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REVIEW OF WATER AND CARBON FOOTPRINT IN GEOTHERMAL ELECTRICITY GENERATION TECHNOLOGIES THROUGH A LIFE CYCLE ASSESSMENT APPROACH

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ABSTRACT

Energy and water are intricately linked, especially in the production of electricity. Renewable and non-renewable energy generation technologies consume water in varying proportions, with the latter consuming the most. Given the realities of climate change, it is considered imperative to shift to renewable energy sources to meet increasing energy demands in a sustainable manner. Geothermal energy, in addition to wind, solar, and hydro energy, is an intriguing renewable source that supplies base load electricity independent of weather conditions. Depending on the reservoir characteristics, diverse power plant technologies (flash, binary, back pressure, and dry steam) are employed to generate electricity. Cooling systems incorporated in these power plant technologies vary (wet recirculating, air-cooled, and hybrid) across power plant technology, as do water consumption amounts. The environmental impacts of a geothermal power plant vary throughout its life cycle based on the plant design. An understanding of the environmental impacts, particularly related to water and carbon footprint, is therefore necessary to ensure sustainable development. This paper provides an overview of the impact of geothermal energy production cooling systems on water, through a Life Cycle Assessment (LCA) approach as well as an examination of potential carbon trade-offs. It also aims to better understand how significant water consumption is and the possible water related challenges that future geothermal projects may face. Such an understanding will provide an opportunity for continual improvement of the current water use practices stemming from more informed decision-making on technological choices for future development of geothermal power plants in middle income countries such as Kenya.

1. INTRODUCTION

Climate change is currently the major challenge confronting today's generation. The reality of climate change globally is driving a call for a reduction of reliance on conventional fossil-based fuels which are non-renewable energy sources. Given the growing population size, energy demand will rapidly increase in the decades ahead, further aggravating the concerns over the impacts of climate change due to global warming. These concerns have elicited a renewed global interest in alternative energy sources that are renewable and presents a reduced environmental footprint in relation to climate change. Energy production, as a driving element for socioeconomic growth and development, is in the limelight since it is the greatest contributor to greenhouse gas emissions and has the capacity to decarbonize nearly completely and more quickly than other industrial sectors (Paulillo et al., 2019). The greenhouse gases cause global warming and climate change. The International Energy Agency (IEA) released its Net Zero by 2050 study, which demonstrates that the electrical industry must transition from being the largest emitting sector in 2020 to being the first to achieve net zero emissions globally by 2040 (IEA, 2021). Non-renewable energy sources (fossil fuels and nuclear) accounted for 72% of global power generation in 2021, while renewable energy sources accounted for 28.3% of primary energy supply (REN21, 2022). Renewable energy sources considered in a carbon-strained world for power generation are hydropower, wind, geothermal, solar and bio-power. One or more of these resources are available in most countries, however, in different capacity per country.

Geothermal energy is an intriguing renewable energy source when compared to other variable renewable energies such as wind or solar energy because of its independence from external or climatic factors (Li et al., 2015). Geothermal energy provides 1.4% to the world's renewable energy mix, and this number may rise as geothermal power plants operate at almost full capacity for most of their lifespan and fulfil base load power demand. Between 2015 and 2020, the overall installed capacity of geothermal energy increased to 3.649 Gigawatt electric (GWe), a 27% increase. Based on published documents of plans and estimations by nation update writers, a further growth of 19% is expected for the period 2020-2025 (Huttrer, 2020). This is because geothermal energy is regarded as an important local renewable energy source with significantly lower emissions than fossil fuels, with certain types of geothermal plants producing near-zero emissions (Huttrer, 2020). Furthermore, geothermal energy contributes to the attainment of the Sustainable Development Goal No. 7 (SDG 7), which aims at guaranteeing access to affordable, reliable, sustainable, and modern energy for all. Despite the fact that geothermal energy is a renewable source of energy, geothermal power plants have the potential of resulting in substantial environmental consequences. Given the potential of continued use of this resource, increased focus has been devoted to the environmental effects of geothermal power production, notably the harnessing of high-temperature fields for electricity generation. In addition, natural background emissions of greenhouse gases are emitted as geothermal sites are being developed (Ármannsson, 2018; Bayer et al., 2013; Paulillo et al., 2019).

Freshwater being an indispensable resource is crucial for socio-economic and ecological activities, such as food and energy production, industrial development, transportation, and human health. Despite playing these vital roles, freshwater resources are spread unevenly and irregularly, with certain parts worldwide experiencing severe water scarcity. With global population growth being witnessed, water demand indicates an increasing trend, while the capacity to store surface water is shrinking. This is attributed to climate change and increased anthropogenic activities that consume water. The world's population at risk from elevated levels of threat to water security is nearly 80% (Vorosmarty et al., 2000; 2010). Energy production and consumption frequently need a substantial quantity of water to support processes, such as exploitation, construction, operation and maintenance, cooling, and waste disposal. The amount of water consumed for energy generation varies substantially depending on parameters of fuel cycle and the type of facility. Gleick (1994) states that fossil fuel, nuclear, and geothermal power plants all require substantial volumes of water for fuel processing and cooling. The study points out that solar photovoltaic power systems, wind turbines, and other renewable energy sources frequently require minimal water quantities, though some renewable or unconventional energy technologies, such as geothermal plants or hydroelectric plants with reservoirs subject to evaporative water loss, are also water intensive. The withdrawn water might be returned to a water supply, used in operations, or polluted to the point where it is no longer fit for use. Given that water returned to the source is minimal when compared to use in energy-generating facilities, this can potentially cause localised stress in regions as well as changes to natural hydrological and ecological systems. Water scarcity will limit the types and locations of energy installations that can be built (Gleick, 1994). Therefore, understanding the link between the impact on water consumption by geothermal energy development is important to ensure sustainable development is achieved. These impacts (direct or indirect) are realised either in the short or long term during the geothermal development life cycle, making it vital to comprehend the material and energy needs for its development.

Elucidation of the environmental performance of geothermal power generation is vital and can be done through effective analytical methodologies such as the LCA approach. LCA is an environmental analysis approach that captures the total environmental performance of particular systems by comparing processes and analysing each stage's environmental effect (cradle-grave). This gives a perspective that is considerate of supply chains and their interaction with associated environmental impacts. The analysis guides decision makers to pinpoint hot spots of weak points in processes and enables improvement of efficiency of systems.

The goal of this study is to evaluate the various geothermal power generation technologies to better understand the factors that determine the quantity of water consumed and potential water constraints that future geothermal projects may encounter. It also aims to understand the significant role that water plays in the geothermal power generation life cycle as well as identify possible environmental trade-offs with carbon emission. In addition, this study will endeavour to highlight the existing best practices with an aim of recommending optimal water use in geothermal power plant operations taking into consideration the Best Available Technologies (BATs). Geothermal power plant technologies will be briefly introduced, followed by a review of available literature on the impacts of geothermal power plant development on water, which will be reviewed and contrasted with a qualitative and, where feasible, quantitative discussion. The outcome of this study will provide an opportunity for the continual improvement of current water use practices and support more informed decision-making on technological choices for future development of geothermal plants considering water demand and climate change which affect the availability of water resources. Efficient management of water resources will ensure sustainable development improving the environmental performance of geothermal power plants.

1.1 Overview of geothermal energy development and utilisation

Overreliance on Fossil Energy Resources (FER) has resulted in environmental and ecological challenges that have an impact on people's daily lives. The continued reliance on these sources and the associated greenhouse gas emissions accelerates the rate of global warming, with severe implications (Stern et al., 2007). The International Panel on Climate Change (IPCC) in its special report on global warming of 1.5°C, proposed maintaining atmospheric greenhouse gases below 450 ppm in order to maintain a temperature rise under the 2°C objective. Since this has emerged as an issue, all sectors' operations must change from business as usual. Unless this shift is achieved, global environmental challenges will have a significant influence on global energy consumption patterns. In this regard, Renewable and Clean Energy Resources (RCER) are considered attractive for sustainable energy development and pollution reduction. The widespread use of Renewable Energy Resources (RER) might be one of the currently feasible solutions to the challenges posed by FER. RER have risen rapidly in the last decade or two, particularly solar and wind energy, yet their usage is still far from its worldwide potential (Li et al., 2015). In addition to wind and solar energy, geothermal energy has grown considerably in recent years. Less than 0.5% (73 GWh) of worldwide power in 2015 was produced from geothermal energy (Bertani, 2016). However, overall capacity is likely to expand dramatically, with a prediction of 118 GWh by 2025 (Huttrer, 2020), as illustrated in Figure 1. Given the growing need to transition to renewable energy sources, geothermal stands out since it contributes to the attainment of Sustainable Development Goals (SDGs). The SDGs, in particular, include ensuring that everyone has access to affordable, reliable, sustainable, modern energy, as well as assisting in the promotion of measures to address climate change and its consequences.

