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Assessing the Environmental Impacts of Deep Geothermal Drilling in the ORCHYD Project

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ABSTRACT

This paper examines the environmental impacts of the ORCHYD (Novel Drilling Technology Combining Hydro-Jet and Percussion For ROP Improvement in Deep Geothermal Drilling) Horizon 2020 project in a holistic manner. ORCHYD's goal is to increase the rate of penetration (ROP) of hard rock drilling from 1 to 2 meters per hour (m/h) to 4 to 10 m/h by combining two previously distinct, mature technologies: High Pressure Water Jetting (HPWJ) and Percussive Drilling. Based on a literature review, the environmental impacts of deep geothermal energy development on the lithosphere, atmosphere, hydrosphere, and biosphere were cataloged and assessed. These were compared to the novel drilling techniques developed by ORCHYD. Lithospheric impacts concern soil subsistence; microseismicity; soil profile; groundwater; solid waste; land use; and visual intrusion. Impacts related to the hydrosphere concerned water quantity and quality as well as wastewater. Atmospheric impacts concerned greenhouse gas emissions; local air pollution; odors; and noise. Lastly, impacts on the biosphere concerned ecosystems; human health; socioeconomic issues; material use; energy consumption; and energy security. Impacts were characterized on the basis of six different categories. Positive/negative to the environment; temporary/long term; reversible/irreversible; direct/indirect (nature): direct or indirect; not likely/potential/certain; and local/regional/national/international. The importance of impacts was assessed by the project partners via an online scoping survey. The assessment of impacts considered most important was complemented with a Life Cycle Assessment (LCA). The LCA was based on an assessment of alternate drilling scenarios. LCA considered ozone depletion, smog, acidification, eutrophication, and energy use for drilling, in addition to carbon emissions, which were measured in carbon dioxide equivalents. The effect of the distance between geothermal operations and major urban areas, as well as the effect of drill bit usage lifetime, were also taken into account. In comparison to ROP rates of 2 m/h in hard rock formations, scenarios with ROP rates of 4 to 10 m/h would result in the following reductions: carbon dioxide equivalent by 65.2%; energy consumption (as MJ surplus) by 68.9%; chlorofluorocarbons (CFC) equivalent by 3.8%; ozone equivalent by 66.2%; sulfur dioxide equivalent by 66.7%; and nitrogen equivalent by 67.1%. An Ecological Footprint Assessment (EFA) supplemented the LCA study from a biocapacity perspective expressed in global hectares, and found that the ecological footprint of geothermal drilling was reduced by 65.2%. All in all, most impact categories were inversely proportional to ROP. It was concluded that ORCHYD technologies will reduce emissions and the average energy required for drilling per meter, thus improving the environment profile of deep geothermal drilling.

1. INTRODUCTION

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). This paper aims to document the environmental impacts of deep geothermal drilling both qualitatively and use appropriate methods (life cycle assessment (LCA), carbon footprint analysis, ecological footprint analysis, and risk analysis) to assess the most important impacts of the novel drilling technology developed within the ORCHYD Horizon 2020 research project quantitatively. 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 formations; 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.

This paper is structured in the following sections. Section 2 describes the methodology that will be followed for the analysis. Section 3 assesses the environmental impacts of deep geothermal drilling 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 covers the characterization of impacts through a combination of scoping survey and literature review. Section 5 reviews 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 6 presents the EFA which supplements the LCA. Finally, Section 7 summarizes and concludes the study

2. METHODOLOGY

Initially, the literature review highlights the environmental impacts of deep geothermal drilling to their full extent. 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. Life cycle assessment compares 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 standards ISO 14040/44 (International Organization for Standardization, 2006) have set out that LCA is 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 the LCA of deep-drilling geothermal systems is to calculate the carbon intensity of geothermal operations and identify the key factors that affect it, with the ultimate aim of identifying processes and points of potential emission reduction. Geothermal plants have negligible direct emissions during operation but require a lot of materials and energy for exploration, development, and construction. A range of scenarios based on the improvement of ROP that ORCHYD seeks to achieve were built for a better realization of the environmental impacts of the proposed drilling technique. The effect of the distance between geothermal operations and major urban areas and the effect of drill bit usage lifetime were also considered.

An EFA complements the LCA study. Ecological Footprint Assessment 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 at Columbia University. It is a tool that aims to quantify human activity in the biosphere in ecological terms. It determines the extent of land required to produce all raw materials needed for human activities, including waste production and treatment. An area's biocapacity is always accounted for by developing 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 a hectare of land with the average biocapacity factor.

3 ENVIRONMENTAL IMPACTS OF DEEP GEOTHERMAL ENERGY

Any examination of the environment must follow the conceptual model, which views the environment as a system of four (conceptual) spheres: the atmosphere, hydrosphere, lithosphere, and biosphere. The abiotic environment is found in the first three spheres, while the biotic environment is found in the fourth.

3.1 Lithosphere

A geothermal drilling site typically occupies a space of 200 to 2500 m^2 (Yousefi et al., 2007). Geothermal drilling operations in this region change the physicochemical characteristics of soils. Due to the severity of the disturbance, high-temperature geothermal systems often have a more negative impact on the soil than low-temperature geothermal systems. A geothermal project's drilling and construction phases are often when the biggest alteration takes place. Development operations may result in decreased soil aeration, the formation's permeability, and water-holding capacity. According to Dhar et al. (2020), soil admixing and compaction can affect the viability of future plants. Additionally, increased surface runoff has the potential to cause additional sheet, rill, and gully erosion. Landslides, subsurface subsidence, and induced seismicity are some of the geological risks associated with geothermal drilling activities.

3.1.1 Subsidence

Geothermal drilling puts the geophysical environment in danger at selected sites (Yousefi et al., 2007; Ármannsson et al., 2000). One possible consequence of drilling for geothermal energy is soil subsidence (Yousefi et al., 2007). Subsidence of the earth's surface may result from the removal of huge amounts of fluid (such as geothermal water) from underground and groundwater (geothermal) reservoirs. For geothermal sites with thermally changed soil, landslides can also occur and can be fairly severe. This might limit the locations that can be used for geothermal development (Yousefi et al., 2007). When huge volumes of hot water were dumped into a river without reinjection, subsidence rates of up to 40 cm per year have been documented (Yousefi et al., 2007; Allis, 2000). Reinjecting water under pressure is another need for the construction of a geothermal plant in order to renew the geothermal resource. Such reinjection, when combined with drilling activities, can assist in causing minor natural cracks in the drilled rocks to become active or spread. According to Yousefi et al. (2007), the presence of a highly compressible formation above or in the upper part of a shallow reservoir, a pressure drop in a reservoir caused by fluid withdrawal, and the existence of high permeability paths between a reservoir and a compressible formation all increase the likelihood that subsidence will happen. Reinjection normally takes place some distance from the production well to avoid reducing the temperature of the production fluid with the colder rejected waste fluid. Therefore it might not be able to prevent subsidence. The following section discusses how microseismicity may also be related to large-scale subsidence.

3.1.2 Seismicity

Deep drilling for oil and gas frequently results in induced seismicity, which manifests as small seismic tremors known as micro-earthquakes. This phenomenon is brought on by changes in the fluid pressure inside cracked or defective rock formations. Rapid slide on a fault plane, a preexisting area of weakness in the crust, causes seismicity. As noted by Buijze et al. (2020), faulting mostly takes place as a brittle process in the upper crust. Because even tiny increases in stress can result in massive seismic occurrences, critically stressed faults are the main source of induced seismicity in a particular stress regime. When energy is released and transferred through the rock, seismic waves are produced. The incidence and intensity of such events are influenced by site-specific geophysical regime features, which are fairly frequent occurrences during geothermal production.

Numerous geothermal systems have been in use for many years without experiencing any seismic activity. In some cases, geothermal projects are situated in distant places with considerable natural seismicity or seismic activity that does not influence populations. However, induced seismicity is a problem for geothermal projects close to urban or rural people to supply electricity to a heat network since it might endanger infrastructure and lead to civil unrest (Buijze et al., 2020).

