y., Shabbir, M. S., Siddiqi, A. F., Ilyashenko, L. K., & Ahmadi, E. (2019). Review of two decade geothermal energy development in Iran, benefits, challenges, and future policy. Geothermics, 77, 257–266. https://doi.org/10.1016/j.geothermics.2018.10.004

[145] Norwegian Oil & Gas Association (2017). *Norwegian Oil and gas recommended guidelines for barite quality.* Translated version, No 046. https://www.norskoljeoggass.no/contentassets/1625c65822fa4c97bb2e1085134d09f9/046-guidelines-for-barite-quality-050117.pdf

[146] Okamoto, K., Yi, L., Asanuma, H., Okabe, T., Abe, Y., & Tsuzuki, M. (2018). Triggering processes of microseismic events associated with water injection in Okuaizu geothermal field, Japan. *Earth, Planets and Space*, 70(15). https://doi.org/10.1186/s40623-018-0787-7

[147] Omodeo-Salé, S., Eruteya, O. E., Cassola, T., Baniasad, A., & Moscariello, A. (2020). A basin thermal modelling approach to mitigate geothermal energy exploration risks: The St. Gallen Case Study (eastern Switzerland). *Geothermics*, 87, 101876. https://doi.org/10.1016/j.geothermics.2020.101876

[148] OpenLCA(2021). The Open Source Life Cycle and Sustainability Assessment Software. OpenLCA. https://www.openlca.org/

[149] Ouyang, S., Hu, X., & Zhou, Q. (2015). Envelopment–internalization synergistic effects and metabolic mechanisms of graphene oxide on single-cell chlorella vulgaris are dependent on the nanomaterial particle size. *ACS Applied Materials & Interfaces*, 7(32), 18104-18112. http://doi.org/10.1021/acsami.5b05328

[150] Padey. P., Girard, R., le Boulch, D., & Blanc, I. (2013). From LCAs to simplified models: A generic methodology applied to wind power electricity. *Environmental Science and Technology*, 47(3), 1231-1238. https://doi.org/10.1021/es303435e

[151] Pan, S.-Y., Gao, M., Shah, K. J., Zheng, J., Pei, S.-L., & Chiang, P.-C. (2019). Establishment of enhanced geothermal energy utilization plans: Barriers and strategies. Renewable Energy, 132, 19–32. https://doi.org/10.1016/j.renene.2018.07.126

[152] Park, S.-W., Choi, B.-S., Song, K.-W., Oh, K.-J., & Lee, J.-W. (2007). Absorption of carbon dioxide into aqueous xanthan gum solution containing monoethanolamine. *Separation Science and Technology*, 42(16), 3537-3554. https://doi.org/10.1080/01496390701710646

[153] Patel, A. D. (2009, April 20-22). *Design and development of quaternary amine compounds: Shale inhibition with improved environmental profile.* Paper Number SPE-121737-MS, SPE International Symposium on Oilfield Chemistry, The Woodlands, Texas. https://doi.org/10.2118/121737-MS

[154] Paulillo, A., Striolo, A., & Lettieri, P. (2019). The environmental impacts and the carbon intensity of geothermal energy: A case study on the Hellisheiði plant. *Environment International*, 133, 105226. https://doi.org/10.1016/j.envint.2019.105226

[155] Paydar, P., & Ahmadi, M. (2017). Characteristics of water-based drilling mud containing Gilsonite with Boehmite nanoparticles. *Bulletin De La Société Royale Des Sciences De Liège*, 86(Special), 248-258. http://doi.org/10.25518/0037-9565.6695

[156] Pellizzone, A., Allansdottir, A., De Franco, R., Muttoni, G., & Manzella, A. (2017). Geothermal energy and the public: A case study on DELIBERATIVE Citizens' engagement in central Italy. Energy Policy, 101, 561–570. https://doi.org/10.1016/j.enpol.2016.11.013

[157] PERFORM (n.d.). Helping to avoid or mitigate the problems of geothermal plants. https://www.geothermperform.eu/

[158] Petersen, J. B., Hung, C., Solli, C., Steenveldt, R., Kerr, S., & Aas, N. (2013, September 3-6). *A guide to better wells: Environmental life-cycle assessment of historical, current and future best practice in drilling* [Paper Number SPE-166615-MS]. Society of Petroleum Engineers (SPE) Offshore Europe Oil and Gas Conference and Exhibition, Aberdeen, UK. https://doi.org/10.2118/166615-MS

[159] Porter, R. T. J., Striolo, A., Mahgerefteh, H., & Faure Walker, J. (2018). Addressing the risks of induced seismicity in Subsurface Energy Operations. *WIREs Energy and Environment*, *8*(2). https://doi.org/10.1002/wene.324

[160] Pratiwi, A., Ravier, G., & Genter, A. (2018). Life-cycle climate-change impact assessment of enhanced geothermal system plants in the Upper Rhine Valley. *Geothermics*, 75, 26-39. https://doi.org/10.1016/j.geothermics.2018.03.012

[161] PRe. (2016). ReCiPe. PRe. Fact-based sustainability. Retrieved from https://pre-sustainability.com/articles/recipe/

[162] Prixton, D. S., & Hall, D. R. (2002). *Advanced Mud Hammer Systems*. Novatek & US Department of Energy's Federal Energy Technology Center. https://netl.doe.gov/sites/default/files/2018-05/ng3b-5.pdf

[163] Qalandari, R., & Qalandari, E. (2018). A review on the potential application of nano graphene as drilling fluid modifier in petroleum industry. International *Refereed Journal of Engineering and Science (IRJES),* 7(2), 1-7. http://www.irjes.com/Papers/vol7-issue2/A07020107.pdf

[164] Qu, G., Liu, S., Zhang, S., Wang, L., Wang, X., Sun, B., Yin, N., Gao, X., Xia, T., Chen, J.-J., & Jiang, G.-B. (2013). Graphene oxide induces Toll-Like Receptor 4 (TLR4)-dependent necrosis in macrophages. *ACS Nano*, 7(7), 5732-5745. http://doi.org/10.1021/nn402330b

[165] Rabet, R. S., Simsek, C., Baba, A., & Murathan, A. (2016). Blowout mechanism of Alasehir (TURKEY) geothermal field and its effects on Groundwater chemistry. Environmental Earth Sciences, 76(1). https://doi.org/10.1007/s12665-016-6334-6

[166] Redburn, M., & Heath, G. (2017, March 29-31). *Improved fluid characteristics with clear calcium chloride brine drilling fluid*. 13th Offshore Mediterranean Conference and Exhibition, Ravenna, Italy. https://www.newpark.com/assets/pdfs/Improved_Fluid_Characteristics_With_Clear_Calcium_%20Chloride_Brine_Drilling_Fluid.pdf

[167] REFLECT (2021). Redefining geothermal fluid properties at extreme conditions to optimize future geothermal energy extraction. CORDIS. https://cordis.europa.eu/project/id/850626

[168] Reinecker, J., Hochschild, T., Kraml, M., Löschan, G., & Kreuter, H. (2019). Experiences and Challenges in Geothermal Exploration in the Upper Rhine Graben. In *European Geothermal Congress 2019*. Den Haag; EGEC Geothermal.