Geothermal energy is now employed in 88 countries and is known in more than 90. It is used to generate electricity in 29 countries, with a total installed capacity of 15,950 MWe and a utilization rate of 95.098 GWh/a. Other than usage for electricity generation, it also has direct use in 88 countries with an installed capacity of 107.7 GWt and utilization at 1,020,887 TJ/year. It is currently number five of the renewable energy sources in the world’s electricity production after hydro, biomass, wind, and solar (Lund and Toth, 2021; Huttrer, 2020).

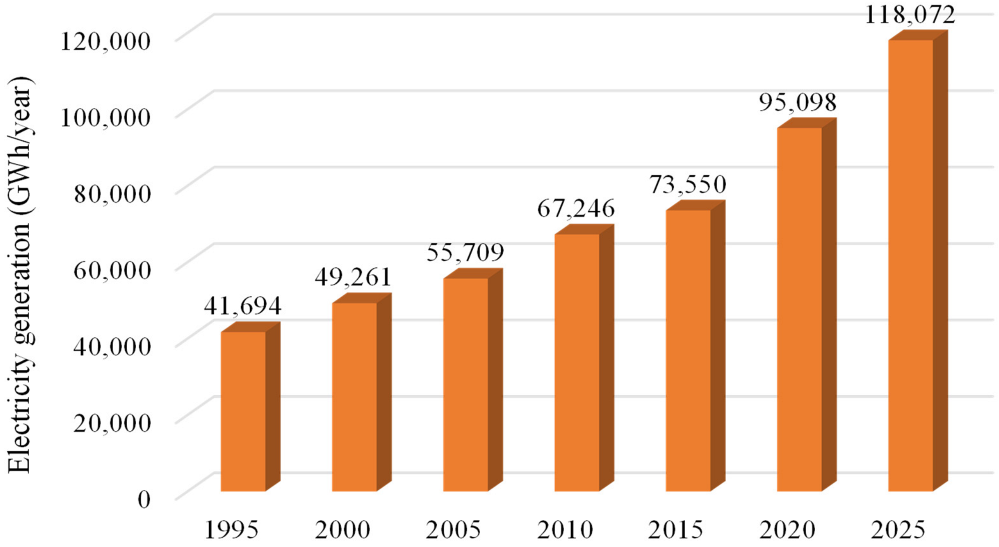

FIGURE 1: Total geothermal electricity generation 1995-2020 and forecast for 2025 (Huttrer, 2020)

2. DESCRIPTION OF GEOTHERMAL ELECTRICITY GENERATION TECHNOLOGIES

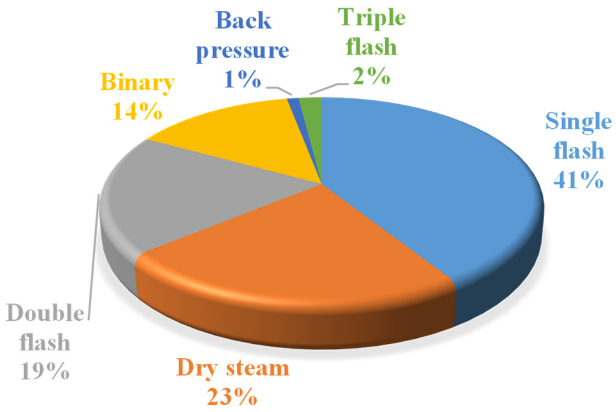

FIGURE 2: Share of different geothermal plant technologies in global electricity production (Bertani, 2016)

Geothermal power plants use steam or hot geothermal fluid from far under the earth's surface to generate energy based on the heat content or temperature of the fluid. Depending on temperature (and enthalpy), geothermal fields are classified as high temperature (>200°C at 1 km deep) and low temperature (150°C at 1 km depth) (Ragnarsson, 2015). Based on the reservoir characteristics of a geothermal field, different technologies, as shown in Figure 2, are used to harness the resource. The most prevalent form of geothermal reservoir is liquid-dominated, with the produced fluid being a two-phase composition of liquid and vapour. Only the vapour is utilised to power a steam turbine once the two-phase flow is separated. Given the difference in density between the liquid and vapour phases, separation is achieved by centrifugal action. The separated liquid can be injected, utilised for thermal energy through heat exchangers for different direct heat applications, or flashed to lower pressure using control valves, creating additional steam for use in low-pressure turbines while the steam is discharged into the atmosphere. Single flash plants collect only the primary high-pressure steam, whereas double flash plants extract both high and low-pressure steam. Double-flash technology provides 20-25% more power than single-flash plants at the same geofluid mass flow rate, resulting in higher efficiency (Bayer et al., 2013).

Vapour-dominated (or dry steam) reservoirs have high temperatures (>200°C) and are exploited using dry steam plants. The extracted steam is fed into a turbine, which drives a generator unit to generate electricity. These reservoirs being limited, the two known significant fields are Larderello in Italy and the Geysers in California, USA. (Bayer et al., 2013)

Binary power plants run on water that has a lower temperature (100°C-150°C). The heat produced by the hot water is used to heat a working fluid, which is often an organic compound with a low boiling point. In a heat exchanger, the working fluid is vaporised and utilised to spin a turbine. To guarantee little or no air emissions, the water and working fluid are separated throughout the process. Hydrocarbons and other working fluids are used (e.g., isobutane, isopentane, propane) (Bayer et al., 2013). After that, the geothermal water is reinjected into the earth to be warmed. The cooling system is dependent on air or a separate source of make-up water for a wet cooling system since the geothermal fluid is not available as it is in the case of flash power plants.

Other than the commonly explored technologies stated above, Enhanced Geothermal Systems (EGS) are having a considerable upcoming interest given the advancement in technology. Due to low permeability, binary cycles evolved into EGS, which do not vary in surface equipment type for the Organic Rankine Cycle (ORC), but rather permit exploitation of geothermal systems without hydrothermal resources or geothermal fluid. Extraction of heat from locations with a high thermal gradient can be accomplished by fracturing the hot rocks and injecting water which is heated by the rocks via conduction (Olasolo et al., 2016). EGS systems have, however, not been extensively developed commercially due to the high well costs with depth and the development is much more expensive than hydrothermal resources.

3. GEOTHERMAL ENERGY PRODUCTION AND ENVIRONMENTAL ASPECTS

Geothermal electricity production has environmental impacts that can be categorised as direct and indirect impacts based on their impacts on land, water and atmosphere. These include resource use, emissions, energy consumption, and societal effects. Efforts have been undertaken in recent years to examine the environmental effects of geothermal energy development (Bayer et al., 2013; Karlsdóttir et al., 2015; Zuffi et al., 2022), but information on areas such as the influence on water consumption is still limited. Some of the effects are temporary, while others last throughout the life of the power plant. The environmental and social impacts of geothermal power generation are depicted in Figure 3.