Deep geothermal drilling is concerned with induced seismicity since such activities inside crystalline basement are prone to create (the so called "felt") seismicity. Before fluid flow between wells can be produced, i.e., bigger pressure fluctuations, the crystalline basement must typically be stimulated. According to Buijze et al. (2020), minor stress increases (0.01-1 MPa) can be sufficient to generate seismicity on existing severely stressed faults. Overall, the principal factor contributing to generated seismicity in geothermal activities is fracturing and pore pressure variability during reinjection of geothermal fluids. Induced seismicity can also be caused by poroelastic stress. Rock volume varies as a result of pore pressure fluctuations. According to Buijze et al. (2020), the amplitude of poroelastic stress is affected by pressure variations, the elastic characteristics of the rock, and its shape. Post-injection seismicity is also conceivable because liquid diffusion can raise pore pressure long after the injection ends. Some of the most significant seismic occurrences in Enhanced Geothermal Systems (EGS) occurred after the stimulation was discontinued, for example, Soultz-sous-Forêts and Basel (Buijze et al., 2020).

Deep drilling operations are frequently stigmatized by the public due to unfavorable conceptions about shale gas fracturing. Fracking and geothermal exploration have similarities but significant distinctions (Homewood, 2018). Deep geothermal drilling techniques differ significantly from fracking techniques, which should be explained to the public. Although the two procedures share fundamental principles, it is vital to note that geothermal drilling occurs at far higher depths, in the basement up to 4 km (far beyond the water table), and fracking occurs at 1.5 km. Because of this, surface vibrations are uncommon in deep geothermal drilling techniques. The geothermal method of increasing water flow in rock (such as granite) is analogous to the fracking process of capturing shale gas. The procedure for opening and enhancing pre-existing fractures in rock (such as granite) is a hydro-shearing process that uses the surface roughness of rock fractures to allow self-propping of open fractures, eliminating the requirement for chemical additives in the pressured water (in the case of the site discussed by Homewood, 2018). Only a portion of the fluid returns to the surface, and operators are expected to keep gas leaks to a minimum. Gaseous emissions from geothermal drilling may be discharged only when essential for safety.

Seismicity can impede geothermal development since it can significantly affect the stability of geothermal pipes, drains, and well casing (Yousefi et al., 2007; Noorolahi, 2005). Reinjection increases pressure while decreasing the chance of subsidence, as Archer (2020) suggests. For proactive project management, geological risk assessment technologies such as regular seismic monitoring should be employed. Administrative authorities may request such surveillance. Because of their modest scale, such incidents may go unnoticed by the general population (Bošnjaković, Stojkov & Jurjević, 2019).

3.1.3 Soil profile

Geothermal drilling is also associated with soil profile alterations. Surface disturbances and soil movement generate soil erosion, the most severe environmental problem in the lithosphere since runaway soil erosion leads to desertification, a worldwide environmental threat. The earth at a drilling location is likely to be compressed and altered, and waste soil and drill mud may be deposited around the drill (Yousefi et al., 2007). Flooding may be connected to bogging with hot waters. Emitted elements can pollute soils either through air or polluted litter fall, causing necrosis, defoliation, decreased growth, early senescence and chlorosis, as Dhar et al. (2020), suggest. Furthermore, a rise in the quantities of boron, ammonia, sulfur, arsenic and mercury can be observed in the vicinity of geothermal plants. Soil mineralization is another major environmental problem. Arsenic (As), boron (B), fluorine (F), mercury (Hg), and sulfur (S) concentrations may need to be investigated in the context of a soil management plan, depending on the particular geological qualities of each location.

3.1.4 Groundwater

Groundwater resources are an essential supply of drinkable water for humans and a source of water for rivers and wetlands. Water sources constantly change in composition according to lithological properties and site-specific geo-climatic circumstances. Because geothermal drilling occurs deep below the water table, heavy metals and other pollutants found in thermal waters or drilling fluids are unlikely to contaminate the water table or subsurface aquifers. The physical repercussions of fluid loss are even more concerning (Yousefi et al., 2007; Ármannsson et al., 2000). However, improper geothermal well drilling and blowout devices can impact geothermal fluid incursion into aquifers (Rabet et al., 2016).

The usage of huge amounts of synthetic substances in agriculture, industrial production processes, residences, animal husbandry, and human healthcare has led to their continuing widespread presence in aquatic and terrestrial habitats, as Garcia-Gil et al. (2018) claim. Significant chloride and salt concentrations and high lithium, chromium, and boron concentrations have been found in groundwater and surface waters around geothermal wells, as Tomaszewska et al. (2020) point out. Heavy metals can also collect around geothermal drilling sites, causing pollution of waters used for irrigation. Consumption of crops and animal products grown near drilling sites can have significant consequences for human health, as Yilmaz & Ali Kaptan (2017) suggest. According to Soltani et al. (2021), well drilling and construction must be properly planned and conducted since well casing failure is one of the most common causes of fast groundwater downflow and surface water contamination. Shah et al. (2018) emphasized the relevance of hydrochemical parameters of water and aquifer hydraulic features for drilling operations and groundwater management.

3.1.5 Liquid and solid waste

Geothermal drilling activities require a significant volume of water, which results in a large amount of wastewater. The majority of disposal difficulties are connected to the handling of geothermal water rather than drilling fluids. According to Kabay et al. (2017), geothermal water that ascends to the surface interacts with the wall rocks, producing mineral disintegration. As a result, geothermal waters are rich in boron, arsenic, fluoride, and heavy metals. Some elements, notably boron, which exists at high percentages, hinder the direct use of geothermal fluids as irrigation or drinkable water and create chemical contamination and environmental concerns in groundwater and surface waters. According to Sayed et al. (2020), fluids from geothermal fields are often saturated with formation ingredients (such as carbonate/sulfate salts, silica, and silicate salts), which precipitate when temperatures decrease and generate solid wastes that must be appropriately managed. The final use or disposal of the water is also governed by regulation and is an essential consideration. Industrial water waste can be dumped directly into streams, rivers, and other surface water bodies. The usage of evaporation ponds is a frequent practice. However, Finster et al. (2015) pointed out that their utilization is constrained by huge acreage needs, loss of water recycling capacity, time-consuming operations, the possibility of air quality difficulties, and salt deposition problems.

Drill mud leftovers, cuttings, and other drilling additives are the primary source of solid waste at geothermal sites. Cuttings, cement residues, and drilling mud are common drilling wastes. Shale shakers are machines used to separate drilling mud from drilling cuttings. Domestic trash such as paper, plastics, food waste, and so on are generated by office operations (connected to geothermal drilling) (Utami et al., 2020). The overall amount of solid waste produced is minor and does not pose a significant environmental risk (Bayer et al., 2013).

Waste management should be founded on the concepts of waste reuse, recycling, and safe waste disposal. The recovery and recycling of wastewater is a significant part of geothermal drilling operations. Management choices vary depending on the physical and chemical qualities of the water, as well as the volume and pace of water creation. Waste generation is reduced by the right installation of equipment and frequent inspection, soil and water monitoring, complete injection, solid waste separation and storage at designated places, and hazardous waste labeling, as Soltani et al. (2021) noted. Tong and Elimelech (2016) stated that wastewater reuse not only decreases the volume and environmental danger of discharged wastewater but also alleviates the demand on ecosystems arising from freshwater extraction. Through reuse, wastewater is no longer considered a “pure waste” that possibly hurts the environment but rather an extra resource that may be exploited to achieve water sustainability. Inadequate wastewater treatment of discharges into the aquatic environment can result in severe contamination and public health hazards.