[169] RESULT (n.d.). Enhancing reservoirs in urban development: smart wells and reservoir development. http://www.geothermica.eu/projects/call-2/result/

[170] Rosberg, J.-E., & Erlström, M. (2021). Evaluation of deep geothermal exploration drillings in the crystalline basement of the Fennoscandian Shield Border Zone in South Sweden. Geothermal Energy, 9(1). https://doi.org/10.1186/s40517-021-00203-1

[171] Rothert, E., & Shapiro, S. A. (2007). Statistics of Fracture Strength and fluid-induced microseismicity. Journal of Geophysical Research: *Solid Earth*, 112(B4). https://doi.org/10.1029/2005jb003959

[172] Sadovski, A. N. (2019). Study on pH in water and potassium chloride for Bulgarian soils. *Eurasian Journal of Soil Science*, 8(1), 11-16. https://doi.org/10.18393/ejss.477560

[173] Salas, D. A., Ramirez, A. D., Rodríguez, C. R., Petroche, D. M., Boero, A. J., & Duque-Rivera, J. (2016). Environmental impacts, life cycle assessment and potential improvement measures for cement production: A literature review. *Journal of Cleaner Production*, 113, 114-122. https://doi.org/10.1016/j.jclepro.2015.11.078

[174] Saleh, F. K., Teodoriu, C., Ezeakacha, C., & Salehi, S. S. (2020, February 10-12). *Geothermal drilling: A review of drilling challenges with mud design and lost circulation problem*. 45th

Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California. https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Saleh.pdf

[175] Sayed, E. T., Wilberforce, T., Elsaid, K., H., Rabaia, M. K., Abdelkareem, M. A., Chae, K. J., & Olabi, A. G. (2020). A critical review on evironmental impacts of renewable energy systems and mitigation strategies: Wind, hydro, biomass and geothermal. *Science of the Total Environment*, 766, 144505. https://doi.org/10.1016/j.scitotenv.2020.144505

[176] Schinwald, A., Murphy, F. A., Jones, A., MacNee, W., & Donaldson, K. (2012). Graphene-based nanoplatelets: A new risk to the respiratory system as a consequence of their unusual aerodynamic properties. *ACS Nano*, 6(1), 736-746. http://doi.org/10.1021/nn204229f

[177] Schlumberger (2021). *Soda Ash*. https://www.slb.com/-/media/files/mi/product-sheet/soda-ash-ps.ashx

[178] Schlumberger Oilfield Glossary (n.d.). *Potassium Mud*. Retrieved July 31, 2021 from https://glossary.oilfield.slb.com/en/terms/p/potassium_mud

[179] Schumacher, S., Pierau, R., & Wirth, W. (2020). Probability of success studies for geothermal projects in clastic reservoirs: From subsurface data to geological risk analysis. *Geothermics*, *83*, 101725. https://doi.org/10.1016/j.geothermics.2019.101725

[180] SEE4GEO (n.d.). Seismoelectric effects for geothermal resource assessment and monitoring. http://www.geothermica.eu/projects/call-2/see4geo/

[181] Semedi, J. M., Willemen, L., Nurlambang, T., van der Meer, F., & Koestoer, R. H. (2017). Developing a framework for assessing the impact of geothermal development phases on ecosystem services. *IOP Conference Series: Earth and Environmental Science*, 103, 012003. https://doi.org/10.1088/1755-1315/103/1/012003

[182] Seyedmohammadi, J. (2017). The effects of drilling fluids and environment protection from pollutants using some models. *Modeling Earth Systems and Environment*, 3(23). http://doi.org/10.1007/s40808-017-0299-7

[183] Shah, M., Sircar, A., Shaikh, N., Patel, K., Thakar, V., Sharma, D., Sarkar, P., & Vaidya, D. (2018). Groundwater analysis OF dholera GEOTHERMAL field, Gujarat, India for suitable applications. Groundwater for Sustainable Development, 7, 143-156. https://doi.org/10.1016/j.gsd.2018.05.002

[184] Shapiro, S. A., Dinske, C., Langenbruch, C., & Wenzel, F. (2010). Seismogenic index and magnitude probability of earthquakes induced during reservoir fluid stimulations. *The Leading Edge*, *29*(3), 304–309. https://doi.org/10.1190/1.3353727

[185] Shortall, R., Davidsdottir, B., & Axelsson, G. (2015). Geothermal Energy for Sustainable Development: A review of sustainability impacts and assessment frameworks. *Renewable and Sustainable Energy Reviews*, *44*, 391–406. https://doi.org/10.1016/j.rser.2014.12.020

[186] SimaPro (2021). LCA software for fact-based sustainability. SimaPro. https://simapro.com/

[187] Skrúcaný, T., Šarkan, B., Figlus, T., Synák, F., & Vrábel, J. (2017). Measuring of noise emitted by moving vehicles. *MATEC Web of Conferences*, 107, 00072. http://doi.org/10.1051/matecconf/201710700072

[188] Smith, S. (2020). *Rystad Energy: Geothermal power on the rise*. Energy Global. Retrieved from https://www.energyglobal.com/other-renewables/14102020/rystad-energy-geothermal-power-on-the-rise/.

[189] Soltani, M., Moradi Kashkooli, F., Souri, M., Rafiei, B., Jabarifar, M., Gharali, K., & Nathwani, J. S. (2021). Environmental, economic, and social impacts of geothermal energy systems. *Renewable and Sustainable Energy Reviews*, 140, 110750. https://doi.org/10.1016/j.rser.2021.110750

[190] Soltani, M., Moradi Kashkooli, F., Souri, M., Rafiei, B., Jabarifar, M., Gharali, K., & Nathwani, J. S. (2021). Environmental, economic, and social impacts of geothermal energy systems. Renewable and Sustainable Energy Reviews, 140, 110750. https://doi.org/10.1016/j.rser.2021.110750

[191] Somma, R., Blessent, D., Raymond, J., Constance, M., Cotton, L., Natale, G. D., Fedele, A., Jurado, M. J., Marcia, K., Miranda, M., Troise, C., & Wiersberg, T. (2021). Review of recent drilling projects in unconventional geothermal resources at Campi Flegrei Caldera, Cornubian

Batholith, and Williston Sedimentary Basin. *Energies*, 14(11), 3306. https://doi.org/10.3390/en14113306

[192] Spada, M., Sutra, E., & Burgherr, P. (2021). Comparative accident risk assessment with focus on Deep Geothermal Energy Systems in the Organization for Economic Co-operation and Development (OECD) countries. *Geothermics*, 95, 102142. https://doi.org/10.1016/j.geothermics.2021.102142