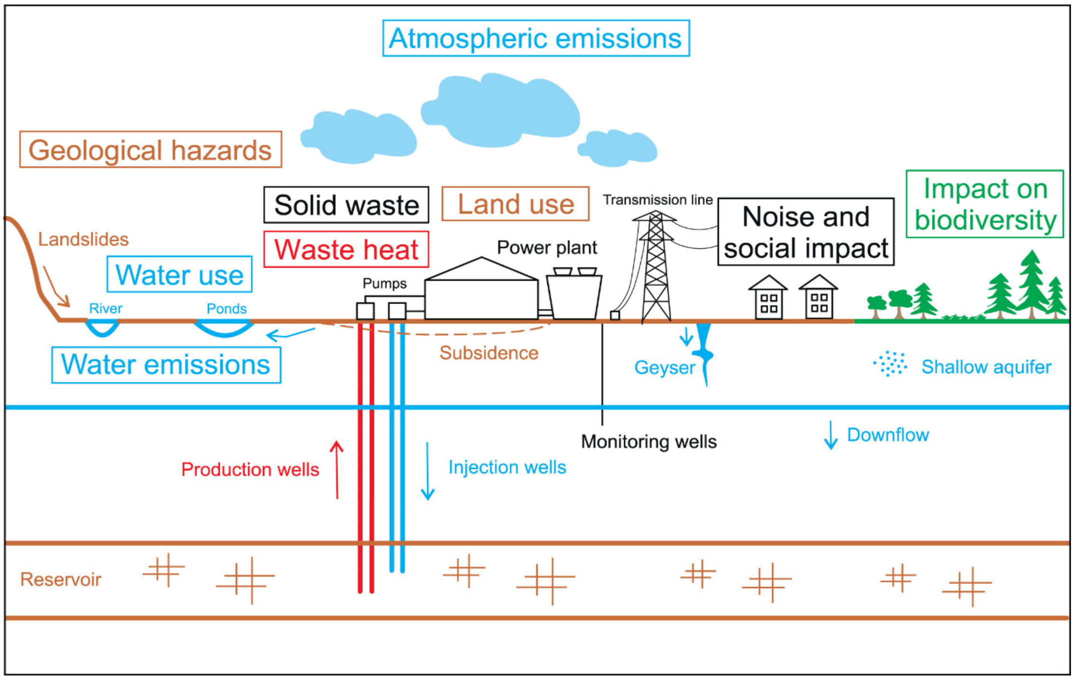

FIGURE 3: Environmental and social impacts of geothermal power production throughout lifecycle (Bayer et al., 2013)

3.1 Impact on water resources

Geothermal resources are typically situated in water-stressed areas, and a rise in water demand within these areas can bring forth challenges. Examining water consumption within the life cycle of a geothermal power plant is therefore important to better understand how the quantities consumed can be minimised. Water consumption refers to the water that is withdrawn from a resource such as a river, lake, or non-geothermal aquifer that is not returned to that resource.

The development of geothermal power plants necessitates the use of water throughout the power plant's life cycle, and depending on the technology utilised for electricity generation, production might decrease the water table over time, harming the surrounding environment (Clark et al., 2011). The usage of freshwater is determined by a variety of parameters, including the size of the plant, the technological version, the operating temperatures and cooling mechanism, and the availability of substitute salt water, sewage (grey water), or geothermal water (Bayer et al., 2013). Geology, reservoir characteristics, and local climate have various effects on elements such as drilling rate, the number of production wells, and production flow rates.

Over the life cycle of a geothermal power plant, from construction through 30 years of operation, plant operations are where the vast majority of water consumption occurs (Clark et al., 2011; 2013). In geothermal development, fresh water has various uses including drilling of geothermal wells, quenching of wells, cold reinjection, construction of power plants, dust suppression, cooling of steam in the cooling towers, reservoir stimulation as well as domestic use by staff.

Several LCA studies have already been conducted, with an emphasis on enhanced geothermal systems (EGS) and binary power plants as the most recently explored technologies. However, according to Bertani (2016), most of the electricity from geothermal sources produced globally is generated by flash power plants located in high-temperature geothermal areas. Single flash technology accounts for 41% of total installed capacity; dry steam and double flash technologies contribute around 23% and 19%, respectively, while binary plants in hydrothermal and Petro thermal systems account for 14%. Karlsdóttir et al. (2015) states that material burdens are prominent in the building stage, whereas resource consumption such as groundwater, geothermal fluids, and environmental burdens is dominant in the operational stage.

4. ASSESSING ENVIRONMENTAL IMPACTS, THE LIFE CYCLE ASSESSMENT (LCA) APPROACH

4.1 Contextual framework

LCA is an ISO 14040 and 14044 standardised approach for assessing the environmental implications of product systems and services at various phases of their life cycle. This method simulates the interaction of life cycle stages with the environment, considering all processes from raw material procurement through final disposal or recycling (end of life), as illustrated in Figure 4.

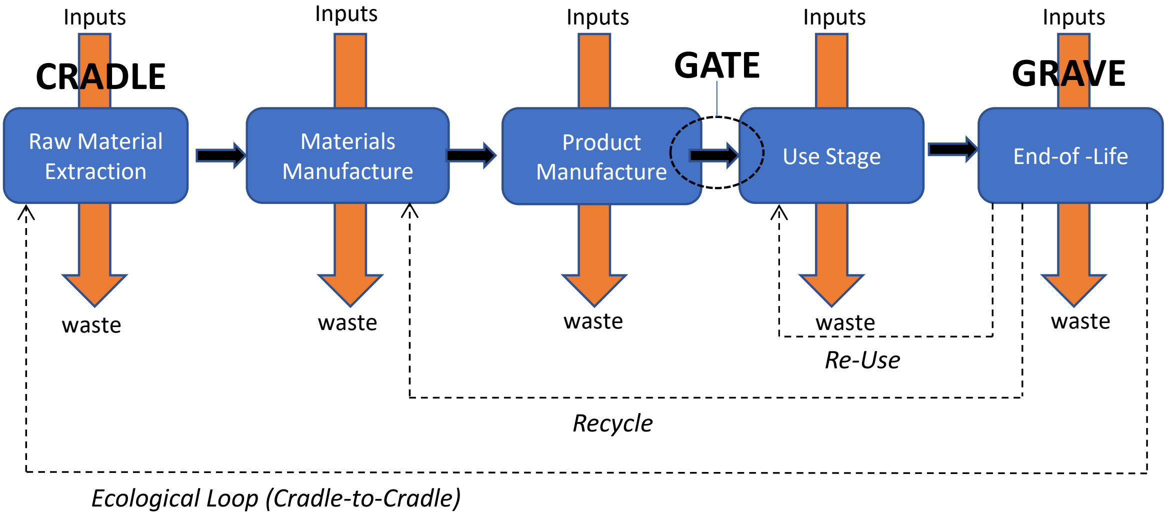

FIGURE 4: Diagram of life cycle assessment stages from raw material acquisition to end of life

An LCA analysis is conducted in four steps, according to ISO 14040 guidelines, as depicted in Figure 5. The goal and scope definition phase outlines the general purpose of the research, as well as the system boundaries and functional unit that will be used as a reference for subsequent steps. The inventory analysis describes all environmental inputs, such as material and energy fluxes, in addition to output emissions to the environment. Using numerous indicators, the impact assessment phase evaluates and quantifies the extent of the possible environmental impacts generated by the previous stage's emissions to the environment. Finally, the inventory analysis and effect assessment results are examined, and conclusions are drawn, followed by recommendations to identify key components, alternative approaches, or product system improvement (Asdrubali et al., 2015; Nieuwlaar, 2004).

In energy technologies, a LCA gives a comprehensive framework that is defined to facilitate comparative studies allowing an evaluation of environmental consequences from "cradle to grave." Additionally, the sustainability of different renewable energy sources is evaluated through a LCA since it is recognized as an effective tool to help policymakers recommend the best energy sources for specific purposes (Asdrubali et al., 2015).

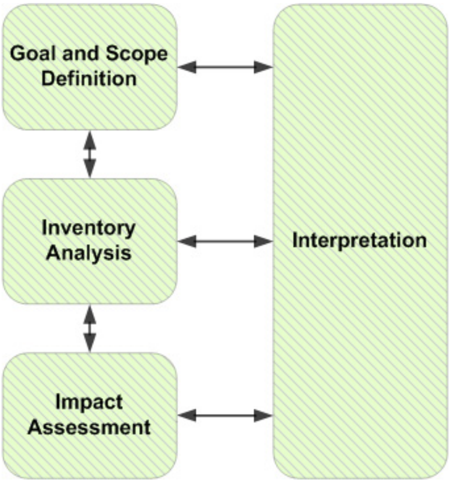

FIGURE 5: Phases of life cycle assessment (ISO 14040, 1997)

4.2 LCA in geothermal energy production

Geothermal is a sustainable energy source in a carbon-constrained society, but its use has significant environmental consequences. As a result, it is critical to evaluate its environmental performance across a system's life cycle. This is particularly important when comparing various technologies since it reveals hidden influences in upstream and downstream processes. The holistic evaluation identifies hotspots that need to be rectified to guarantee the resource's development and ensure consumption is sustainable and environmentally responsible. The LCA also reveals potential environmental trade-offs between various energy generation technologies.

According to recent assessments by Tomasini-Montenegro et al. (2017) and Asdrubali et al. (2015), there are few LCA studies on geothermal energy generation. Despite being the most widely used technology in geothermal energy generation, they claim that there is a lack of published information on flash technologies. Bayer et al. (2013) also emphasised the overall scarcity of LCA in geothermal energy generation. Because of the increased interest in LCA in the geothermal industry, more scientists have published papers on LCA methodology.