3.1.6 Land use

Land use changes are connected to the area occupied by a geothermal plant (including drilling sites). According to Bošnjaković, Stojkov and Jurjević (2019), the average amount of land disruption during the construction of a 50 MW power plant may be about 0.85 km^2, 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 and Jurjević (2019) suggest that a 50 MW power plant can contain up to 25 production and 10 reinjection wells, although binary-type facilities are typically smaller, ranging from 0.5 to 10 MWe. Dhar et al. (2020) said that the minimum spacing of wells to minimize interference is at least 200 m, which is an important aspect of any geothermal project. Land use constraints frequently hinder geothermal installations. Exploration and utilization of geothermal reservoirs are complicated since they may be located near forest protection areas, national parks, tourist regions, historical sites, very productive farmlands, and/or under a metropolis (e.g., Paris). According to Goldstein et al. (2013), instances of unobtrusive, scenically landscaped projects (Matsukawa, Japan) and integrated tourism/energy developments (Wairakei, New Zealand, and Blue Lagoon, Iceland) exist. The mobilization and demobilization of rails for the movement of drilling equipment in a few days influence the transport network of a specific target region, necessitating the development of a traffic management strategy. Nonetheless, directional drilling methods and associated pipeline networks have enabled the use of adjacent land for various purposes, such as farming, horticulture, and forestry.

3.1.7 Visual intrusion

Landscape disturbances (such as land removal and the construction of access roads) caused by geothermal drilling (including exploration, production, and restoration) have aesthetic and visual implications. When intense deep geothermal production needs many wells, the construction of drilling sites and access infrastructures, particularly in wooded areas, can deface landscapes. Because drilling happens continually (24/7), nighttime light pollution may be a concern. The drill rig will likely be 25 to 60 meters tall and visible outside the drilling location (Homewood, 2018). However, the visual impact of drilling activities is anticipated to be minor and transient, as drilling towers are only present during the drilling phase (Finger & Blankenship, 2010). Construction of roads, well pads, and power plant infrastructure results in cut-and-fill slopes and other reworkings of an area's topography (including soil movement), although these modifications are not considered substantial (Yousefi et al., 2007). It is suggested that while visual/scenery consequences may be detrimental, geothermal manifestations (associated with geothermal drilling) may enhance tourism and be historically significant (Yousefi et al., 2007).

3.2 Hydrosphere

Hydrosphere issues related to geothermal drilling include water consumption; surface and stormwater runoff; thermal and chemical pollution of surface waters impacting causing eutrophication and impacting water quality (Ármannsson et al., 2000); and the unlikely event of contamination of groundwater (which was discussed in the lithosphere section) are extensively presented in this section.

3.2.1 Water quantity and quality

Water is used extensively during the life cycle of a geothermal plant. The amount of water consumed is determined by the size of the plant, the operating principle, the cooling method, and the working temperature. Drilling activities need a large amount of water as well. Water resources are mostly utilized during the drilling phase of closed-loop geothermal facilities. According to Dhar et al. (2020), around 5 to 30 m^3 of water is required to build 1 m of well. While water is commonly employed in geothermal energy extraction, most of it is lost or squandered in subterranean fields owing to leaks (Sayed et al., 2020). When traversing broken rocks, high mud consumption is common. Aside from the large amounts of water required, deep geothermal drilling needs a well-designed drilling plan that minimizes the danger of damaging groundwater supplies. The major sources of water pollution include well casing failure, pipeline leakage, and spills. Furthermore, drilling can create formation damage, which can lead to aquifer pollution.

3.2.2 Wastewater

Water created during drilling operations makes up a portion of a geothermal power plant's effluent. Its composition is site-specific, and temperature influences the proportion of certain molecules. Water is cycled in a closed loop during geothermal operation, so no gas or minerals are released at the surface. When the geothermal field is water-vapor dominating, pollutants are usually found in steam, making them easier to regulate and treat. Liquid waste contamination is more common in water-dominated reservoirs. According to the properties of geothermal fluids, geothermal resources are typically classed as low, medium, and high enthalpy (or temperature) systems. Water (or liquid) dominated geothermal systems are distinguished from vapor (or dry steam) dominated geothermal systems (Duque, 2013). Water-dominated geothermal systems are the most frequent kind, with temperatures reaching 225°C. A continuous phase of vapor and a water phase coexist in vapor-dominated systems, with the vapor phase regulating the pressure. Most contaminants are in a steam state in water vapor-dominated geothermal fields, and surface water pollution is easier to regulate than in water-dominant reservoirs. Sodium chloride (NaCl), potassium chloride (KCl), and calcium chloride are the most frequent contaminants ($CaCl_2$). Smaller amounts of carbonates, sulfates, magnesium (Mg), lithium (Li), and mercury (Hg) may also be discovered. The dissolved mineral concentration in geothermal waters in Croatia ranged 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 prevalent components (Bošnjaković, Stojkov & Jurjević, 2019). In terms of the presence of (heavy) metals, arsenic (As) and boron (B) can pollute freshwater and cause public health hazards depending on their composition and concentration. Minerals dissolved in water may be commercially extracted (Homewood, 2018). Specific lithium and silica extraction initiatives are based on this premise.

3.3 Atmosphere

In a geothermal plant, geothermal steam is a significant source of atmospheric effects. Other emissions are also released into the atmosphere during drilling operations, depending on the circumstances at the site. The atmospheric effects of a geothermal plant, like all other impact categories, are geographically and geologically dependent; hence each site should be analyzed independently (Pratiwi, Ravier & Genter, 2018). The next part will examine greenhouse gas emissions, local air and traffic pollution, smells, and noise.

3.3.1 Greenhouse gas emissions

Greenhouse Gas (GHG) emissions are one of the most serious issues raised by geothermal drilling. According to Tomasini-Montenegro et al. (2016), the key mechanism contributing to global warming is the burning of diesel during drilling. Lacirignola et al. (2014) identified drilling depth, number of wells, and fuel consumption for drilling processes such as casing, cementation, and mud circulation as factors of significant relevance for the overall quantity of GHG emissions from a geothermal project. Lacirignola et al. (2014) found that drilling depth and number of wells, in conjunction with installed capacity, accounted for 75% of the variable in GHG performance among sample geothermal facilities investigated.

3.3.2 Local air pollution

Carbon dioxide (CO_2), methane (CH_4), hydrogen sulfide (H_2S), ammonia (NH_3), hydrogen (H_2), nitrogen (N), argon (Ar), and radon (Rn) are all gasses found in geysers. The most deadly is hydrogen sulfide. Carbon dioxide (CO_2), hydrogen sulfide (H_2S), ammonia (NH_3), volatile metals, minerals, silicates, carbonates, metal sulfides, and sulfates are all emitted into the atmosphere by geothermal drilling (Dhar et al., 2020). Thermal air pollution is also caused by geothermal energy (Yousefi et al., 2007; Ármannsson et al., 2000). Geothermal drilling is also indirectly responsible for air pollution caused by traffic and the development of roads to serve the wells, as Soltani et al. (2021) explain. Watering dirt roads during heavy traffic hours and throughout the warm months can be a typical measure to minimize the relevant effects.

3.3.3 Odors

Odors are a frequent neighborhood complaint about geothermal drilling. After geothermal emissions are vented and distributed, hydrogen sulfide (H_2S) is poisonous and connected to foul smells (Sayed et al., 2020). However, it is seldom present in sufficient amounts to be dangerous (Goldstein et al., 2011). As a result, H_2S odor emissions are rarely examined in LCA studies (Marchand et al., 2015).

3.3.4 Noise

Noise is a localized consequence of geothermal development that should be considered in close proximity to urban areas (Tarlock & Waller, 1977; Marchand et al., 2015). Noise is unavoidable during drilling (Homewood, 2018), when new wells are drilled, and when geothermal plant operations begin (Bayer et al., 2013). Diesel generators emit noise, which might harm the geothermal site's flora and wildlife. While noise levels of roughly 80 dB lessen disruption greatly in the first 10 meters, noise levels of 120 dB exceed 75 dB even at 100 meters. Installing noise barriers would reduce the impact of loud geothermal drilling activities.