[193] SPINE (n.d.). Stress profiling in EGS.http://www.geothermica.eu/projects/call-2/spine/

[194] Stober, I., & Bucher, K. (2021). Drilling Techniques for Deep Wellbores Top drive. In I. Stober & K. Bucher (Eds.), *Geothermal Energy: From Theoretical Models to Exploration and Development* (2nd Ed., pp. 287-309). Springer Nature Switzerland AG. ISBN: 978-3-642-13352-7

[195] Stuver, S., & Alonzo, J. (2014). *A comparison of air emission estimation methods for drilling rig emissions* [White paper]. Houston, Texas: Houston Advance Research Center – HARC and the Texas A&M Global Petroleum Research Institute - GPRI. http://efdsystems.org/pdf/A_Comparison_of_Estimation_Protocols_for_Drilling_Rig_Emissions.pdf

[196] SURE (2021). Novel productivity enhancement concept for a sustainable utilization of a geothermal resource. CORDIS. https://cordis.europa.eu/project/id/654662

[197] TEST-CEM (n.d.). Sustainable geothermal well cements for challenging thermo-mechanical conditions. http://www.geothermica.eu/projects/call-2/test-cem/

[198] The Human-Induced Earthquake Database (HiQuake). (2021). Retrieved 2021, from https://inducedearthquakes.org/.

[199] THERM (2019). Transport of Heat in hEteRogeneous Media. CORDIS. https://cordis.europa.eu/project/id/838508

[200] ThermoDrill (2020). Fast track innovative drilling system for deep geothermal challenges in Europe. CORDIS. https://cordis.europa.eu/project/id/641202

[201] Thomas, L. K., Tinjum, J. M., & Holcomb, F. H. (2020, February 10-12). *Environmental life cycle assessment of a deep direct-use geothermal system in champaign, Illinois*. In 45th Workshop on Geothermal Reservoir Engineering. Stanford University, Stanford, California. https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2020/Thomas.pdf

[202] Tinjum, J., Thomas, L., & Holcomb, F. (2020). Environmental Life Cycle Assessment Spreadsheet tool for Deep Direct-Use Geothermal at the University of Illinois at Urbana-Champaign Campus. *U.S. Department of Energy Office of Scientific and Technical Information*. Retrieved fromhttps://www.osti.gov/dataexplorer/biblio/dataset/1601452

[203] Tomasini-Montenegro, C., Santoyo-Castelazo, E., Gujba, H., Romero, R. J., & Santoyo, E. (2016). Life cycle assessment of geothermal power generation technologies: An updated review. *Applied Thermal Engineering*, 114, 1119-1136. https://doi.org/10.1016/j.applthermaleng.2016.10.074

[204] Tomaszewska, B., Bundschuh, J., Pająk, L., Dendys, M., Delgado Quezada, V., Bodzek, M., Armienta, M. A., Muñoz, M. O., & Kasztelewicz, A. (2020). Use of Low-enthalpy and WASTE geothermal energy sources to Solve Arsenic problems in freshwater production in selected regions of Latin America using a Process membrane distillation – research into model solutions. Science of The Total Environment, 714, 136853. https://doi.org/10.1016/j.scitotenv.2020.136853

[205] Tong, T., & Elimelech, M. (2016). The global rise of zero liquid discharge for wastewater management: Drivers, technologies, and future directions. Environmental Science & Technology, 50(13), 6846-6855. https://doi.org/10.1021/acs.est.6b01000

[206] Tosti, L., Ferrara, N., Basosi, R., & Parisi, M. L. (2020). Complete data inventory of a geothermal power plant for robust cradle-to-grave life cycle assessment results. *Energies*, 13(11), 2839. https://doi.org/10.3390/en13112839

[207] Treyer, K., Oshikawa, H., Bauer, C., & Miotti, M. (2015). Environment. In S. Hirschberg, S. Wiemer, & P. Burgherr (Eds.), Energy from the Earth - Deep Geothermal as a Resource for the Future? (pp. 183-228). essay, vdf Hochschulverlag. ISBN: 978-3-7281-3654-1

[208] United States Department of Agriculture (USDA) (2020, November). *Soil nutrients and your crops*. Natural Resources Conservation Service, Alaska. https://www.nrcs.usda.gov/wps/cmis_proxy/https/ecm.nrcs.usda.gov%3A443/fncmis/resources/WEBP/ContentStream/idd_C0C8D875-0000-CE37-9B84-81D03678C7B4/0/STATEWIDE-+Soil+Nutrients+and+Your+Crops+-+Final+Nov2020.pdf

[209] United States Geological Survey. (2021). *"Felt" Earthquakes = Ones That People Feel*. U.S. Geological Survey. Retrieved from https://www.usgs.gov/observatories/hawaiian-volcano-observatory/felt-earthquakes.

[210] Utami, A., Aji, N., Fadyah, A., Ghifari, A., Anam, M. B., Ramadhani, S., Rasyid, F. H., & Maulana, R. R. (2020). Geothermal energy solid waste management: Source, type of waste, and the management. In AIP Conference Proceedings. 2nd International Conference on Earth Science, Mineral and Energy https://doi.org/10.1063/5.0007299

[211] Vidal, J., Genter, A., & Schmittbuhl, J. (2015). How do permeable fractures in the Triassic sediments of northern Alsace characterize the top of hydrothermal convective cells? evidence from soultz geothermal boreholes (France). *Geothermal Energy*, 3(1). https://doi.org/10.1186/s40517-015-0026-4

[212] Vogtländer, J. G. (2016). *A practical guide to LCA for students, designers and business managers: Cradle-to-grave and cradle-to-cradle*. Delft Academic Press. https://www.researchgate.net/publication/258220969_Lca_a_practical_guide_for_students_designers_and_business_managers

[213] Vryzas, Z., & Kelessidis, V. C. (2017). Nano-based drilling fluids: A review. *Energies*, 10(4), 540. http://doi.org/10.3390/en10040540

[214] Wackernagel, M., Beyers, B., & Rout, K. (2019). *Ecological footprint: Managing our biocapacity budget*. New Society Publishers.