5. MATERIALS AND METHODS

5.1 Screening approach

The methodology used in this study entailed a review of the available publications using works cited lists, keyword searches, known reference repositories, and peer-reviewed scientific literature on the impact of geothermal development on water through a LCA. The data was then compiled for comparison. The screening method was done in reference to previous screening methods utilised by Meldrum et al. (2013) and Tomasini-Montenegro et al. (2017). Due to time limitations, this study review considered publications only from the years 2010 to 2022. Online search engines utilised were Google Scholar, Scopus, and Research rabbit. By using the keywords “life cycle”, “water consumption”, “water use”, and “geothermal energy” the search in Scopus gave 30 papers of which only 6 were relevant for the study within the stipulated period. To increase the scope, research rabbit was utilised to link the different papers and authors that have done similar work (Research rabbit, 2021). The materials and data reviewed for this study focus on the impact of different technologies for geothermal development on the water footprint through different life cycle stages and consider possible trade-offs between the water footprint and the carbon footprint. This study's data was obtained directly from summary life cycle impact tables. Except for unit conversion, the data obtained on water usage estimates was not altered. Since estimates were used as published, some data had inconsistencies limiting direct comparability. Freshwater from surface sources or groundwater was considered; thus geothermal fluid (brine and condensate) was not included in this study.

The aim of the review methodology was:

i) To gather documented information about water consumption of geothermal power generation through an LCA.
ii) To identify the different geothermal harnessing technologies impacts on water through a LCA based on available publications.
iii) To identify system boundaries within LCAs which have been conducted on water consumption by geothermal power generation technologies.
iv) To identify possible trade-offs in environmental impacts of geothermal power generation as well as information gaps with focus on the water and carbon footprint.
v) To summarise gathered information on water consumption and technologies.
vi) Draw inferences and provide suggestions based on results from the published literature.

Besides data documented in the reviewed literature, a comparison was made between power plants in Kenya and Iceland with different geothermal development technologies. This also provided information on different geographical locations contributing to the overall impact on water consumption based on water availability.

The goal of this study is to evaluate the life cycle water consumption of geothermal power generation technologies to better understand the elements that affect water consumption and potential water constraints that future geothermal projects may encounter. It also aims to understand how significant water usage in the geothermal power generation life cycle is and identify possible environmental trade-offs with carbon emission. The purpose is to compare the different cooling technologies used in geothermal power plants in relation to water consumption and carbon emission and determine their significance. Given that LCAs use different units, to make the comparison homogenous the functional unit used is water consumed in gallons per kWh of electricity produced. The conversion factor used was 264.2 gallons for 1 m^3 of water. This will allow comparisons of the different power plants as a sole product process.

In LCA studies, the full cycle involves assessment from a cradle to grave (end-of-life) approach. However, given the minimal impact on water by the decommissioning phase in power plants, which is the end-of-life phase, the system boundary for this study uses the cradle-to-gate approach. Previous analyses also note that water consumption during the development of pipelines is also negligible per lifetime of energy output (Clark et al., 2011). Therefore, the system boundary includes drilling, construction, operation and hydraulic stimulation for EGS systems.

5.2 Limitations

LCA publications on geothermal power generation are few as previously noted. Geothermal energy being a localised resource, results in localised and case-specific environmental impacts, make it difficult to draw general conclusions from single studies. Given that geothermal energy can be found in varied geographical locations, conditions such as climate, input resources like water and biodiversity vary greatly and the magnitude of impacts are of a wide range (Macknick et al., 2011; Turchi et al., 2010). Moreover, water sources, quantity, quality, and subsequent uses differ from region to region leading to localised stress on the resource. Data availability on EGS is limited given that the technology is new and has not been as widely explored as conventional geothermal electricity generation technologies. The literature review conducted for this study reveals that, other than scarcity in publications on geothermal water consumption, some publications are not freely accessible (e.g., Sullivan et al., 2013; Bett and Jalilinasrabady, 2021), while a majority have focused on water consumption in thermoelectric power plants (e.g., Ou et al., 2016; Fthenakis and Kim, 2010) and other renewable energy sources such as photovoltaics and wind power. Furthermore, most papers do not cover all life cycle stages (e.g., Macknick et al., 2013; Meldrum et al., 2013) save for the operation phase. A number of evaluations depend on a subset of accessible data referencing publications by Clark et al. (2011; 2012; 2013). Several impact assessment methods are applied in the existing LCAs, thereby making it difficult to compare study results. The lifetimes considered for different publications also vary from 20-100 years and performance declines are frequently reported (Kaya et al., 2011). The captured limitations, therefore, affected the breadth of data as well as the results of this study.

6. RESULTS: WATER CONSUMPTION AND CARBON FOOTPRINT FOR GEOTHERMAL POWER PLANT COOLING TECHNOLOGIES

Water consumption for different geothermal technology configurations can vary greatly due to differences in reinjection techniques, vapour temperature and mass, local climate, cooling system type, efficiency of the system, and reservoir characteristics. For example, EGS binary and hydrothermal binary technologies are similar in operation although EGS requires additional water to meet hydraulic stimulation purposes. Geothermal power plants may use water from geothermal fluid, which may have little or no influence on freshwater locally; but, over time, the efficiency of some plants may deteriorate and necessitate the consumption of additional fresh or brackish water, which may have an impact on local water tables (Clark et al., 2011). Because some of the published data examined in this study did not describe the locations nor climatic conditions of the power plants, the water consumption estimations are geographically indiscriminate. However, it is important to note that climatic conditions of various locations vary (e.g., hot temperatures) and may significantly affect a plant's efficiency and water use as well as water availability (Averyt et al., 2013; Macknick et al., 2011). Additionally, based on the demand for water use by various sectors depending on the water source, the availability may vary.

Aside from water footprint, carbon footprint is a significant factor in geothermal energy generation. This is attributable, in part, to the contribution of atmospheric carbon emissions to global warming potential. Carbon emissions from various geothermal energy production technologies differ in scale and at different life cycle phases. The total carbon released per kilowatt hour (kWh) of energy produced also varies across technologies. Given that carbon dioxide (CO_2) accounts for more than 90% of non-condensable gases produced during the operation of geothermal power plants, it is essential to evaluate its emission levels and support emission reduction or abatement.

Water use in geothermal electricity production has various uses through the life cycle phases from drilling to decommissioning phase. Freshwater may be used in managing dissolved solids, as makeup water, replenishing reservoirs and reducing scaling (Clark et al., 2011). Depending on the water availability and geographical location of power plants, the supply of water for drilling might be either groundwater or surface water. Other than freshwater, geothermal drilling fluid is also used in drilling of geothermal wells depending on their chemistry. Water is used in the drilling phase of the geothermal power plant life cycle as a drilling fluid and for cementing works. In addition, the drilling fluids, water inclusive, play a vital role in cooling the drill bit, bringing the cuttings to the surface from the bottom and maintaining downhole pressure. Reviewed LCAs on geothermal energy development provide limited data on water consumption in the drilling phase, posing a challenge for direct comparison. This is also contributed by the dynamic considerations (well depth, reservoir type, geology, technology, different pumping rates) to determine water consumption during drilling. According to Clark et al. (2013), EGS plants consume 0.003 gal/kWh whereas binary and flash plants each consume 0.001 gal/kWh during drilling. Clark et al. (2011) approximates total water consumption for a 1 m well to be 5 m^3 to 30 m^3 and Dumas et al. (2013) states that a continuous water supply of at least 2 m^3/min, preferably 3 m^3/min, is required for drilling activity. In a recent study by Schroeder et al. (2015), they provide estimates of 1700 m^3/1000 m, 1900 m^3/1000 m, and 2300 m^3/1000 m for observation, exploration, and production/reinjection wells, respectively. However, the rate may vary depending on the geological formation, nature of the reservoir, technology, number of liner sand depth, and type of well (e.g., observation, exploration, production, or reinjection well). It is also observed that, the depth and number of wells affect the volume of water requirements. When drilling into a permeable zone, losses are experienced thus water is used when drilling ‘blind’ as well as drilling the last section of a geothermal well.