3.4 Biosphere

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

3.4.1 Ecosystems

Flora and fauna habitats can be affected or deteriorated by geothermal drilling due to erosion, runoff, and noise created by seismic surveys and the operation of drilling gear (Sayed et al., 2020). Wildlife breeding or disturbance, foraging, migration of endangered species, seed bank depletion, and loss of native plant species are all possibilities (Dhar et al., 2020). Geothermal drilling might endanger uncommon habitats and have an impact on biodiversity. Drilling may influence paleontological resources.

3.4.2 Health impacts

Public health should be a goal for every project, and it is undoubtedly an essential problem related to geothermal energy's societal perspective. Geothermal development potential targets are often located in the vicinity of densely inhabited areas, as Chen et al. (2020) suggest. These areas of geothermal interest constitute the residence of roughly 500 million people worldwide. Because of their minimal emissions throughout their life cycle, geothermal plants are considered ecologically beneficial. Compared to coal and hydrocarbon plants, geothermal energy does not negatively influence human health (Pan et al., 2019). It may be claimed that microearthquakes are the most dangerous to human health, yet their magnitudes are rarely large enough to cause illness or fatalities (Pellizzone et al., 2017). However, the growth of geothermal facilities has been connected to human health risks owing to the emissions or buildup of heavy metals, radioactive elements, and poisonous chemicals. Furthermore, geothermal drilling may produce noise, which is a public nuisance and may be related to health risks (if long-term). Assessing the health implications of geothermal plants, particularly geothermal drilling, is difficult for governments, investors, and academics.

Human health problems may be linked to air pollution. Acute and chronic respiratory effects and cardiovascular health concerns have been recorded in areas near geothermal power facilities (Bustaffa et al., 2020). Human health consequences are primarily associated with carbon dioxide (CO_2), hydrogen sulfide (H_2S), methane (CH_4), mercury (Hg), and ammonia (NH_3) emissions (Pan et al., 2019). However, their levels are insignificant to warrant worry (Noorollahi et al., 2019). Like all fuel usage, particulate matter emissions can cause respiratory problems and potentially lead to cancer. Apart from particulate matter, sulfur dioxide (SO_2) created during diesel-fueled drilling operations poses a substantial hazard to human health, despite the fact that SO_2 emissions from geothermal facilities are much lower than those produced by fossil fuel plants.

The inherent radioactivity of rocks has a significant influence. Deep geothermal drilling is often carried out in granite rock formations (as planned by ORCHYD). Some granites and clays naturally create radon and background radiation; radioactive decay is the reason such granites produce heat (Homewood, 2018). This sort of rock naturally emits radon and background radiation. The radon levels released during drilling operations are extremely low and pose no danger to humans. However, a rigorous hazardous waste management strategy should be implemented to minimize the accumulation of radioactive materials. Water quality must also be checked, even though no radon gas is released when all water is cycled in a closed circuit.

Filter deposits may also include radioactive elements, which occur naturally (in low amounts) during water-rock processes. Heavy metals can seep into water aquifers if they escape the well casing. According to Dhar et al. (2020), waste fluids from drilling and testing can create gullying and, depending on composition, lead to pollution of freshwater bodies. Thermal waters from Tibet's Yangbajing geothermal area brought excessive proportions of boron and arsenic into a downstream river, causing health concerns among residents.

Accidents are a worry in deep geothermal drilling operations. The major category of interest is induced seismicity, as explained. Blowout incidents are considered a concern during geothermal drilling operations since they can have disastrous consequences for the whole project and the personnel. Blowouts are prevalent in any drilling operation and result from a lack of well control. Spada, Sutra, and Burgherr (2021) classify them as the third most critical accident type during the life cycle of a geothermal project.

To minimize and eliminate negative effects on human health from geothermal exploration, rigorous site selection, strategic environmental evaluation, and effective monitoring and control are required. Pan et al. (2019) advocate incorporating design lessons acquired from previous development into new developments. Bustaffa et al. (2020) propose additional epidemiological cohort studies defined by continuous human biomonitoring of communities living in geothermal zones. As ORCHYD aims to develop new drilling techniques that effectively improve ROP, reduce drilling time, and reduce diesel consumption from generators, it is reasonable to expect that particulate matter and gaseous emissions into the atmosphere will be reduced, contributing to fewer health impacts on humans.

3.4.3 Socioeconomic impacts

ORCHYD aims to create a revolutionary drilling technology that will improve energy output by reducing drilling costs in hard rock sections by 65% and the total cost of deep geothermal well building by 30%. Furthermore, the novel linked HPWJ-Percussion system system can drill wells, is less expensive, uses less water, and is more controlled than conventional fracking stimulations.

The socioeconomic implications of such a project are significant (Yousefi et al., 2007; Ármannsson et al., 2000). Local community perception, governmental regulations, non-governmental organizations (NGOs), and other social elements all impact the growth of geothermal activities in each location. Environmental and economic consequences are critical for the public acceptability of geothermal projects. The cultural and economic factors of local populations, as well as the attitude to development and strategies chosen by energy firms, all influence social acceptability. Deep geothermal drilling activities can have a favorable impact on the energy and labor markets from the standpoint of economic growth. The percentage of geothermal energy in various states' energy mix will increase significantly, thus lowering the cost of power production for customers. New job opportunities will cut unemployment rates at the local and national levels, often creating well-paying work.

3.4.4 Energy security

Improved availability of geothermal energy will also impact state energy security. According to Adiansyah, Biswas, and Haque (2021), geothermal energy is dispersed in over 30 nations globally, with the ten countries with the most geothermal capacity being the United States, Indonesia, the Philippines, Turkey, Kenya, Mexico, New Zealand, Italy, Japan, and Iceland. Indonesia has the world's biggest geothermal potential, including promising locations in Java, Sumatera, Sulawesi, and East Nusa Tenggara. These authors agreed that geothermal energy might help a country's energy security. According to another source (Lacirignola & Blanc, 2013), the majority of the installed geothermal capacity is divided among a few nations, notably the United States (29%), the Philippines (17.8%), Indonesia (11%), Mexico (9%), and Italy (7.8%).

ORCHYD's work is projected to improve the energy security of particular governments and regions worldwide since it will increase the areas with geothermal resources worth researching and make drilling cheaper and faster. According to Lacirignola et al. (2014), large regions of Europe have a high vertical gradient, a geothermal anomaly that makes them suitable for EGS. These locations include France, Germany, Italy, Hungary, Serbia, Romania, Spain, and Turkey.

3.4.5 Energy consumption

Drilling geothermal wells is the most energy-intensive step of a geothermal project's life cycle. The energy consumption during geothermal drilling accounts for a large portion of the total energy recovery process efficiency. The total energy consumed during the drilling phase is the sum of the energy necessary to drive and move the drill string, attach casings, apply cementation, pump mud, and carry supplies and equipment. The literature has evaluated various energy consumption rates for geothermal drilling. Drilling operations for a 6 km geothermal well need a total of 0.384 TJ/day, resulting in daily consumption of 8475 kg/day, as stated by Li & Lior (2015), using the specific chemical energy of diesel (45.3 MJ/kg). McKay, Feliks, and Roberts (2019) offered an approximate quantity of 3785 L per day for digging boreholes in granite formations. Frick, Kaltschmitt, and Schröder (2010) proposed a rate of 6 to 8 GJ per drilled meter, whereas Paulillo, Striolo, and Lettieri (2019) proposed a much lower figure of 2 MJ/m. Karlsdóttir et al. (2015) and Legarth and Saadat (2015) proposed a linear link between drilling depth and diesel fuel utilized (2005). Diesel consumption in various geothermal locations is determined by drill selection and geological circumstances (Karlsdóttir et al., 2015). However, for various types of soil and subterranean rock stresses, the rate of penetration (ROP, m/day) and time required to drill wells of the same depth will fluctuate, as Li and Lior (2015) pointed out. Geological factors and current technology restrict the ability to increase total drilling efficiency. ORCHYD aims to improve drilling process efficiency by boosting ROP, and minimizing energy consumption.

3.4.6 Material use

Materials used in geothermal drilling operations are diverse. The complete list of materials that will be utilized in ORCHYD has not yet been determined. However, an illustrative list of components for drilling activities comprises drilling rig materials, well casing and cementing drilling fluids and worker supplies.