[215] Wackernagel, M., Schulz, N. B., Deumling, D., Linares, A. C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., & Randers, J. (2002). Tracking the ecological overshoot of the human economy. *Proceedings of the National Academy of Sciences*, *99*(14), 9266–9271. https://doi.org/10.1073/pnas.142033699

[216] Wang, G.-ling, Zhang, W., Ma, F., Lin, W.-jing, Liang, J.-yun, & Zhu, X. (2018). Overview on hydrothermal and hot dry rock researches in China. *China Geology*, 1, 273–285. https://doi.org/10.31035/cg2018021

[217] Wang, K., Ruan, J., Song, H., Zhang, J., Wo, Y., Guo, S., & Cui, D. (2010). Biocompatibility of graphene oxide. *Nanoscale Research Letters*, 6(8). http://doi.org/10.1007/s11671-010-9751-6

[218] Wang, Z., Yang, L., Wu, J., Zhang, H., Zhu, L., & Zhan, X. (2018). Potential application of a low-viscosity and high-transparency xanthan gum produced from Xanthomonas campestris CCTCC M2015714 in foods. *Preparative Biochemistry & Biotechnology*, 48(5), 402-407. https://doi.org/10.1080/10826068.2018.1451884

[219] Witter, J. B., Trainor-Guitton, W. J., & Siler, D. L. (2019). Uncertainty and risk evaluation during the exploration stage of Geothermal Development: A Review. Geothermics, 78, 233–242. https://doi.org/10.1016/j.geothermics.2018.12.011

[220] World Road Association (WRA) (2019). *Traffic noise - Best practice guide*. Technical Committee E.2, Environmental considerations in road projects, 2019R36EN. https://www.piarc.org/en/order-library/31457-en-Traffic%20Noise%20%E2%80%93%20Best%20Practice%20Guide

[221] Yadav, K., & Sircar, A. (2017). Review of deep drilling techniques for high enthalpy geothermal reservoirs. *International Journal of Advanced Research*, 5(6), 2359-2370. https://doi.org/10.21474/ijar01/4681

[222] Yilmaz, E., & Ali Kaptan, M. (2017). Environmental impact of geothermal power plants in Aydin, Turkey. E3S Web of Conferences, 19, 02028. https://doi.org/10.1051/e3sconf/20171902028

[223] Yousefi, H., Ehara, S., Noorollahi, Y., & Saffarzadeh, A. (2007). *Environmental aspects of geothermal energy development in Iran.* The 5th International Workshop on Earth Sciences and Technology, Fukuoka, Japan. https://www.researchgate.net/publication/239537049_ENVIRONMENTAL_ASPECTS_OF_GEOTHERMAL_ENERGY_DEVELOPMENT_IN_IRAN

[224] Yu, B., Li, X., Qiao, Y., & Shi, L. (2015). Low-carbon transition of iron and steel industry in China: Carbon intensity, economic growth and policy intervention. *Journal of Environmental Sciences*, 28, 137-147. https://doi.org/10.1016/j.jes.2014.04.020

[225] Zhang, D., Wang, Y., Sha, J., & He, Y. (2021). Performance prediction of a turbodrill based on the properties of the drilling fluid. *Machines*, 9(4), 76. https://doi.org/10.3390/machines9040076

[226] Zhang, Q., Hou, Q., Huang, G., & Fan, Q. (2019). Removal of heavy metals in aquatic environment by graphene oxide composites: A review. *Environmental Science and Pollution Research*, 27, 190-209. https://doi.org/10.1007/s11356-019-06683-w

[227] Zhu, Z., Wang, C., Guan, Z., & Lei, W. (2021). Thermal characteristics of borehole stability drilling in hot dry rock. *ACS Omega*, 6(29), 19026-19037. https://doi.org/10.1021/acsomega.1c02311

[228] ZORDEX (n.d.). http://www.geothermica.eu/projects/zodrex/

7. APPENDIX A: HORIZON 2020 Geothermal Projects

Table 7.1. HORIZON 2020 Geothermal Projects (project coordinator listed first in consortium)

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
DESCRAMBLE	Drilling in dEep, Super-CRiticalAMBient of continentaL Europe	ENEL Green Power - (EGP) (IT) CNR - Institute of Geosciences and Earth Resources (IT) RWTH - Institute for Applied Geophysics and Geothermal Energy, E.ON Ener (DE) CAU - Institute of Geosciences (DE) TU BAF - Institute of Geophysics and Geoinformatics (DE) SINTEF Petroleum AS - Drilling and Well (NO) STIFTELSEN SINTEF - Dept. of Instrumentation (NO)	15,615,955	2015 to 2018	Targeted novel drilling technique for reaching deep geothermal resources. Demonstrated safe drilling of a deep super-critical geothermal well. Aimed to reduce technical and financial risks related to drilling and exploitation of deep geothermal wells.	http://www.descramble-h2020.eu
GEODEPower	Cutting-edge deep geothermal system and drilling technology suitable for all users and locations	Rock Energy AS (NO)	71,429	2018	Development of geothermal plants based on deep-drilling and enhanced geothermal well-system patented technology. Would allow delivering energy even in very low geothermal gradients, thus allowing exploitation of any location (no matter geological its activity).	https://cordis.europa.eu/project/id/807809

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
GEOTech	Geothermal Technology for Economic Cooling and Heating	Solintel M&P SL (ES) RINA Consulting SPA (IT) Groenholland Geo-Engineering BV (NL) Conrad Stanen BV (NL) Comsa Instalaciones y Sistemas Industriales SA (ES) Armengol & Ros Consultors i Associats, SLP (ES) Stuwa Konrad Stukerjurgen GmbH (DE) GEOTHEX B.V. (NL) HiRef SPA (IT) Tecnalia Research & Innovation (ES) De Montfort University (GB) Polytechnic University of Valencia (ES) University of Bologna (IT) Catholic University of Leuven (BE) University of Padua (IT) University of Leeds (GB)	9,025,459	2015 to 2019	Targeted shallow geothermal ground source heat pumps. Development of a drilling concept that is based on the dry auger method (cheaper equipment, better safety, less risky).	http://www.geotech-project.eu/ (not working) https://cordis.europa.eu/project/id/656889

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
GeoTherm SWS	The First Truly Mobile Geothermal Drilling Rig	QMATEC Drilling AS (NO)	71,429	2019	Aimed to develop the first truly mobile compact drilling rig with drastic cost optimization (70% in small scale deep geothermal systems). Core/diamond rotation and down-the-hole methods were used. Facilitated the development of small geothermal projects even in isolated rural areas, reducing carbon emissions(by replacing diesel generators) by 90%.	https://cordis.europa.eu/project/id/855257
GeoWell	Innovative materials and designs for long-life high-temperature geothermal wells	Islenskar Orkurannsoknir – Iceland GeoSurvey (IS) Norwegian Research Centre (NORCE) (NO) GFZ German Research Centre for Geosciences (DE) Netherlands Organisation for Applied Scientific Research (NL) Bureau de Recherches Géologiques et Minières (FR) Equinor Energy AS (NO) HS Orka HF (IS) Akiet BV (NL) Huisman Well Technology BV (NL)	4,704,913	2016 to 2019	Aimed to develop innovative materials for long life high temperature geothermal wells to address high cost. Novel cement and scaling technologies, casing materials, and flexible couplings were studies.	https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/geothermal/geowell

