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Techno-Economic Analysis of Geothermal-Hydrogen Power Generation for Load Management in Kenya

케냐의 전력부하관리를 위한 지열수소발전의 기술 및 경제성 분석

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Abstract

The energy supply worldwide is transitioning from fossil fuels to more sustainable, renewable energy sources. This shift is prompted by the need to mitigate the detrimental impacts of climate change, primarily caused by the combustion of fossil fuels. Within this energy transition, the role of green hydrogen has garnered increasing attention as a promising candidate for the next energy frontier. Kenya is growing into a middle-income country. The country also resorts to fossil fuels during peak hours or when there is an inadequate supply of intermittent renewable energies, wind, and solar. These conventional fossil fuels are not only expensive but also detrimental to the environment.

In Kenya, geothermal power plants often generate surplus electricity during off-peak hours, which is vented off. This process is wasteful and harms the environment. Large-scale battery energy storage systems (BESS) have substantial capital expenditure (CAPEX) is a significant challenge. This excess geothermal energy combined with hydrogen through electrolysis offers a sustainable and efficient solution. Geothermal hydrogen can address peak energy demand challenges and ensure a constant power supply. Moreover, incorporating electrolysis could further reduce the production cost of electricity, making geothermal-hydrogen hybrid power generation a cost-effective option for Kenya.

This study aims to conduct a techno-economic analysis of geothermal-hydrogen power generation in Kenya and propose necessary policy interventions to enhance the development of this cutting-edge technology. By achieving the mentioned research objectives, this research could contribute to Kenya's more sustainable, balanced, and future-oriented energy mix.

The paper provides an in-depth review of Kenya's diverse energy technologies and capacities, the daily and annual energy consumption patterns, and the status of geothermal power generation. A holistic understanding of the nation's energy scenario is important in charting future pathways for successfully integrating geothermal hydrogen power generation. A detailed literature review provides an

overview of geothermal hydrogen technology, insights into electrolyzer and hydrogen storage technologies, techno-economic analysis, and a review of various studies in the field, all playing an essential role in the comprehensive understanding of the subject.

Therefore, this thesis will adopt a comprehensive techno-economic approach to geothermal-hydrogen power generation in Kenya using Alkaline Water Electrolysis (AWE). It focuses on the Levelized Cost of Hydrogen (LCOH) by assessing various aspects of this prospective energy solution. A critical indicator of the economic feasibility of hydrogen production. A model was developed considering several parameters, including capital costs, operational expenses, electricity costs, and the Higher Heating Value (HHV) of hydrogen. The calculated LCOH for this investigation ranges from $3.3 to $5.01 per kilogram of hydrogen under varying conditions and assumptions. It is worth noting that electricity costs and capital expenses significantly influence the LCOH, underlining their crucial role in determining the economics of hydrogen production.

This investigation integrates a sensitivity analysis to comprehend the effect of changes in technical and economic parameters on the LCOH. The role of the sensitivity analysis is to demonstrate how changes in variables such as electrolyzer efficiency, electricity price, and capital costs can affect the economic viability of geothermal hydrogen power generation. The results of this analysis are critical to the economic implications of potential variations in these parameters.

Further, this study delves into the implications of integrating a Compressed Air energy Storage facility to counteract the intermittent nature of renewable energy. The inclusion of a storage facility adds to the costs and energy losses, yet it markedly enhances the system's operability by ensuring a consistent supply of hydrogen. Despite the additional cost, the capability of uninterrupted hydrogen supply holds significant potential for practical applications, pushing the LCOH toward the upper limit of the projected range.

A novel solution proposed by the study to mitigate high operational costs involves harnessing excess geothermal energy currently vented and unused by redirecting this underutilized energy to hydrogen production. The research emphasizes the prospect of capitalizing on the excess geothermal energy currently

vented for hydrogen production at reduced costs. Proposing a system where this excess energy is charged at $0.01/kWh to cover the operational costs of the geothermal power plant, this innovative approach has the potential to decrease the LCOH, thereby enhancing the economic feasibility of hydrogen production. The Levelized cost of hydrogen significantly reduces from 3.3$/kgH2 to 1.754$/kgH2 at 1MW. 2.9$/kgH2 to 1.485$/kgH2 at 50 MW due to economies of scale.

Fundamentally, this study proposes policy implication, development, and application of the policy on standards and safety of efficient realization of geothermal-hydrogen power generation in Kenya. This new cutting-edge technology will require international cooperation for technology exchange and expertise. Fiscal incentives and the provision of financial support for institutions investing in this field will be vital for the adoption of geothermal hydrogen. Besides energy generation, other Power-to-X technologies such as manufacturing, transport, and agriculture-fertilizer production can benefit from green hydrogen for social, environmental, and economic benefits.

Water consumption and purification have been highlighted on the detrimental side of this technology. Water is a requirement for hydrogen generation. Large-scale hydrogen power plants will require vast amounts of water, which might affect the ecosystem of rivers and lakes. Purification of the water is detrimental to the environment. Conducting an environmental assessment for water availability is essential before project implementation.