Metals are a significant component of the materials used in geothermal drilling. In various applications and amounts, soft and low alloyed metals, stainless steel, titanium and titanium alloys, nickel alloys, copper-based alloys, cobalt alloys, and aluminum alloys are employed. Menberg et al. (2021) proposed an indicative steel casing quantity of 124.4 kg/m±5%. Drilling bits are made of metal and other materials such as tungsten carbide, diamond, and graded materials. Metal materials used in the drill-hole have little recycling value. Metals from the surface might be recycled. Drilling operations frequently make use of concrete and cement. Concrete is made up of silica, sand, and Portland cement, whereas casing is made out of phosphate glass cements. For wells sunk to depths ranging from 1800 to 3000 m, the cement quantity ranges between 180 and 400 t. (McKay, Feliks & Roberts 2019). Again, wellbore cement and concrete have no recycling potential, but surface cement and concrete can be recycled. Elastomers, such as fluorine elastomers, are employed as pipeline-connecting components. Other elastomers can be utilized as valve seals. In water lines, fiber-reinforced materials are employed as anti-corrosives. These materials have very poor recycling potential. In most situations, drilling fluids are composed of water and bentonite. Other additions include different salts, xanthan gum, and barite compounds. The specific volumes and compositions differ depending on the geological regime of drilling operations. Climate and seasonal circumstances, vocational background, and other things determine workers' materials. These are difficult to quantify, but it is reasonable to presume that paper, plastic, and metal will be utilized and have recycling potential.

Figure 1 depicts numerous processes' contribution to a geothermal plant's life cycle (Martin-Gamboa, Iribarren, & Dufour, 2015). Diesel and steel production are the two most significant contributors to environmental consequences in the context of drilling activities. Diesel consumption appears to be a determining factor in terms of abiotic depletion potential, acidification potential, and cumulative energy demand. It has a little but considerable impact on the potential for global warming and photochemical oxidant production. Steel has a strong influence on the potential for photochemical oxidant production but a moderate impact on the potential for abiotic depletion, global warming, acidification, and cumulative energy consumption.

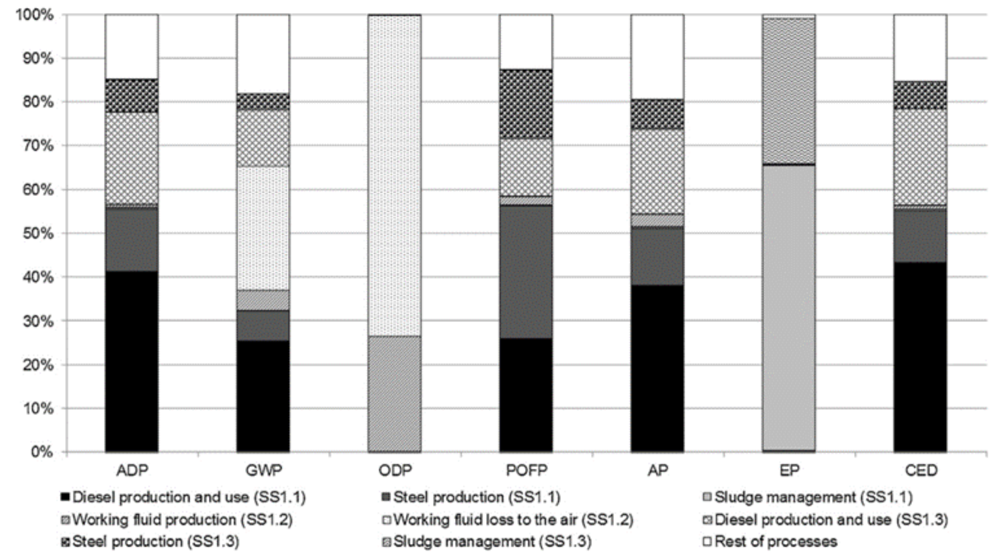


Figure 1: Contribution of different materials used in geothermal processes to environmental impacts (ADP: abiotic depletion potential; GWP: global warming potential; ODP: ozone layer depletion potential; POFP: photochemical oxidant formation potential; AP: acidification potential; CED: cumulative energy demand) (Martín-Gamboa, Iribarren & Dufour, 2015)

SINTEF (Norway) has developed a general technological platform for the development of functionalized polyhedral oligomeric silsesquioxanes (POSS) as additives to tune or improve material qualities. POSS has also been functionalized on graphene derivatives via covalent bonding. The lubricating characteristics of graphene-incorporated POSS sol-gel coatings have been shown.

One goal is to use ecologically safe additives with excellent thermal stability in order to minimize friction and regulate wettability. The following additions are of interest as friction reducers: (1) POSS-based additives, (2) graphene and its derivatives, and (3) their composites. Graphene will be functionalized to increase processability and compatibility with the specified drilling fluids.In the context of the ORCHYD project, SINTEF provides access to material and property data via a generic database platform. Drillstar has made strides in the development of percussive hammers, including novel designs and mud-resistant materials.

4. IMPACT CHARACTERIZATION AND QUANTIFICATION

4.1 Scoping survey

An online questionnaire was used to submit a list of the environmental consequences given and addressed in Section 3 of this paper to the judgment of the ORCHYD partners.The different educational backgrounds and level of experience that respondents participating in the consortium of ORCHYD, including university professors, (postdoctoral) researchers, and professionals, many of whom has previous experience in Horizon 2020 projects, provided an insight on the focus points of the environmental impact assessment. The survey is limited by the number of respondents (16) intentionally, for the realization of the viewpoint of the associating research teams (namely ARMINES ParisTech, SINTEF, Imperial College London and Drillstar Industries) on environmental impacts of deep geothermal drilling. A larger scale questionnaire open to the public was designed and analyzed by UPRC (Paravantis et al. 2023), as well. Respondents were asked to rate the significance of each influence on a Likert scale ranging from 1 to 5. The study of reactions was evaluated alongside the characterisation of the effects and aided the University of Piraeus team in establishing priorities for quantifying the most significant impacts. In this regard, the survey served as the scoping phase of a standard environmental impact assessment study. Table 1 has a comprehensive list of the mean, minimum, and maximum values for each category (each item is listed with an abbreviated textual description). A higher mean value indicated that respondents valued the environmental and socioeconomic elements of the given item; a lower mean value indicated the reverse. As a result, extra work was put into this study to thoroughly investigate the most significant elements using quantitative methodologies (where possible).

Table 1: Descriptive statistics of response items

Item	*Mean*	*Minimum*	*Maximum*
Overall environmental	3.75	2	5
Overall socioeconomic	3.94	3	5
ATMOSPHERE			
Greenhouse gasses	3.50	2	5
Gaseous pollutants drilling	3.00	1	5
Local air pollution	2.94	1	4
Odors	2.56	1	5
Noise	3.63	2	5
GEOSPHERE/LITHOSPHERE			
Subsidence landslide	2.93	1	5
Microseismicity	4.00	2	5
Soil erosion	2.33	1	4
Soil mineralization	2.81	1	5
Soil waterlogging flooding	2.79	1	4
Groundwater pollution	3.50	2	5
Liquid solid waste	3.31	1	5
Land use	2.56	1	4
Aesthetics visual intrusion	2.27	1	5
HYDROSPHERE			

Item	*Mean*	*Minimum*	*Maximum*
Quantity water aquifers	2.88	1	5
Water consumption drilling	3.00	1	5
Quality water aquifers	3.25	1	5
Pollution surface waters	3.19	1	5
Eutrophication	2.29	1	5
Generation disposal wastewater	3.13	2	5
BIOSPHERE (Ecosystems and manmade environment)			
Ecosystems vegetation wildlife	2.94	1	5
Biodiversity flora fauna	2.00	1	4
Paleontological resources drilling	2.00	1	4
Human public health	2.44	1	5
Overall socioeconomic 2	3.38	1	4
Local communities	3.06	1	5
Unemployment	2.69	1	5
Farming	2.38	1	4
Tourism	2.00	1	4
Energy markets	4.00	1	5
Energy security	3.63	1	5
Energy consumption drilling	3.56	1	5
Materials cement metal muds	2.75	1	4
Traffic networks	2.38	1	5
Public perceptions	3.88	1	5
Public health explosions	2.50	1	4
Public health radioactive	2.13	1	5
Incidents accidents	3.00	1	5

A number of conclusions were drawn from Table 1.