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
Cheap-GSHPs	Cheap and efficient application of reliable ground source heat exchangers and pumps	National Research Council (IT) University of Padua (IT) Tecnalia Research & Innovation (ES) Energesis Group SL (ES) R.E.D. SRL (IT) Galletti Belgium (BE) Societatea Romana Geoexchange (RO) Aner Sistemas Informaticos SL (ES) Rehau Verwaltungszentrale AG (DE) Friedrich–Alexander University Erlangen–Nürnberg (DE) Centre for Renewable Energy Sources and Saving (GR) University of Applied Sciences and Arts of Southern Switzerland (CH) SLR Environmental Consulting (Ireland) Limited (IE) Hydra SRL (IT) Geo Green (BE) UNESCO (FR) Pietre Edil SRL (RO) Polytechnic University of Valencia (ES)	5,717,356	2015 to 2019	Addressed ground source heat exchangers and pumps. Aimed to develop helicoidal ground source heat exchangers (GSHEs) with a smaller external diameter of the heat basket to facilitate drilling at greater depths. Also designed a modified dry drilling methodology.	https://cheap-gshp.eu/ (not working) https://ec.europa.eu/inea/en/horizon-2020/projects/h2020-energy/geothermal/cheap-gshps

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
CROWDTHERMAL	Crowdfunding our way to a geothermal future	European Federation of Geologists (BE) IZES - Institute for Future Energy Systems (DE) University of Glasgow (GB) GeoThermal Engineering GmbH (DE) La Palma Research Centre (ES) CrowdfundingHub BV (NL) District Heating Company of Szeged (HU) Spanish Geothermal Technology Platform (ES) Geothermal Research Cluster (IS) EIMUR (IS)	2,305,801	2019 to 2022	Encouragement of public participation in the development of geothermal projects through social engagement tools and alternative financing schemes like crowdfunding Raise of public awareness and the transparency of geothermal projects and technologies Creation of a social acceptance model to be used as a baseline for inspiring public support	https://www.crowdthermalproject.eu
DEEPEGS	Deployment of Deep Enhanced Geothermal Systems for Sustainable Energy Business	HS Orka HF (IS) Fonroche Géothermie SAS (FR) Equinor Energy AS (NO) Landsvirkjun (National Power Company of Iceland) (IS) Bureau de Recherches Géologiques et Minières (FR) Iceland GeoSurvey (IS) Herrenknecht Vertical GmbH (DE) ENEL Green Power SPA (IT) Karlsruhe Institute of Technology (DE) GEORG Rannsokn Arklasi I Jardhita (IS)	42,173,550	2015 to 2020	Delivery of innovative solutions and models for wider deployment of enhanced geothermal systems in deep wells in different geologies across Europe.	https://deepegs.eu

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
DESTRESS	Demonstration of Soft Stimulation Treatments of Geothermal Reservoirs	GFZ German Research Centre for Earth Sciences (DE) Energie Baden-Württemberg (EnBW) (DE) és-Géothermie (ESG) (FR) University of Glasgow (GB) Geo-Energie Suisse AG (CH) Research, Development and Consultancy Organisation TNO (NL) Swiss Federal Institute of Technology in Zürich (CH) Geothermie Neubrandenburg GmbH (DE) University of Strasbourg (FR) Delft University of Technology (NL) NexGeo INC (KR) Seoul National University (KR) Korea Institute of Civil Engineering and Building Technology (KR) ECW (Energy Combination Wieringermeer) Geomanagement BV (NL) Trias Westland BV (NL) Korea Institute of Geoscience and Mineral Resources (KR) Utrecht University (NL)	24,713,964	2016 to 2021	Development of stimulation treatments with minimized environmental hazard (“soft stimulation”), to enhance the reservoir in several geological settings covering granites, sandstones, and other rock types	http://www.destress-h2020.eu/en/home/

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
GECO	Geothermal Emission Control	Reykjavík Energy (OR) (IS) Iceland GeoSurvey (ISOR) (IS) Centre National de la Recherche Scientifique (CNRS) (FR) Georg-Rannsoknarklasi I Jardhita (IS) University of Iceland (IS) IFP Energies Nouvelles (FR) University of Firenze (IT) Graziella Green Power S.P.A. (IT) Storengy SA (FR) Fundación CIRCE - Centro de Investigación de Recursos y Consumos Energéticos (ES) Green Minerals (NL) Zorlu Enerji Elektrik Uretim AS (TR) United Kingdom Research and Innovation (GB) Middle East Technical University (TR) National Research Council (IT) Bochum University of Applied Sciences (DE) Institute for Energy Technology (NO) Technology Centre (AIMEN) (ES)	18,220,330	2018 to 2022	Development of a waste gas storage technique which increases the reservoir permeability and promotes the fixation of the dissolved gases as stable mineral phases, leading to the long-term environmentally friendly storage of waste gases, while it lowers considerably the cost of cleaning geothermal gas compared to standard industry solutions	https://geco-h2020.eu

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
GEO4CIVHIC	Most Easy, Efficient and Low Cost Geothermal Systems for Retrofitting Civil and Historical Buildings	Institute of atmospheric sciences and climate (ISAC) (IT) Construction technologies institute (ITC) (IT) University of Padua (IT) Valencia Polytechnic University (ES) Research and Environmental Devices SRL (RED) (IT) Terra Geoserv Limited (IE) Galletti Belgium (BE) Tecnalia Research & Innovation (ES) Thyssenkrupp Infrastructure GmbH (DE) UNESCO (FR) University of Erlangen-Nuremberg (DE) Societatea Romana Geoexchange (RO) Centre for Renewable Energy Sources and Saving (GR) Hydra SRL (IT) Ubeg Dr Erich Mands u Marc Sauer GBR (DE) Geo Green SPRL (BE) Pietre Edil SRL (RO) Solintel M&P SL (ES) Din L-Art Helwa (MT) University of Applied Sciences and Arts of Southern Switzerland (CH)	8,143,120	2018 to 2022	Development of easy, efficient, and low-cost geothermal systems for retrofitting civil and historical buildings. Exploitation of shallow geothermal reservoirs through different applications, fitted to the different building type. Development of borehole heat exchangers of higher efficiency coupled with cost effective drilling techniques and equipment.	https://geo4civhic.eu/

GEMex	Cooperation in Geothermal energy research Europe-Mexico for development of Enhanced Geothermal Systems and Superhot Geothermal Systems	GFZ German Research Centre for Geosciences (DE) Iceland GeoSurvey (IS) Netherlands Organisation for Applied Scientific Research (NL) University of Bari Aldo Moro (IT) Utrecht University (NL) RWTH Aachen University (DE) National Research Council (IT) Technical University of Darmstadt (DE) Bureau de Recherches Géologiques et Minières (FR) Institute for Energy Technology (NO) Centre for Renewable Energy Sources and Saving (GR) National Institute of Oceanography and Applied Geophysics (IT) Norwegian Research Centre (NO) Roma Tre University (IT) Agenzia Nazionale per le Nuove Technologie, l'Energia e lo Sviluppo Economico Sostenibile (IT) Sant'Anna School of Advanced Studies (IT) Karslruher Institut für Technologie (DE) United Kingdom Research and Innovation (GB) Bochum University of Applied Sciences (DE)	9,999,792	2016 to 2020	Development of geothermal cooperation between Europe and Mexico in the basis of super-hot enhanced geothermal systems Two unconventional geothermal sites at Acoculco and Los Humeros were resource assessed Characterization of reservoirs using techniques and approaches developed at conventional geothermal sites took place All existing and newly collected data were applied for the definition of drill paths, well completion design, suitable material selection and enhancement of stimulation and operation procedures for safe and economic exploitation	http://www.gemex-h2020.eu/index.php?lang=en