Lastly, the present study presents unique challenges and limitations. Geothermal-hydrogen technology is a developing technology with scanty and inadequate standardized data. The economic assumptions remain unclear due to the novelty of various factors such as geographical location and market forces. The thesis provides some insights into the potential for geothermal hydrogen power generation in Kenya, applying AWE, thus paving the way for further research.

Keywords: Alkaline Water Electrolysis (AWE), Geothermal power, Green Hydrogen, Levelized Cost of Hydrogen (LCOH), Compressed Air Energy Storage (CAES), Power-to-X (P2X) technology
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Chapter I

Introduction

1.1. Background

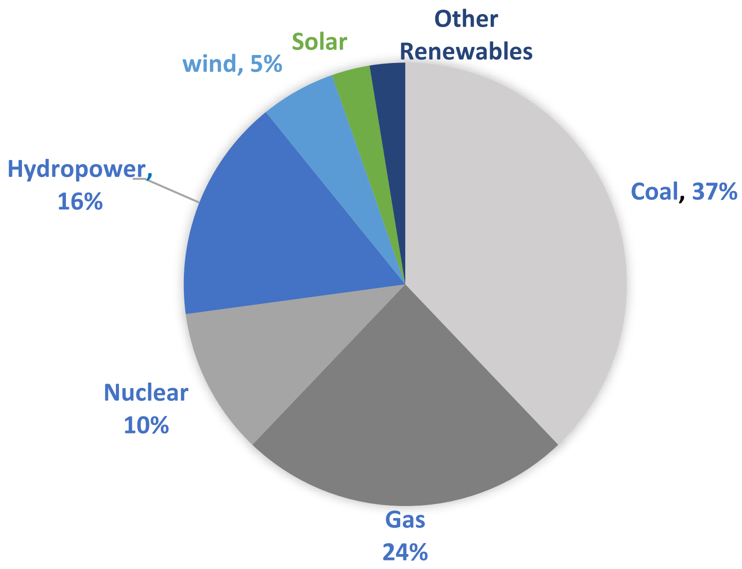
1.1.1. Global Status

Global power supply has been predominantly reliant on fossil fuels. A foundation that has significantly molded our modern civilization. However, this dependence on fossil fuels, albeit instrumental in driving economic growth and development, has brought dire environmental consequences. The substantial carbon dioxide and other greenhouse gas (hereafter, GHG) emissions resulting from burning fossil fuels have significantly affected climate change. To avert this, the world is progressively shifting its energy paradigm from conventional fossil fuels to renewable energy resources.

In 2021, the International Energy Agency highlighted that over 26,000 terawatt-hours of electricity were produced globally (IEA, 2021). The majority of this production, about 63%, came from fossil fuels, including oil, gas, and coal. To combat climate change, we must reduce the reliance on fossil fuels and shift to sustainable resources of energy (Zakeri et al., 2022).

This necessity was underscored in 2015 with the introduction of the Paris Agreement, an international treaty endorsed by 196 countries to address global warming (Nadeau et al., 2022). This treaty seeks to decrease global temperatures to below 2 degrees Celsius, ideally 1.5 degrees Celsius, relative to pre-industrial levels (Rogelj et al., 2016). This target requires a significant reduction in GHG emissions, leading to the imperative for a carbon-neutral world by the mid-century.

Figure 1-1. Global Electricity Generation



Source: International Energy Agency, IEA, 2021

By 2021, renewable energy sources, including wind, solar, geothermal, hydroelectric power, and low-carbon technologies, contributed 36.7% to the world's electricity generation. Despite this progress, experts caution that the current rate of renewable energy growth is insufficient to achieve net-zero emissions by 2050 (Electricity Production Data | World Electricity Statistics | Enerdata, n.d.).

To reach the net-zero emissions target, it is suggested that at least 80% of electricity should be derived from renewable energy sources (IEA 2021-Global Energy Review 2021). This challenging task necessitates swift technological advancement and reduced renewable energy procurement costs. There is also a need for strong commitment and significant investment from countries worldwide in renewable energy sectors. One promising solution lies in the form of hydrogen power, especially green hydrogen. This renewable form of energy is produced through the electrolysis of water using electricity, preferably derived from renewable sources, thus ensuring zero carbon emissions. Green hydrogen's potential of being an energy carrier is increasingly recognized, given its excellent energy storage capability, ease of transportation, and wide range of applications, from powering vehicles to heating buildings and serving as feedstock for industrial processes. The global trend unequivocally moves towards clean, efficient, and sustainable energy solutions like green hydrogen. As these technologies continue to mature and become more cost-effective, they will inevitably play a critical role in our collective endeavour toward a cleaner, low-carbon, and sustainable future (Ishaq & Dincer, 2020).

1.1.2. Kenyan Status

Electricity serves as a cornerstone in realizing Kenya's national development objectives, such as the Sustainable Development Goals (hereafter SDGs) and the Vision 2030 blueprint (Kivisi, 2019). As the East African nation with the largest economy, Kenya recorded a Gross Domestic Product (GDP) of 107.530 billion dollars in 2020 (Kenya National Bureau of Statistics, 2021). Notwithstanding the devastating impact of the COVID-19 pandemic, the economy still experienced a 4% growth rate.