Water requirements for construction are mainly limited to use in concrete mixes. As there are upstream water requirements in the manufacture of materials, this was not considered in this study nor the reviewed studies. According to the literature, the average water consumption (Table 1) for binary and flash plants was 0.001 gal/kWh, whereas EGS consumed 0.01 gal/kWh (Frick et al., 2010; Clark et al., 2011; 2012; 2013).The consumption estimates for the flash plant is however slightly lower than 0.005 gal/kWh and 0.004 gal/kWh captured by Karlsdóttir et al. (2015) for single flash and double flash power plants, respectively. This indicates slightly lower values for LCA calculated estimates compared to data captured from operating power plants.

TABLE 1: Construction phase water consumption in gal/kWh

REFERENCES	**EGS**	**BINARY**	**FLASH** [c]
Clark et al., 2013	0.009	0.001	0.001
Clark et al., 2011[a],2012	0.01	0.001	0.001
Frick et al., 2010[b]	0.01	-	-
Karlsdóttir et al., 2015	-	-	0.005
Karlsdóttir et al., 2015	-	-	0.004[d]

[a] Construction including drilling
[b] Construction including drilling and cementation
[c] Single flash plant
[d] Double flash plant

The operating factors of different power plants vary, such as water requirements, auxiliary power demand, and capacity factor. Plant operations account for the great majority of where water consumption occurs during the life cycle of a geothermal power plant (Clark et al., 2011; Karlsdóttir et al., 2015). Zuffi et al. (2022), in their study of flash and EGS power plants, assume relative importance on water consumption either due to direct use (plant operation or wells stimulation) or indirect use (in the production of sodium hydroxide used for the realisation of wells). During the lifetime operation of a geothermal power plant, water is mainly used for cooling during production. Macknick et al. (2012) points out that plant operation is a greater determinant of water usage in terms of consumption and withdrawal of the cooling system employed other than the particular technology generating electricity. Pan et al. (2018) agrees with Macknick et al. (2012) in emphasising that cooling systems utilise the majority of the water in the life cycle of electricity generation, providing a possibility to minimise freshwater consumption.

6.1 Enhanced Geothermal Systems (EGS)

Drilling and Hydraulic Stimulation

Because EGS wells are substantially deeper, the water needs for drilling are higher than for binary and flash hydrothermal wells. Due to the structure and physical state of the reservoir, EGS wells require hydraulic stimulation, which increases the demand for water during drilling. According to the reviewed literature, the average drilling water consumption per lifetime energy production for EGS power plants is 0.003 gal/kWh, whereas binary and flash power plants each consume 0.001 gal/kWh (Clark et al., 2013).

In this study, hydraulic stimulation was considered only for EGS technology reservoirs, and no stimulation was assumed for the hydrothermal binary and flash plants. Water is the major resource used in well stimulation activities. The volume of water required for well stimulation is determined by the environment of the well reservoir and the stimulation technique used. Well reservoir variables likely to influence water requirements include well depth, construction, lithostratigraphy of injection/production boreholes, geology and geochemistry of the host reservoir, presence/absence of intrinsic fractures, and stress regime. Well stimulation is often performed after EGS well drilling to increase well production by (1) opening routes to permeable zones not intersected by the well and (2) increasing near-well permeability diminished by drilling operation clogging pathways (Clark et al., 2013). In EGS reservoirs, three forms of well stimulation are used: hydraulic, thermal, and chemical stimulation. Hydraulic stimulation involves injecting water, a mixture of water and sand, or water and gel proppant fluids into a geothermal reservoir. Thermal stimulation is accomplished using chilled water, whereas chemical stimulation is accomplished using aqueous solutions to let acids, bases, and chelating agents into the reservoir. The published literature on EGS stimulation is minimal, and the available data are from various geological characteristics. According to Frick et al. (2010), well stimulation or "reservoir stimulation" contributes significantly to EGS power plant water consumption requirements. During hydraulic stimulation, the average water consumption is estimated to be 0.003 gal/kWh (Clark et al., 2013).

Operation and Maintenance

EGS can utilise flash or binary technology depending on the resource temperature. However, given the inflated cost of wells posing constraints, these systems produce fluids with a moderate temperature range thus binary technology is characterised for EGS resources (EPRI; DOE., 1997). The data gathered from literature shows that most EGS plants utilise dry (air-cooled) systems for cooling during operation. However, EGS extra water requirements are attributed to low flow rates per well, which increase the total number of wells required per plant, as well as the previously noted depth and hydraulic stimulation. Schroeder et al. (2014) evaluated water consumption for modern technologies and reported that below-ground reservoir loss accounted for 80.6% to 97.4% of total water consumption in EGS binary scenarios, whereas wet-cooled EGS flash scenarios were dominated by above ground operational water losses.

They ascribed the aboveground water losses to geofluid flashing and incomplete fluid condensing. Given that dry cooling systems do not utilise water, the consumption assumptions are estimated to constitute non-cooling-related water consumption in daily operations such as domestic use, make-up for geofluid loss and injection exceeding reported production levels, dust suppression, and maintenance (Clark et al., 2013; Macknick et al., 2011). However, it is not clear from literature what the key water consumption activities for dry cooling systems for EGS plants are. The estimated consumption was 0.04 to 0.51 gal/kWh for dry cooled systems as per Table 2. The estimation by Macknick et al. (2011) was 1.04 gal/kWh, which is slightly higher compared to the other studies and is a result of high non-cooling related water consumption activities of the studied plants. Since most EGS power plants utilise dry cooling system, only two studies calculated water consumption by wet cooling systems averaging at 2.05 gal/kWh and one study calculated a hybrid system to consume 1.41 gal/kWh. Wet cooling system scenarios indicated high water consumption, followed by the hybrid system, with dry cooling systems having the lowest water consumption.

TABLE 2: EGS operational cooling system water consumption in gal/kWh

REFERENCES	**DRY (air-cooled)**	**WET (evaporative)**	**HYBRID (air & wet)**
Clark et al., 2011; 2012	0.04	-	-
Clark et al., 2011, 2012,2013	0.04	-	-
Macknick et al., 2011	1.04	4.02	1.41
Clark et al., 2011	0.51	-	-
Meldrum et al., 2013	0.51	-	-
Bayer et al., 2013	0.51	-	-
Frick et al., 2010	-	0.08	-

6.2 Hydrothermal binary plants

The operation of hydrothermal binary plants is generally a closed-loop system, with all geothermal fluid being reinjected straight back into the reservoir. This necessitates the use of external water if wet or hybrid cooling systems are utilised, compared to hydrothermal flash plants where geothermal fluid may be used as makeup water for cooling systems. According to the data collected, the operating water consumption for dry cooled systems in binary plants is minimal since there is no direct water consumption but just non-cooling use. As shown in Table 3, dry cooling systems range from 0.001 to 0.45 gal/kWh, 2.8 gal/kWh for wet, and 0.22 gal/kWh to 1.11 gal/kWh for the hybrid cooling system. According to Schroeder et al. (2015), hybrid cooling systems can exhibit a broad range of variations in water consumption since the nature of their operation allows for a broad range governed by judgments on how frequently to activate the wet cooling system against the dry cooling system. From the analysis, wet cooling system utilises more water compared to hybrid and dry cooling systems.

TABLE 3: Hydrothermal binary plant operational cooling system water consumption in gal/kWh

REFERENCES	**DRY (air-cooled)**	**WET (evaporative)**	**HYBRID (air & wet)**
Clark et al., 2011; 2012; 2013	0.04	-	-
Clark et al., 2013	0.04	-	1.0
Macknick et al., 2011	0.27	2.83	0.22
Clark et al., 2011	0.27	-	-
Meldrum et al., 2013	0.45	-	0.46
Schroeder et al., 2015	0.001[a]	2.77	1.11
(Kutscher and Costenaro, 2002, Kozubal and Kutscher, 2003, in Macknick et al., 2012)	-	-	0.46

[a] Water consumption includes maintenance, domestic use and dust suppression

6.3 Hydrothermal flash plants

The only systems that use geothermal fluid are flash systems and geopressured systems. Clark et al. (2011) highlights that hydrothermal flash plants have lower makeup water requirements due to the use of condensate; yet the reservoir's long-term sustainability is less secure due to evaporative losses. They estimate that 2.7 gal/kWh of geofluid is lost owing to evaporative losses, drift, and blowdown. The size of the geothermal power plant, as well as the technology utilised, affect the amount of water consumed. About 50% of water is used by cooling towers since injection of steam in flash systems requires cooling, however, dry cooling such as in binary systems utilises dry-coolers and a closed system and thus does not require excess water.