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
		University of Turin (IT) Polish Geological Institute (PL) European Geothermal Energy Council (BE) Helmholtz Centre for Environmental Research - UFZ (DE) IGA Service GmbH (DE)				
GEOCOND	Advanced materials and processes to improve performance and cost-efficiency of Shallow Geothermal systems and Underground Thermal Storage	Valencia Polytechnic University (ES) AIMPLAS – Technological Institute of Plastics (ES) RISE CBI Betonginstitutet AB (SE) Sabancı University (TR) SILMA SRL (IT) Extruline Systems S.L. (ES) Carmel Olefins Ltd. (IL) Çimsa Çimento Sanayi ve Ticaret A.Ş (TR) UBeG GmbH & Co. (DE) Exergy LTD (GB) RISE Research Institutes of Sweden AB (SE)	3,955,740	2017 to 2021	Developed advanced materials and processes to improve performance and cost-efficiency of shallow geothermal systems and underground geothermal storage	https://cordis.europa.eu/project/id/727583

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
Geo-Drill	Optimising technology for geothermal extraction	TWI Limited (GB) Bochum University of Applied Sciences (DE) Geolorn Limited (GB) Jardboranir HF (IS) Precision Varionic International Limited (GB) Technovative Solutions Ltd. (GB) Flowphys AS (NO) Alternative Energies and Atomic Energy Commission (FR) Gerosion EHF (IS) University of Iceland (IS) RINA Consulting – Centro Sviluppo Materiali S.p.A (IT) Graphenea SA (ES) Fraunhofer Society (DE)	4,996,400	2019 to 2022	Development of optimized drilling equipment to cut costs and increase the rate of penetration in geothermal extraction. This innovative drilling technology will combine durable mud hammers operated with bi-stable fluidic amplifiers, 3D-printed sensors and cables to enhance monitoring, and graphene coatings to improve drill resistance and lifetime. Reducing drilling costs by up to 60%, it will motivate investment and make geothermal energy more widely accessible	https://cordis.europa.eu/project/id/815319

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
GEOENVI	Tackling the environmental concerns for deploying geothermal energy in Europe	European Geothermal Energy Council (BE) RETE Geothermica (IT) ENEL Green Power SPA (IT) Consorzio per lo Sviluppo delle Aree Geotermiche Scrl (IT) Center for Colloid and Surface Science (IT) National Research Council (IT) Bureau de Recherches Géologiques et Minières (FR) ÉS-Géothermie (FR) Association pour la Recherche et le Développement des Méthodes et Processus Industriels (FR) Iceland GeoSurvey (IS) GEORG Rannsoknarklasi I Jardhita (IS) Orkustofnun (National Energy Authority) (IS) Flemish institute for technological research (BE) Geothermal Power Plant Investors Association (TR) Dokuz Eylul University (TR) Mining and Geological Survey of Hungary (HU)	2,495,871	2018 to 2021	Development of a robust strategy to respond to environmental impacts and risks Assessment of environmental impacts and risks of geothermal projects operational or in development in Europe Development of a robust framework to propose recommendations on environmental regulations to the decision-makers, an adapted methodology for assessing environment impact to the project developers Proper communicating on environmental concerns with the general public Engagement with both decision-makers and geothermal market actors, to have the recommendations on regulations adopted and to see the LCA methodology implemented by geothermal stakeholders	https://www.geoenvi.eu/about-us/

Geofit	Deployment of novel GEOthermal systems, technologies and tools for energy efficient building retroFITting.	R2M Solution Srl (IT) IDP Ingeniería y Arquitectura Iberia S.L.U. (ES) Comsa Corporación de Infraestructuras SL (ES) National Research Council (IT) Ajuntament de Sant Cugat del Vallès (IT) University of Perugia (IT) IDS Georadar Srl (IT) Ochsner Wärmepumpen GmbH (AT) NOBATEK/INEF4 (FR) AIT Austrian Institute of Technology GmbH (AT) Catalana de Perforacions SA (ES) Uponor Oyj (FI) National University of Ireland Galway (IE) Fahrenheit GmbH (DE) Enervalis (BE) Luleå University of Technology (SE) Groenholland Geo-energy systems (NL) KTH Royal Institute of Technology (SE) Eurecat Technology Centre (ES) Comet Gesinco S.L. (ES) SIART – Sistemi Informativi Analisi di Rischio Ambientale e Territoriale (IT) Comharchumann Fuinnimh Olleáin Árann Teoranta (IE)	9,861,980	2018 to 2022	Development of innovative enhanced geothermal systems and their components such as non-standard heat exchanger configurations, cooling components, a novel hybrid heat pump and an electrically driven compression heat pump. Development of a suite of tools including low invasive risk assessment technologies, site-inspection and worksite building monitoring techniques (SHM) and control systems for cost-effective and optimized EGS in operation.	https://geofit-project.eu

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
		Carel Industries SPA (IT) Spanish Association for Standardization (ES) i.LECO (BE) Comet Global Innovation (ES)				

GEORISK	Developing geothermal and renewable energy projects by mitigating their risks	European Geothermal Energy Council (BE) Association Française des Professionnels de la Géothermie (FR) Bureau de Recherches Géologiques et Minières (FR) Scientific and Technological Research Council of Turkey (TR) Jeotermal Elektrik Santral Yatırımcıları Derneği (TR) Geotermia Expressz Mérnöki Tanácsadó Iroda Korlátolt Felelősségű Társaság (HU) Mining and Geological Survey of Hungary (HU) Mineral and Energy Economy Research Institute of the Polish Academy of Sciences (PL) Centre for Renewable Energy Sources and Saving (GR) Anonimi Etairia Diaxeirisis Ananeosimon Pigon Energeias (GR) Federal Department for Environment, Transport, Energy and Communications (CH) GEC-CO Global Engineering & Consulting – Company GmbH (DE) Bundesverband Geothermie (DE) Türkiye Kalkınma Bankası (TR) Geothermie-Schweiz (CH)	2,184,118	2018 to 2021	Development of geothermal and renewable energy projects by mitigating their risks	https://cordis.europa.eu/project/id/818232