- The most significant items (mean=4) were microseismicity and repercussions on energy markets, with microseismicity receiving a minimum rating of 2 (compared to a minimum rating of 1 for impacts on energy markets).
- The second most important factor was public perception, which had a mean rating of 3.88.
- Noise and energy security came in third (mean=3.63).
- The following most important factors were energy usage during drilling (mean=3.56) and greenhouse gas emissions (mean=3.5). These two components represent a critical feature of the project: its climate change emissions, which are evaluated in this study using Life Cycle Assessment (LCA). Although local air pollution was not evaluated as less important (mean=2.94), it is discussed in this study in the context of LCA.
- Finally, groundwater contamination was equivalent to the preceding two categories in significance (mean=3.5), and it was also explored in greater depth in this study.

4.2 Characterization of environmental impacts

Impact types may be characterized as follows: positive/negative (type): favorable or unfavorable to the environment (including the viability of species, habitats and communities); 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; reversible/irreversible (nature): depending on whether the impacted species and communities will recover (on their own) or that (special) mitigation measures will be required; direct/indirect (nature): referring to the source/origin of the impact and whether it acts directly or indirectly on the environmental target; not likely/potential/certain (likelihood): with probability cutoffs to be determined, e.g., up to 10%, 10 to 70%, over 70%; local/regional/national/international (scale): characterizing geographical restrictions to specific habitats, communities, and regions. Table 2 contains such a characterization of the impacts discussed in previous sections.

Table 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

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 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
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

5. LIFE CYCLE ANALYSIS (LCA)

5.1 Setup of the 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, knowing the final diesel consumption and materials required in specific drilling sites. At this stage, LCA has a preliminary and approximate character based on evaluating expected results.

Apart from carbon emissions, which will be expressed in terms of CO_2 equivalent, the present LCA will also cover additional 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 harmful ultraviolet (UV) radiation for humans and terrestrial and aquatic ecosystems. Smog, which is a reaction of nitrogen oxides (NOx) 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 damage 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 to 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 global civilization as a result of producing 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) explained that in Soultz-sous-Forêts the average speed in soft sediments above 1 km of depth was 8m/h. In hard sediments below 1 km of depth the respective speed was 5m/h. Finally, in granite zones the drilling speed was just 2m/h. Higher ROP values than the mean value, generally occurs as an effect of a localized fractured 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.

We developed eight scenarios with average total ROPs, ROPs in the hard rock zone, and drilling operation lengths for each scenario, as shown in Tables 3 and 4.

Table 3: 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: 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 for the expression of emission factors and material quantities. The Life Cycle Inventory utilized included 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 used, 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 m³ of concrete (approximately 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 the 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), (McKay, Feliks, and Roberts, 2019).

Other material categories were also examined and presented in the respective parts of the table for each scenario. It is important to note that special calculations are required for cement and concrete use, as they are highly dependent on the borehole diameter and drilling depth.

As Kipsang (2013) noted that drilling of geothermal wells is done in stages, with each stage having a lower diameter than the preceding stage and each secured by steel casings that are cemented in place before drilling the next stage. The drilling depth is 5100 m and it is divided in four sections, two in sedimentary rock and two in fractured granite formation. The first section from the surface to 574 m was drilled at a 24-inch diameter. The second section between 574 m and 1447 m was drilled at a 17½ inch diameter. The third section between 1447 m and 4580 m was reopened (initially drilled in an 8½ inch diameter) at a 12¼ inch diameter. The final section was drilled at an 8 ½ inch diameter down to 5100 m.

A total of 33 tricone bits were used, working an average of 40 hours each. It is critical to extend drill bit longevity and minimize drill bit consumption for all drilling operations, particularly deep EGS drillings, in order to lower total cost. It can take up to 18 hours to replace a drill bit at 3 km depth, and the daily drilling cost can be 30,000 Euros or higher.When developing the drilling program and selecting the best-suited drill bits, it is therefore advantageous to draw on expertise from previous drilling operations in similar geological settings, in this instance the crystalline basement, as Rosberg and Erlstrom (2021) point out. In the developed scenarios, an improvement in 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.

5.1.2 Analysis of scenarios

The baseline scenario considers an average ROP of 3.4 m/h, progressively leading to an average ROP of 9.2 m/h in scenario 8. The total impacts of all scenarios are illustrated in Figure 2. The results underscore the favorable environmental impacts of higher ROP and highlight the importance of ORCHYD in the path toward sustainable geothermal drilling.

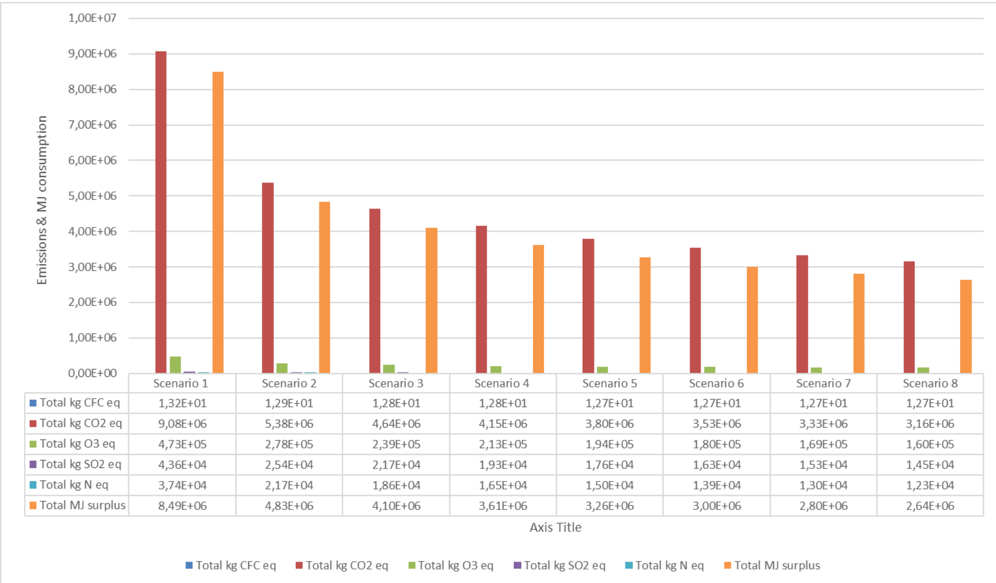
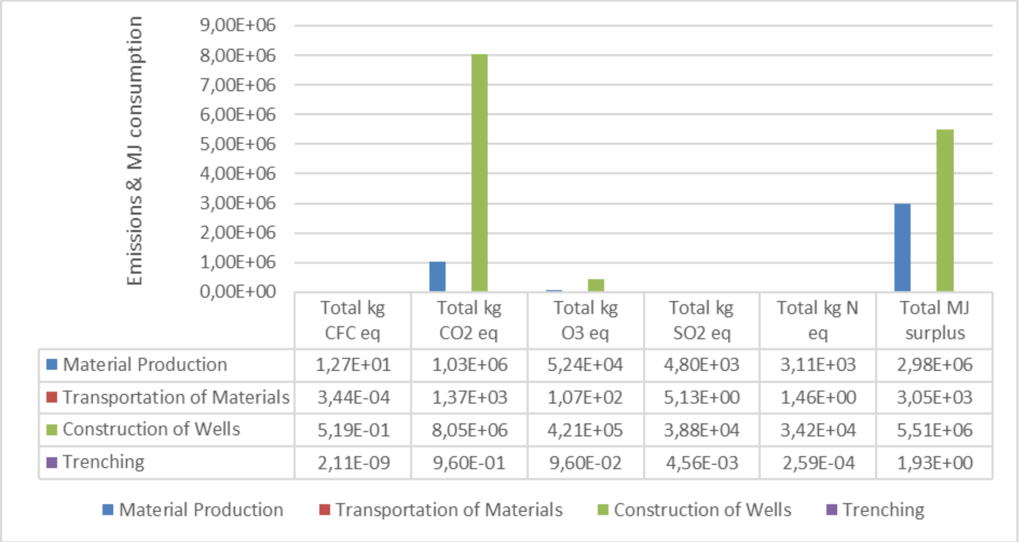