The operational water usage of a hydrothermal flash cooling system is depicted in Table 4. There were data limitations in dry and hybrid cooling systems for the flash power plants. Wet cooling systems had a range of 0.005 gal/kWh to 2.26 gal/kWh, and hybrid had 0.32 gal/kWh. One outlier of 2.26 gal/kWh in the wet cooling system was estimated by Schroeder et al. (2015), who adds that sources are estimates made before a power plant is built and so may differ from actual water consumption during operations. Similar to binary wet cooling systems, flash plants utilising wet cooling systems also depict high water consumption in comparison to dry and hybrid cooling systems.

TABLE 4: Hydrothermal flash plant operational cooling system water consumption in gal/kWh

REFERENCES	**DRY (air-cooled)**	**WET (evaporative)**	**HYBRID (air & wet)**
Clark et al., 2012	0.18	0.005	-
Clark et al., 2011; 2012; 2013	-	0.04	-
Macknick et al., 2011	0	0.01	-
Clark et al., 2011	0.01	-	-
Meldrum et al., 2013	-	0.18	-
Schroeder et al., 2015	-	2.26	0.32
Adee and Moore 2010	-	0.01	-
(Kagel et al., 2005, Adee and Moore 2010 in Clark et al., 2011)	-	0.18	-
Skone et al., 2012	-	0.01	-
Karlsdóttir et al., 2015	-	0.91	-

6.4 Trend for the three cooling systems

Among EGS, binary and flash power plants, all dry cooling systems were the most efficient when it comes to water consumption, whereas wet (evaporative) cooling systems utilised more water. Hybrid cooling systems utilised moderate water quantities as it relies mostly on dry cooling systems as opposed to wet. In the comparison of the three geothermal energy technologies, EGS wet cooling system turned out to be the most water-consuming plant with a maximum of 4 gal/kWh, while the dry flash cooling plant was the most water efficient technology with a maximum of 0.1 gal/kWh, as shown in Figure 6. The general trend of the different cooling technologies agrees with trends in studies done by Macknick et al. (2011) and Bayer et al. (2013). Water consumption for wet cooled binary plants was higher than wet flash plants. However, Schroeder et al. (2015) attributes lower water consumption for flash relative to binary could be because of flash operating with higher temperature geofluid, making them more thermodynamically efficient and low supplemental water injection for reservoir augmentation. They also argue that injecting makeup water into a geothermal reservoir to replace evaporated geofluid condensate used for cooling in flash plants is elective and does not occur at the majority of flash plants. When supplementary injection is not included, the consumption of non-geofluid operating water is low and comparable to that of dry-cooled systems. Binary plants, on the other hand, are generally operated as closed-loop systems in which all geofluid produced is directly reinjected; hence, binary plants necessitate an external supply of water for cooling if a wet or hybrid cooling system is utilised.

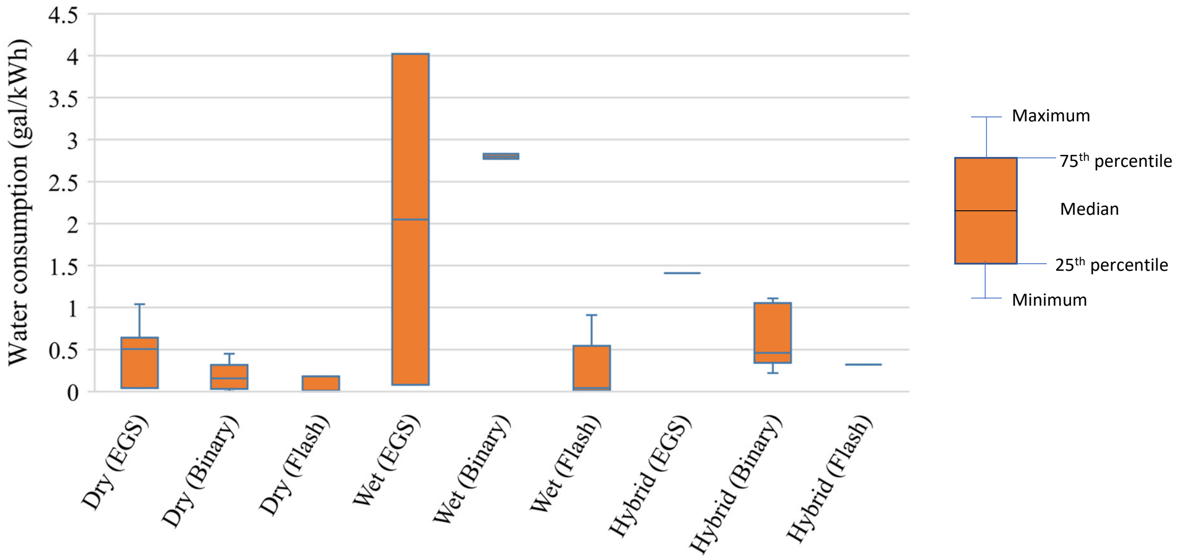

FIGURE 6: Comparison of operational water consumption for different geothermal power plant and cooling technologies

A further comparison of the total water consumption of the three geothermal electricity generation technologies shows that EGS binary and EGS flash power plants have the highest water consumption with values of 2.20 gal/kWh and 2.22 gal/kWh, respectively. Hydrothermal binary plants follow with 0.21 gal/kWh and hydrothermal flash has the least with 0.01 gal/kWh, as shown in Figure 7.

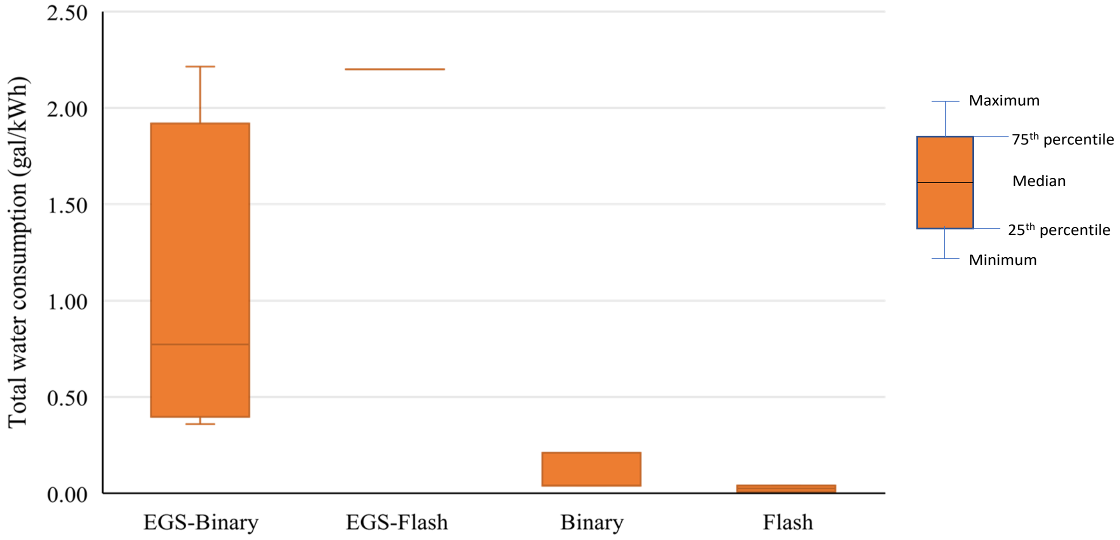

FIGURE 7: Comparison of total life cycle water consumption for different geothermal power plant technologies

6.5 Comparison of Kenya and Iceland

Kenya is listed as the seventh country globally in electricity generation using geothermal resource and the leading in Africa with an installed capacity of 944 MWe. The total geothermal energy potential of the country is about 10 GWe, and its exploitation is currently key as a green energy source that will enable a reduction in greenhouse gas emissions. Kenya is situated along the East African Rift, and all high-temperature prospects are found within the Kenya Rift Valley. The Olkaria Geothermal Field

(OGF), with an installed capacity of 816 MW, is the most productive. Surface water from Lake Naivasha, a RAMSAR site, is the primary source of freshwater in the OGF. The need for power plant start-up and drilling activities is roughly 5.3×10^7 gal/month (KenGen, 2017). With three rigs on-site, 1×10^8 gal/month of water is needed to sufficiently serve the drilling rigs (Ochome, 2017). The Water Resources Authority (WRA) has established the permitted water abstraction limit from Lake Naivasha for the OGF at 6.6×10^7 gal/month. The deficit is supplemented by separated water from power plants. In the month of August 2022, 2.5×10^7 gal of brine was utilised to supplement fresh water for drilling and reservoir management (KenGen, 2022), resulting in reduced pressure on the otherwise utilised water sources. Four power plants within the OGF were considered for quantitative water consumption for comparison with power plants in Iceland. These power plants are all flash plants using a wet (evaporative) cooling system.