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
GeoSmart	Technologies for geothermal to enhance competitiveness in smart and flexible operation	TWI Limited (GB) Flemish Institute for Technological Research (BE) Zorlu Enerji Elektrik Üretim A.Ş. (TR) French Alternative Energies and Atomic Energy Commission (FR) Atlas Copco Airpower NV (BE) European Geothermal Energy Council (BE) Fraunhofer Society (DE) Spike Renewables SRL (IT) Orkuveita Reykjavíkur SF (IS) University of Iceland (IS) Middle East Technical University (TR) Bertin Technologies SAS (FR) Gerosion EHF (IS) Kadir Has University (TR) Technovative Solutions LTD (GB) Flowphys AS (NO) P.Vald EHF (IS) CoSviG - Consorzio Sviluppo Aree Geotermiche (IT) Nýsköpunarmiðstöð Íslands (IS)	19,727,611	2019 to 2023	Development of geothermal energy technologies for the enhancement of competitivenessin smart and flexible operation.	https://cordis.europa.eu/project/id/818576

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
MATChING	Materials Technologies for performance improvement of Cooling Systems in Power Plants	ENEL Global Thermal Generation SRL (IT) Belgisch Laboratorium van de Elektriciteitsindustrie Laborelec CVBA (ES) Endesa Generacion SA (ES) ENEL Green Power SPA (IT) Flemish institute for technological research (BE) DNV Netherlands BV (NL) National Research Council (IT) Electricite de France (FR) Pathema BV (NL) Asociación de Investigación Metalúrgica del Noroeste (ES) SPIG SPA (IT) Danish Technological Institute (DK) Aquastill BV (NL) Materia Nova (BE) Industrias Técnicas de Galicia SA (ES) Ionics (BE) Sweco Nederland BV (NL) ENEL Produzione SpA (IT)	11,790,518	2016 to 2019	Development of material technologies for performance improvement of cooling systems in power plants. The project aims in the reduction of cooling water demand in thermal and geothermal power plants.	https://cordis.europa.eu/project/id/686031

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
MEET	Multidisciplinary and multi-context demonstration of EGS exploration and Exploitation Techniques and potentials	ES-Geothermie (FR) Institut Polytechnique UniLaSalle (FR) Geophysical Inversion & Modeling Labs (FR) CY Cergy Paris Universite (FR) Technical University of Darmstadt (DE) Universitätsenergie Göttingen GmbH (DE) Georg-August-Universität Göttingen Stiftung Öffentlichen Rechts (DE) Vermilion REP SAS (FR) Enogia (FR) GFZ German Research Centre for Geosciences (DE) Febus Optics (FR) Sveučilište u Zagrebu Fakultet elektrotehnike i računarstva (HR) Nýsköpunarmiðstöð Íslands (IS) Institut Royal des Sciences Naturelles de Belgique (BE) Geothermal Engineering GmbH (DE) AYMING (FR)	11,736,955	2018 to 2021	Optimization of the reservoir productivity and stimulation techniques Assessment of the technical, economic, and environmental feasibility of EGS is an integral part of the project, as well as the mapping of the main promising European sites where EGS can or should be implemented in a near future Development of a roadmap of next promising sites where demonstrated EGS solutions could be replicated in a near future for electricity and heat production with an evaluation of the technology, its economic feasibility and environmental positive impacts	https://www.meet-h2020.com

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
REFLECT	Redefining geothermal fluid properties at extreme conditions to optimize future geothermal energy extraction	GFZ German Research Centre for Geosciences, (DE) Delft University of Technology (NL) Bureau de Recherches Géologiques et Minières (FR) University of Neuchâtel (CH) Institute for Energy Technology (NO) Netherlands Organisation for Applied Scientific Research (NL) United Kingdom Research and Innovation (GB) Iceland GeoSurvey (IS) University of Miskolc (HU) Izmir Institute of Technology (TR) Fédération Européenne des Géologues (BE) Hydroisotop GmbH Laboratorium zur Bestimmung von Isotopen in Umwelt und Hydrologie (DE) Landsvirkjun (IS) Pfalzwerke Geofuture GmbH (DE)	4,992,761	2020 to 2022	Implementation of a European geothermal fluid atlas and predictive models which will provide recommendations on the optimum operation of geothermal system is proposed	https://cordis.europa.eu/project/id/850626

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
SURE	Novel Productivity Enhancement Concept for a Sustainable Utilization of a Geothermal Resource	GFZ German Research Centre for Geosciences (DE) Delft University of Technology (NL) Bochum University of Applied Sciences (DE) Iceland GeoSurvey (IS) Netherlands Organisation for Applied Scientific Research (NL) Wellservices BV (NL) Imperial College of Science Technology and Medicine (GB) Geoterma UAB (LT) State Scientific Research Institute Nature Research Centre (LT) Technical University of Denmark (DK)	6,143,415	2016 to 2019	Focus on novel productivity enhancement concept for a sustainable utilization of geothermal resources through radial water jet drilling technique. Advanced modeling provides an insight on the mechanism that promotes rock destruction at the tip of the water jet	https://cordis.europa.eu/project/id/654662
THERM	Transport of Heat in hEteRogeneous Media	Universite de Rennes I (FR)	196,707	2020 to 2022	Research over transport of heat in heterogeneous media and the thermo-hydro-mechanical processes occurring during the lifetime of a geothermal reservoir	https://cordis.europa.eu/project/id/838508

Acro-nym	Title	Consortium	Budget (€)	Duration	Main points	URL
ThermoDrill	Fast track innovative drilling system for deep geothermal challenges in Europe	University of Leoben (AT) ES-Geothermie (FR) Bestec GmbH (DE) Red Drilling & Services GmbH (AT) INERCO Ingeniería, Tecnología y Consultoría, S.A. (ES) Technical University of Munich (DE) Sirius-Es Handels GmbH (AT) Smith International Italia SpA (IT) Geo-Energie Suisse AG (CH)	5,824,745	2015 to 2019	Development of an innovative drilling system based on the combination of conventional rotary drilling with water jetting that will allow at least 50% faster drilling in hard rock, a cost reduction of more than 30% for the subsurface construction and a minimized risk of induced seismic activity Development of enhanced water jet drilling technology for borehole construction and replacement of fracking Assessment of HT/HP crystalline rock jetting and drilling fluids Systematic redesign of the overall drilling process, particularly the casing design and cementing Evaluation of drilling technologies and concepts in terms of HSE (health, safety and environmental) compliance	https://cordis.europa.eu/project/id/641202