Figure 2: Total impacts of all scenarios for the six examined categories

The impact of ORCHYD on the effectiveness of carbon-neutral energy strategies is likely to be significant. Enhancing ROP rates is estimated to lead to reduced CO_2 equivalent by more than half the amount of emissions produced by conventional drilling techniques. The ozone depletion category appears to be the least impacted by implementing 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. Reduction of the carbon footprint of geothermal will be significant even if only the minimum targeted enhancement of ROP by ORCHYD is achieved. Smog is also significantly reduced by the improvements achieved by ORCHYD. Enhancing ROP leads to reducing the carbon equivalent of ozone (O_3). This is attributed mainly to reducing volatile organic compounds (VOCs), as diesel consumption is reduced. Acidification carbon potential is also drastically reduced. Potential damages to groundwater, soil, and surface water are also limited linearly with sulfur emissions (SO_2) minimization. Eutrophication potential is drastically reduced, as well. Nitrogen equivalent production is reduced, leading to a reduction of the likelihood of dense plant growth, which can deplete dissolved oxygen and negatively affect animal life in aquatic environments. The second most important category examined is the potential for fossil fuel depletion, measured in terms of MJ surplus. Obviously, whenever energy from renewable energy sources (RES) is available, it should be preferred over hydrocarbon-generated energy. ROP enhancement can lead to a significant reduction in 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.

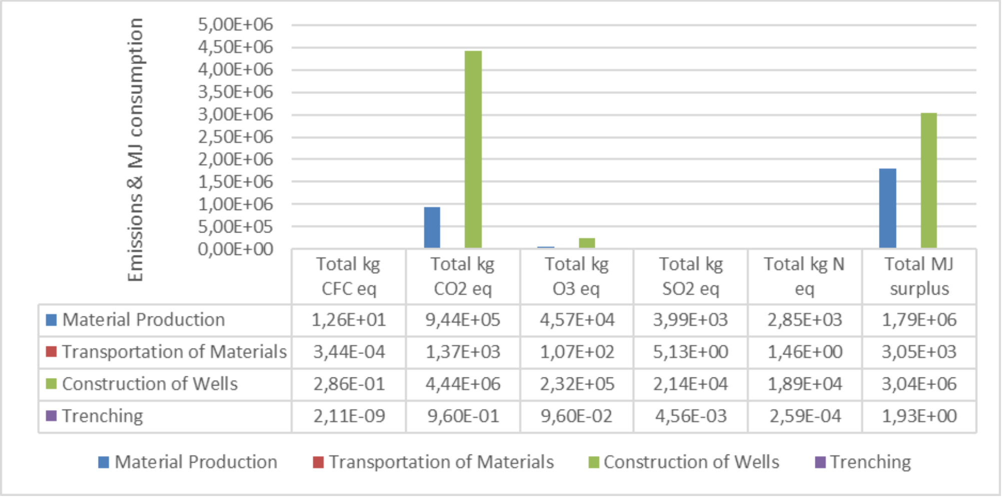
The drilling life cycle approach considers the stages of material production, submersible pump, transportation of materials, construction of wells, and trenching. A comparison of the total impact of all six examined categories among scenarios 1, 2, and 8 is illustrated in Figures 3, 4, and 5, respectively.

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 compared to the existing ones. The most important impacts appear concerning carbon footprint and fossil fuel depletion, while impacts on the other four categories are considered minor. Critical stages include material production and the 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. 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.



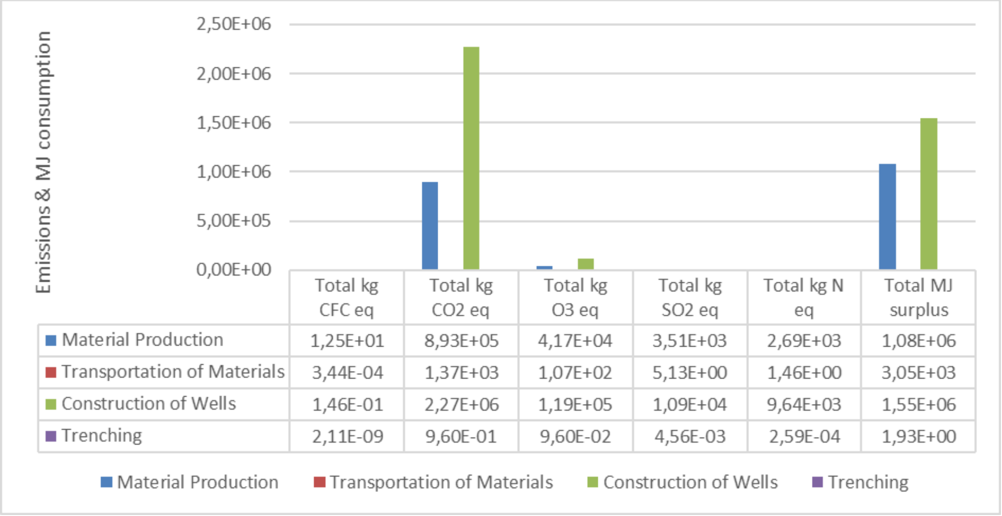
	Total kg CFC eq	Total kg CO2 eq	Total kg O3 eq	Total kg SO2 eq	Total kg N eq	Total MJ surplus
Material Production	1,27E+01	1,03E+06	5,24E+04	4,80E+03	3,11E+03	2,98E+06
Transportation of Materials	3,44E-04	1,37E+03	1,07E+02	5,13E+00	1,46E+00	3,05E+03
Construction of Wells	5,19E-01	8,05E+06	4,21E+05	3,88E+04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

Figure 3: 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

Figure 4: 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

Figure 5: Life cycle stages comparison, Scenario 8

5.1.3 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 6, 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).

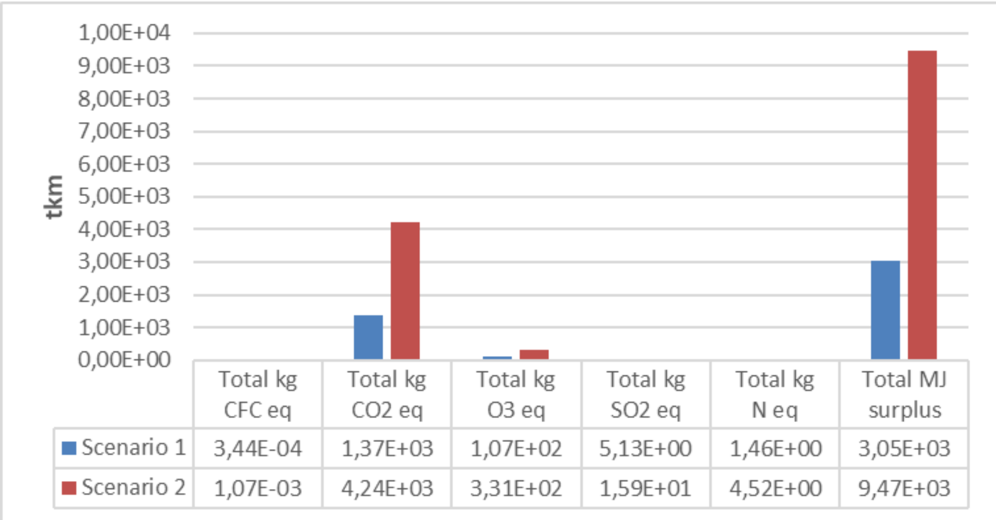


Figure 6: Distance impact on LCA

5.1.4 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). Since 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.