Iceland, on the other hand, ranks as the ninth country in the world in electricity production from geothermal sources with a capacity of 754 MWe. It is also the leading country in terms of annual geothermal energy utilisation for district heating per person (Lund and Boyd, 2016). Geothermal energy accounts for 62% of Iceland's primary source of energy, accounting for 90% of all energy needed for district heating and 29% of power requirements. Industries, mainly aluminium and processing of ferro-silicon, utilise 80% of the generated power in the country (Bertani, 2016). The energy utilised in district heating throughout the country comes from either low-temperature fields or combined heat and electricity production plants and heating plants in high-temperature geothermal fields. Geothermal energy is harnessed from eight sites, which are all located along the three Northeast-Southwest trending volcanic ranges that transect Iceland (Huttrer, 2020). The technology in use for Iceland’s power plants are single, double, and hybrid technology for geothermal electricity generation. Unlike the OGF in Kenya, the main source of freshwater for power plants in Iceland is groundwater. The cooling technologies employed for the power plants are closed and open condensers, wet (evaporative) cooling towers and back pressure units, shown in Table 5.

TABLE 5: Comparison of operating power plants in Kenya and Iceland

POWER PLANT	CAPACITY MWe	TECHNOLOGY	COOLING SYSTEM
Olk 1 AU 4 & 5	150.52	Single Flash	Wet (evaporative)
Olk II	105	Single Flash	Wet (evaporative)
Olk IV	149.85	Single Flash	Wet (evaporative)
Olk V	173.40	Single Flash	Wet (evaporative)
Bjarnarflag	5	Back-pressure unit	Back-pressure unit
Krafla	60	Double Flash	Open condenser
Theistareykir	90	Single Flash	Closed condenser

Water consumption by power plants in Kenya is low compared to those in Iceland. However, given that the water is from a surface source, which is dependent upon by other users, efficient water management is important for future development. Iceland’s power plants do consume more water with closed condensers utilising more water compared to open condensers and back pressure, as depicted in Figure 8. Theistareykir, Krafla, and Bjarnarflag have an annual average consumption of 1.4 gal/kWh, 1.0 gal/kWh, and 0.8 gal/kWh, respectively, which is lower compared to the reviewed literature, i.e., water consumption of 2.20 gal/kWh and 2.22 gal/kWh for EGS binary and EGS flash systems, respectively. Although the source of water for Icelandic power plants is groundwater and water availability may not currently pose as a challenge, looking at the future sustainability of these sources should be investigated given the reality of climate change.

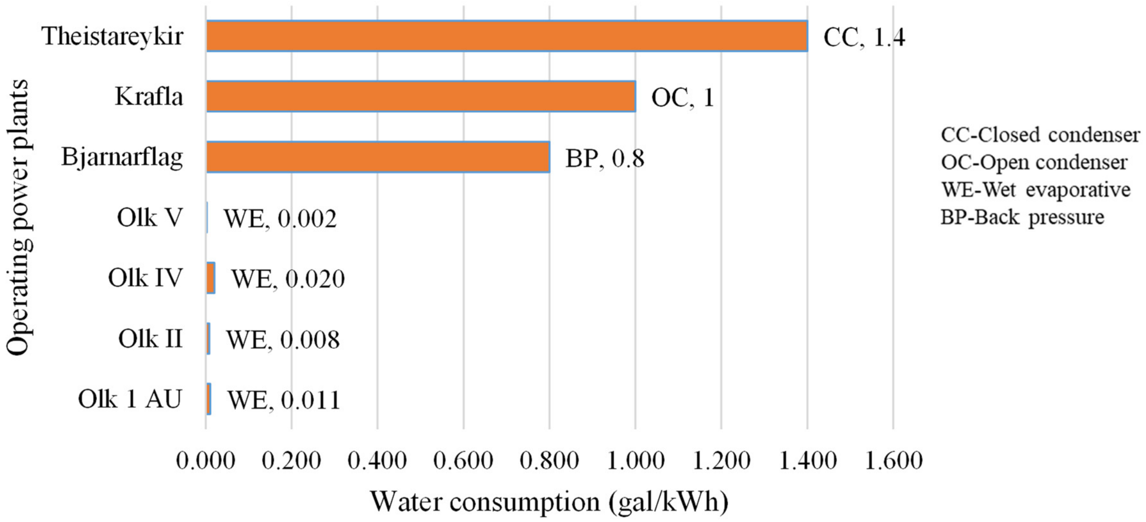

FIGURE 8: Comparison of operational water consumption for power plants in Kenya and Iceland

6.6 Carbon footprint of geothermal technologies

Several studies on greenhouse gas emissions have been conducted by, e.g., Frick et al., 2010; Lacirignola and Blanc, 2013; Skone et al., 2012; Sullivan et al., 2013; Marchand et al., 2015; Martínez-Corona et al., 2017; Heberle et al., 2016, whereas most studies' estimate of total life cycle emission are dominated by other life cycle stages rather than the operation phase due to the type of used cooling systems. Non-condensable gases account for more than 90% of CO_2, with hydrogen sulphide and other gases such as hydrogen and methane accounting for the remainder (Fridriksson et al., 2016). A review by Eberle et a. (2017) of multiple studies on life cycle Green House Gas (GHG) emissions from geothermal electricity, the median estimate (g CO_2eq/kWh) from different studies was 32.0 g CO_2eq/kWh, 47.0 g CO_2eq/kWh, and 11.3 g CO_2eq/kWh for EGS binary, HT flash, and HT binary plants, respectively (shown in Figure 9). They note that the operations phase for the hydrothermal flash plants dominates GHG emissions due to the open nature of the flash cycle whereby CO_2 is released to the atmosphere; this was similarly inferred in other studies (Frick et al., 2010; Karlsdottir et al., 2010; Marchand et al., 2015). However, due to the closed-loop process configuration, binary and EGS facilities have high GHG emissions during construction. They also pointed out that operating emissions from HT flash systems can vary greatly and can be up to ten times higher than those anticipated by the LCA studies they looked at.

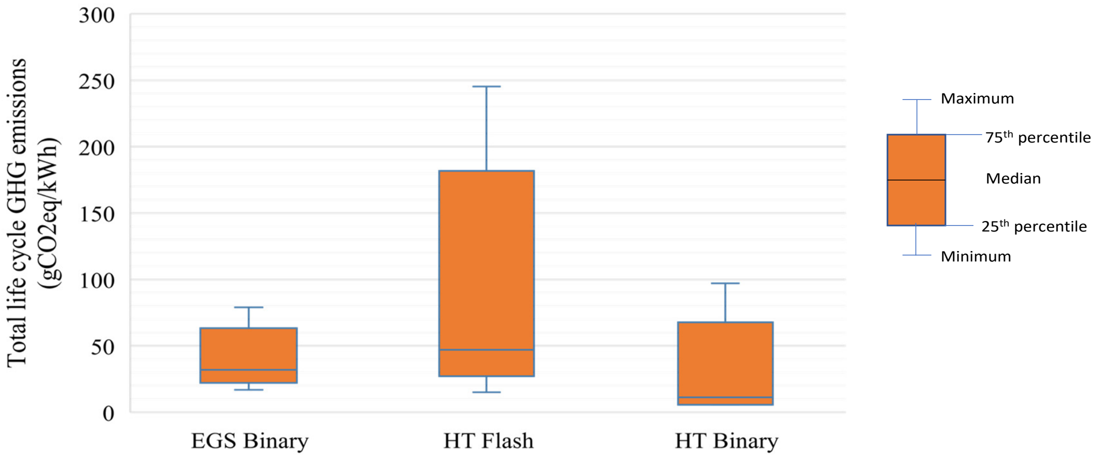

FIGURE 9: Comparison of total life cycle greenhouse gas emission for three geothermal technologies (Eberle et al., 2017)

A comparison of GHG emissions from power plants located in Kenya and Iceland was also conducted, as shown in Figure 10. Power plants in Kenya had a median value of 37.4 g CO_2eq/kWh while those of Iceland had a median value of 7.4 g CO_2eq/kWh. The low emissions for power plants in Iceland is due to the low concentrations of CO_2 in the geofluids of all reservoirs in Iceland (Karlsdóttir et al., 2015), which have an average CO_2 concentration of around 34 g/kWh (Baldvinsson et al., 2011) compared to a world average fossil fuel-based electricity generation, which typically ranges between 350 and 400 g CO_2/kWh based on IPCC estimates (IPCC, 2014). Other than low CO_2 concentrations in the Icelandic reservoirs, technologies such as carbon mineralization are being employed to reduce atmospheric GHG emissions.