GEOTHERMICA	GEOTHERMICA - ERA NET CofundGeothermal	Orkustofnun (National Energy Authority) (IS) Ministry of Economic Affairs and Climate (NL) Federal Department for Environment, Transport, Energy and Communications (CH) Ministry of Education, University and Research (IT) Forschungszentrum Jülich (DE) Agence de l'environnement et de la maîtrise de l'énergie (FR) Icelandic Centre for Research (IS) Scientific and Technological Research Council of Turkey (TR) Ministrstvu za infrastrukturo (SI) Regional Fund for Science and Technology (PT) Ministerio de Economía, Industria y Competitividad (ES) Directorate General for Energy and Geology (PT) Danish Energy Agency (DK) Unitatea Executiva pentru Finantarea Invatamantului Superior, a Cercetarii, Dezvoltarii si Inovarii (RO) Vlaamse Gewest (BE) Ministère de la Transition écologique (FR) Centre for the Development of Industrial Technology (ES)	26,485,554	2017 to 2022	Aims in the combination of the financial resources and know-how of 16 independent geothermal energy research and innovation program owners from 13 countries and the identification of paths towards commercial large-scale implementation of their concepts. Several projects are developed with the support of GEOTHERMICA initiative.	https://cordis.europa.eu/project/id/731117

Acro-nym	*Title*	*Consortium*	*Budget (€)*	*Duration*	*Main points*	*URL*
		Department of Environment, Climate and Communications (IE) State Research Agency (ES) Ministero dell'Università e della Ricerca (IT)				

8. APPENDIX B: ORCHYD online scoping survey

ORCHYD online scoping survey

This short questionnaire is intended to help finalize the importance of environmental issues to be addressed in the ORCHYD Environmental Assessment Report.

In it, you are asked to assess the importance/significance of (both unfavorable/negative and favorable/positive) ORCHYD impacts in the atmosphere, the geosphere/lithosphere, the hydrosphere, and the biosphere (including socioeconomic aspects).

Those impacts that will be considered most significant based on your informed responses, will be analyzed in depth.

Feel free to not answer a question that you are not sure about.

We thank you for your time.

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va.papakostas@gmail.com
nicole.kontoulis@gmail.com

* Required

Personal information

Personal information will only be used for the analysis of the responses of this form within ORCHYD

1. ORCHYD partner's full name (e.g. John Paravantis) or initials (e.g. JP) or an alias (e.g. UPRC researcher, if you would rather not provide your real name) *

2. ORCHYD partner institution or company *

Mark only one oval.

- ( ) Association pour la Recherche et le Développement des Méthodes et Processus Industriels (Armines)
- ( ) Drillstar Industries (DLS)
- ( ) Imperial College London (ICL)
- ( ) SINTEF AS
- ( ) China University of Petroleum (UPC)
- ( ) University of Piraeus (UPRC)
- ( ) Affiliated to other institution or company or working alone

3. Which country are you located in (please type, e.g. Greece)? *

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4. What is your educational level/professional affiliation (please check all that apply)? *

Check all that apply.

- [ ] University or College
- [ ] Postgraduate degree
- [ ] Doctorate
- [ ] Post doctoral
- [ ] Researcher
- [ ] University faculty
- [ ] Prefer not to say

5. What is your scientific field (please type, e.g. petroleum engineering)? *

____

6. Have you worked in other Horizon 2020 projects before?

Mark only one oval.

- Yes
- No
- Not sure

7. Overall, what is the importance of environmental impacts of the ORCHYD project?

Mark only one oval.

	1	2	3	4	5	
Minor						Major

8. Overall, what is the importance of socioeconomic impacts of the ORCHYD project?

Mark only one oval.

	1	2	3	4	5	
Minor						Major

ATMOSPHERE

Please assess the importance of the following ORCHYD impacts in the atmosphere

9. What is the importance of impacts related to the emission of greenhouse gases?

Mark only one oval.

	1	2	3	4	5	
Minor						Major

10. What is the importance of impacts related to the emission of gaseous pollutants from drilling (e.g. hydrogen sulfide)?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

11. What is the importance of impacts related to local air pollution (e.g. due to road construction or traffic)?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

12. What is the importance of impacts related to odors?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

13. What is the importance of impacts related to noise?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

14. Any comments? Did we miss anything related to the atmosphere?

GEOSPHERE/LITHOSPHERE

Please assess the importance of the following ORCHYD impacts in the geosphere/lithosphere

15. What is the importance of impacts related to subsistence and landslide hazards?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

16. What is the importance of impacts related to microseismicity?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

17. What is the importance of impacts related to soil erosion?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

18. What is the importance of impacts related to soil mineralization (e.g. with heavy metals)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

19. What is the importance of impacts related to soil water logging and flooding hazards?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

20. What is the importance of impacts related to groundwater pollution?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

21. What is the importance of impacts related to the generation and disposal of liquid and solid waste to the soil or the subsurface?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

22. What is the importance of land use impacts (in general - you will be asked about farming later on)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

23. What is the importance of impacts related to aesthetics and visual intrusion?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

24. Any comment? Did we miss anything related to the geosphere/lithosphere?

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HYDROSPHERE

Please assess the importance of the following ORCHYD impacts in the hydrosphere

25. How important are impacts to the quantity of available water (i.e. retrieved from aquifers)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

26. What is the importance of impacts related to water consumption (for drilling)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

27. How important are impacts to the quality of available water (e.g. as formation damage may lead to aquifer contamination)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

28. What is the importance of impacts related to the pollution/contamination of surface waters?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

29. What is the importance of impacts related to the eutrophication of surface waters?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

30. What is the importance of impacts related to the (generation and) disposal of wastewater?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

31. Any comment? Did we miss anything related to Hydrosphere?

BIOSPHERE (including the socioeconomic environment)

Please assess the importance of the following ORCHYD impacts in the biosphere (including socioeconomic aspects)

32. What is the importance of impacts related to ecosystems (e.g. vegetation clearing, wildlife disturbances)?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

33. What is the importance of impacts related to biodiversity (of both flora and fauna)?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

34. What is the importance of impacts related to paleontological resources (effected by drilling)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

35. What is the importance of impacts related to human/public health?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

36. Overall, what is the importance of socioeconomic impacts?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

37. What is the importance of socioeconomic and cultural impacts on local communities?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

38. What is the importance of impacts related to unemployment?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

39. What is the importance of impacts related to farming?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

40. What is the importance of impacts related to tourism?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

41. What is the importance of impacts related to energy markets?

Mark only one oval.

	1	2	3	4	5	
Minor	⬭	⬭	⬭	⬭	⬭	Major

42. What is the importance of impacts related to energy security?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

43. What is the importance of impacts related to energy consumption (for drilling operations)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

44. What is the importance of impacts related to the use of materials (cement, metal alloys, muds etc.)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

45. What is the importance of impacts on the (design and) operation of traffic networks (e.g. disruptions, dislocation)?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

46. What is the importance of public perceptions related to the impacts of geothermal drilling?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

47. What is the importance of impacts on public health related to explosions?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

48. What is the importance of impacts on public health related to the buildup of radioactive materials?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

49. What is the importance of impacts related to the occurrence of incidents and accidents?

Mark only one oval.

	1	2	3	4	5	
Minor	◯	◯	◯	◯	◯	Major

50. Any comments? Did we miss anything related to the biosphere (and the socioeconomic environment)?

All done, thank you!

51. Before submitting, you may leave an overall comment below