In total, 33 tricone bits were used to drill the GPK-3 well. For the sedimentary and intermediate zones, 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). 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 7 depicts the life cycle impact of the two techniques on drill bit usage, which is a significant economic component of any geothermal project.

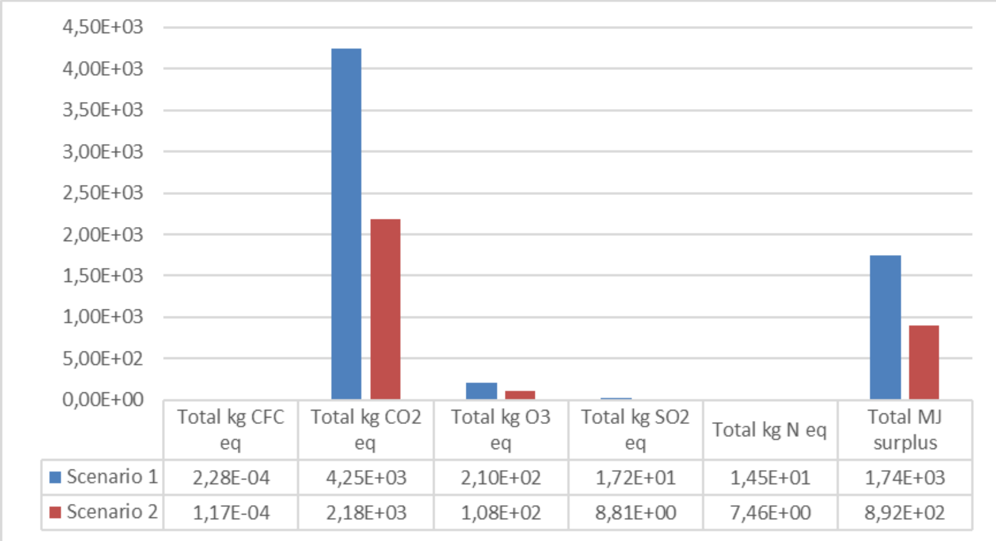


Figure 7: Life cycle emission equivalent and energy surplus vs rotary and percussive/HPWJ of drill bit usage

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 considered in the main LCA study developed in this report. The aforementioned scenarios 1 and 2 examine 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 considered are those caused by the generators' use of diesel fuel. The same holds true for MJ consumption. Figure 8 shows an LCA comparison between rotary and percussive/HPWJ for the replacement of drill bits.

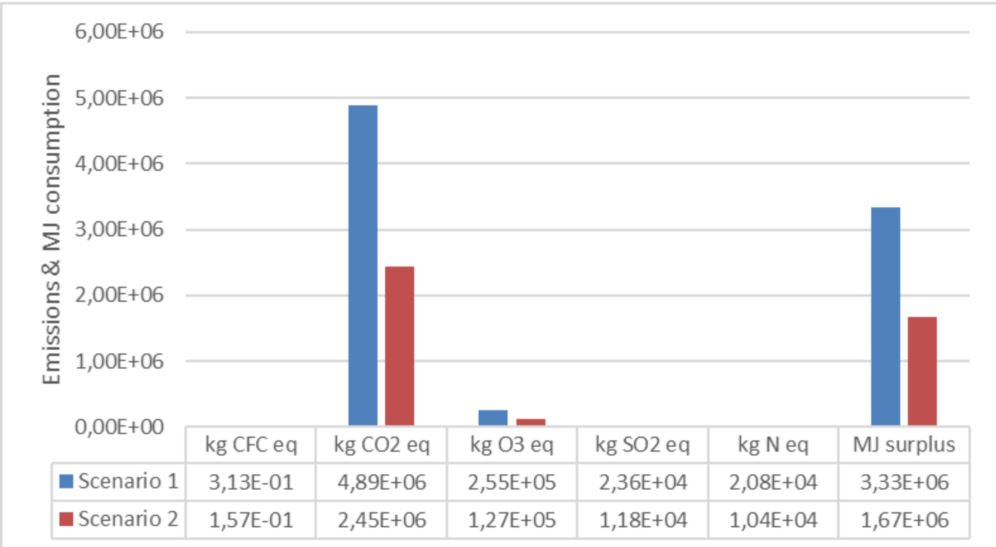


Figure 8: Life cycle emission equivalent and energy surplus vs rotary and percussive/HPWJ of drill bit replacement

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

5.2 Summary of LCA

The conducted LCA on the different scenarios gave important results concerning the impact of ROP in drilling operations' emissions and energy consumption. 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. The techniques developed by ORCHYD will lower emissions, reduce energy consumption, and make geothermal drilling operations more sustainable.

6. ECOLOGICAL FOOTPRINT ASSESSMENT

EFA's pillar is that adequate resources should be left for future generations. Sustainable development attempts to change the present unsustainable trend in the consumption of resources. This section aims 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 land 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 quantification methodology are required. In this section, the LCA's carbon footprint results will be used to determine the ecological footprint of drilling operations using the proposed technique by ORCHYD. All calculations are based on the 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 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 8 scenarios developed within the LCA, the ecological footprint is illustrated in Table 5.

Table 5: 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

7. CONCLUSIONS

The ORCHYD (Novel Drilling Technology Combining Hydro-Jet and Percussion For ROP Improvement in Deep Geothermal Drilling) Horizon 2020 project's environmental implications are examined holistically in this report. ORCHYD's objective is to raise hard rock drilling's rate of penetration (ROP) from 1 to 2 meters per hour (m/h) to 4 to 10 m/h by integrating two previously different, established technologies: High-Pressure Water Jetting (HPWJ) and Percussive Drilling.

Based on a literature review, the environmental impacts of deep geothermal energy development on the lithosphere, atmosphere, hydrosphere, and biosphere were cataloged and assessed. These were compared to the novel drilling techniques developed by ORCHYD. Lithospheric impacts concerned soil subsistence; microseismicity; soil profile; groundwater; solid waste; land use; and visual intrusion. Impacts related to the hydrosphere concerned water quantity, quality, and wastewater. Atmospheric impacts concern greenhouse gas emissions; local air pollution; odors; and noise. Lastly, impacts on the biosphere concern ecosystems; human health; socio economic issues; material use; energy consumption; and energy security. Impacts were characterized based on six different categories. Positive/negative to the environment; temporary/long term; reversible/irreversible; direct/indirect (nature): direct or indirect; not likely/potential/certain; and local/regional/national/international. The significance of impacts was assessed by the project partners via an online scoping survey.

A Life Cycle Assessment supplemented the environmental impact assessment of ORCHYD from a quantitative point of view. The LCA was created by analyzing several drilling scenarios. In addition to carbon emissions assessed in carbon dioxide equivalents, LCA considered ozone depletion, smog, acidification, eutrophication, and energy usage for drilling. The influence of the distance between geothermal activities and large urban centers, as well as drill bit usage lifespan, were also considered. ROP rates of 4 to 10 m/h in hard rock formations may result in the following reductions in the best-case scenario:

- carbon dioxide equivalent by 65.2%;
- energy consumption (as MJ surplus) by 68.9%;
- chlorofluorocarbons (CFC) equivalent by 3.8%;
- ozone equivalent by 66.2%;
- sulfur dioxide equivalent by 66.7%;
- nitrogen equivalent by 67.1%.

Examining the EFA data for all 8 scenarios created inside the LCA analysis reveals that the ecological footprint decreases linearly with CO_2 eq. emission. The reduction of ecological footprint in global hectares ranges between 40.8% and 65.2% when adopting ORCHYD's minimum and maximum ROP improvement goals respectively. The overall conclusion is that using ORCHYD can significantly decrease the environmental problems caused by traditional drilling technology. All in all, most impact categories were proven inversely proportional to ROP. It can be concluded that ORCHYD technologies will reduce emissions and the average energy required for drilling per meter, thus improving the environmental profile of deep geothermal drilling.

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