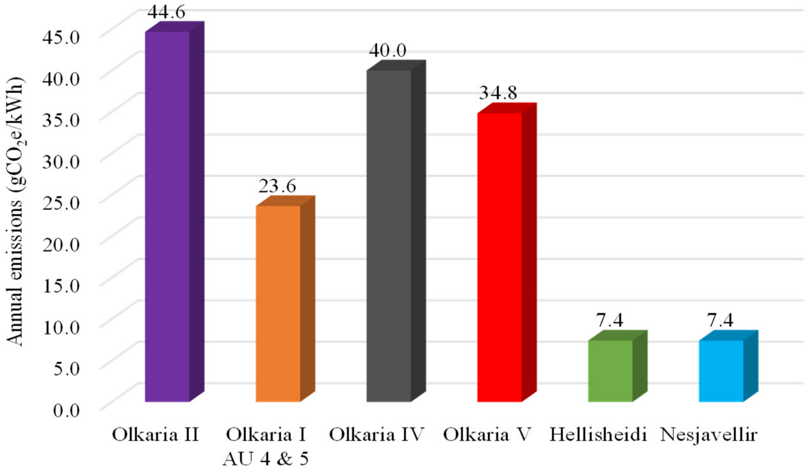

FIGURE 10: Comparison of annual g CO_2e/kWh for power plants in Kenya and Iceland

7. DISCUSSIONS

The environmental performance of geothermal power plants in terms of water usage varies greatly depending on location, capacity, and technology used. Data limitations call for the need for further studies on the different generation technologies accounting for the difference in geographic locations and considering uses based on water availability. Additionally, normalising the use of a similar assessment method should be advocated to enable a fair comparison among the technologies through a defined lifetime. Despite data gaps, general trends and inferences may be derived from the breadth of acquired data. Other than geographical location, considering upstream water use is also necessary to ensure a wholesome picture. Future development of electricity mix may be determined by the choice of cooling system to ensure sustainable water consumption. Given the realities of climate change, various cooling methods can have a significant impact on regional water sources. Therefore, in planning for geothermal development and utilization, countries with limited water sources need to take early precautions to ensure freshwater usage does not conflict with other water use demands.

The amount of water required for drilling operations is determined by well depth, reservoir type, geology, technology, and pumping rates. Because EGS wells are substantially deeper than conventional wells, binary and flash plant wells utilise less water on average than EGS plant wells. This similar trend may be seen during the construction phase, where the amount of water required is limited to use in concrete mixes. Early research on EGS reported combined water consumption for drilling, construction, and cementation; however, subsequent studies show distinct consumption rates, with drilling using more owing to well depth and stimulation factors. It is also worth noting that the calculated LCA estimates for construction water usage for the flash plants are somewhat lower than data obtained from operational power plants. This indicates that actual water use may be higher than reported quantities.

Among the assessed cooling systems, wet and hybrid cooling systems have high water consumption per kilowatt-hour of lifetime energy output. The rate of consumption for hybrid cooling system is however dependent on the frequency of use of air cooling as opposed to wet cooling during the operation of a power plant. Although air-cooled systems do not require water for cooling, the water requirements for non-cooling operation are significant all through the lifespan of a power plant, and losses do exist in practice. Given the limitation on data for the precise non-cooling water consumption processes in the operations phase, effort should be put to minimise the consumption and identification of the key processes for improvement of efficiency.

Total water consumption was generally high for EGS plants compared to hydrothermal binary and flash systems. The additional water consumption for EGS binary plants is for reservoir maintenance rather than cooling, therefore the water does not have to be of excellent quality. Nevertheless, wet or hybrid cooled EGS binary plants show trends of significantly increasing water consumption due to cooling water requirements. Published literature proposes usage of alternative non-fresh water sources, such as treated municipal or industrial wastewater, saline groundwater, or impaired surface water to meet water needs with less impact on competing water users. In spite of these, the cost analysis for the utilization of such sources should be established given that geothermal resources occur in remote or local areas where for example municipal water may not be readily available. Notwithstanding the high-water consumption for EGS systems, they have slightly lower total GHG emissions when compared to HT binary plants.

Flash plants represent the most common technology and are more water-efficient due to their dependence on geothermal fluid for cooling however, they account for the largest contribution to atmospheric emissions mainly in the operation phase. The high GHG emission is attributed to the cooling technology in flash plants that utilises wet (evaporative) cooling whereby gases are flashed into the atmosphere. The reservoir's long-term sustainability is however uncertain for future continuous dependence on the geothermal fluid. The low water consumption makes a trade-off with CO_2 emissions, however, improving the performance of these plants calls for the extraction of CO_2 through technologies such as the mineralization of CO_2 (Karlsdóttir et al., 2015) and carbon capture and storage technologies (Okoko and Olaka, 2021).

Binary plants’ water consumption was low when utilising dry (air-cooled) or hybrid (air & water) cooling systems, but high for wet (evaporative) cooling systems. Additionally, these plants eliminate atmospheric emissions resulting from venting due to air-cooled systems thus reducing carbon footprint. Given that all the geofluid extracted from the reservoir is re-injected, the sustainability of the reservoir is also improved.

Water consumption for Icelandic power plants was high compared to power plants in Kenya. Despite these power plants relying on groundwater as opposed to surface water as in Kenya’s case, the future availability of these water should be evaluated given the projected increase in development and the reality of climate change. CO_2 emissions for power plants in the two countries also varied, Iceland having lower emissions attributed to reservoir characteristics. Improvement of environmental performance for geothermal power plants calls for employment of CO_2 reduction technologies in order to attain the SDGs.

A comparison between water and carbon footprint displays varied intensities across technologies through the life cycle of geothermal power plants. EGS binary plants consume more water per kWh of energy produced and emits low GHG emissions while HT flash plants consume less water and emits high GHG. HT binary plants on the other hand emit slightly lower GHG emissions compared to EGS plants, but higher water consumption compared to HT flash systems.

8. CONCLUSIONS

Climate change risks necessitate both local and global watershed protection and sustainable water usage. Freshwater resource pressures vary with area dependent on utilization. Since these impacts are site-specific, this opens the opportunity for an additional local evaluation of water stressors. Power plants in the Olkaria geothermal field use surface water, which is currently sufficient; however, given the rising demand, future projects should investigate other water sources to further reduce stress on surface water usage, as several users rely on the same resource. Groundwater is the source of water for Iceland's power plants, and while water availability may not be an issue right now, the future sustainability of these sources should be studied given the realities of climate change.

Adopting dry cooling systems or non-fresh water sources for cooling and reservoir stimulation can improve the environmental performance of geothermal power generation technologies. This should be coupled with extensive and enhanced regional data collection on water usage, as well as additional research into the water demands of current and future technologies in order to make informed judgments. Aside from that, the performance or conversion efficiency, as well as the cost of selecting particular technologies, should be analysed in order to make an informed selection. While considering technical options, policymakers and decision-makers should consider environmental trade-offs. Implementing BATs to reduce GHG emissions should also be considered to minimize the global warming potential of geothermal energy production.

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ABBREVIATIONS

BATs	Best Available Technologies
CO_2	Carbon dioxide
°C	Degrees centigrade
EGS	Enhanced Geothermal System
FER	Fossil Energy Resources
gal/kWh	Gallons per kilowatt hour
GHG	Greenhouse gases
GWh/a	Gigawatt hour annually
GWe	Gigawatt electric
GWh	Gigawatt hour
GWt	Gigawatt thermal
HT	Hydrothermal
IEA	International Energy Agency
IPCC	International Panel on Climate Change
ISO	International Standard Organisation
KenGen	Kenya Electricity Generating Company
Km	Kilometre
kWh	Kilowatt hour
LCA	Life Cycle Assessment
m	metre
m^3	Cubic metre
Mwe	Megawatt energy
Olk	Olkaria
ORC	Organic Rankine Cycle
OGF	Olkaria Geothermal Field
ppm	parts per million
RCER	Renewable and Clean Energy Resources
RER	Renewable Energy Resources
SDGs	Sustainable Development Goals
TJ/y	Thermal Joules per year
WRA	Water Resources Authority

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