Kenya's power mix is green, with over 90% of its energy mix sourced from renewable energies. However, periods of high energy demand or renewable energy scarcity exist, during which the country resorts to fossil-fueled power. Fossil power plants, while fulfilling immediate energy needs, pose a threat to the environment and contribute to long-term climate change (Takase et al., 2021). Kenya made notable strides in electricity access, with a 75% electricity access rate achieved in 2021. Unfortunately, this progress is unevenly distributed across the country. In remote regions of the country, beyond the electricity grid, the access rate plummets to a lowly 24%, leading to an over-reliance on traditional energy sources like kerosene and wood biomass (Moner-Girona et al., 2019). In these isolated areas, the population predominantly relies on kerosene and wood biomass for energy, leading to health problems arising from Household Air Pollution (Megahed & Ghoneim, 2021).

However, Kenya holds vast potential in untapped renewable energy resources. A study by (Spittler et al., 2021) suggested that geothermal capacity is around 10,000 MW, wind capacity of 4,600 MW, solar capacity of 15,000 MW, hydro capacity of 6,000 MW, biomass of 131 MW, and marine tidal energy capacity of 1,000 MW (Onundo & Mwema, 2017). With these substantial reserves, Kenya is in an excellent position to eventually rely entirely on renewable sources for its electricity generation.

Furthermore, the emergence of novel technologies and innovations heralds a promising future for clean and sustainable energy generation. Hydrogen power is one such technology that stands at the forefront of potential solutions (Yue et al., 2021a). Hydrogen power holds great promise as a sustainable, versatile, and clean fuel. Green hydrogen from renewable energy resources could provide a viable solution to the pressing global energy challenge (Ishaq & Dincer, 2021).

Hydrogen is a remarkable fuel capable of generating electricity, heat, and mobility, thus presenting a multifaceted solution to energy needs. For Kenya, hydrogen could be produced utilizing existing renewable energy sources such as geothermal, wind, and solar, offering a synergy of renewable technologies. It is also easily stored and transported, which could prove vital in supplying energy to the country's more remote and disconnected parts.

This thesis will focus on conducting a techno-economic analysis for geothermal-hydrogen power generation in Kenya. This study may form the basis for the country's transition to renewable energy sources, fostering self-reliance in energy, stimulating economic development, and embracing sustainability. The deployment of geothermal hydrogen power generation technology could also potentially propel Kenya toward the attainment of its climate change objectives

1.2. Geothermal-Hydrogen power generation

Geothermal energy is a plentiful and environmentally friendly renewable energy source in Kenya. It is derived from the Earth's natural heat and can be harnessed through geothermal power plants (Manzella, 2017). These plants utilize underground reservoirs of steam or hot water to generate electricity, as it is often referred to as the battery of the earth (Chamorro & Mondejar, 2022). On the other hand, hydrogen is a versatile energy carrier with various applications, such as fuel cells and internal combustion engines. Green hydrogen, also known as renewable hydrogen, is an emission-free fuel with significant potential to revolutionize the global energy landscape. It is produced through electrolysis, utilizing renewable energy sources like solar, wind, and hydropower to split water into hydrogen and oxygen. Unlike traditional hydrogen production methods that rely on natural gas or coal, green hydrogen does not release harmful pollutants into the atmosphere.

The combination of geothermal energy and hydrogen production through electrolysis presents a sustainable and efficient method for electricity generation in Kenya (Hadjiat et al., 2021). Geothermal power plants can supply the required electricity for the electrolysis process, while the produced hydrogen can be utilized in fuel cells to generate electricity.

Moreover, the geothermal-hydrogen power generation system can be enhanced by incorporating thermolysis (Alirahmi et al., 2021a). Thermolysis involves utilizing high temperatures ranging from 500 to 2,000 degrees to split water molecules into hydrogen and oxygen. The resulting hydrogen and oxygen can then be used in fuel cells to generate electricity (Ghazvini et al., 2019a). This process falls under power-to-X technology, which involves converting surplus renewable energy into other forms usable in various applications (Hermesmann et al., 2021). These applications include the production of hydrogen through electrolysis or thermolysis, as well as the production of ammonia or other chemical compounds.

The geothermal-hydrogen power generation offers flexible and reliable energy production. Geothermal energy provides a consistent power source, and the addition of electrolysis enables on-demand hydrogen fuel generation. By harnessing the inherent reliability of geothermal energy and coupling it with the flexibility of hydrogen production, the geothermal-hydrogen power generation system offers an adaptable and robust solution for energy needs. It provides a sustainable pathway to address the challenges posed by peak energy demand, grid balancing, and ensuring uninterrupted power supply (El-Emam & Özcan, 2019).

Another advantage is the potential for cost savings. Geothermal energy is often more cost-effective than other forms of renewable energy and incorporating electrolysis can further reduce the production cost of hydrogen (Amin et al., 2022). This makes geothermal-hydrogen hybrid power generation a viable and cost-effective option for Kenya. Furthermore, geothermal-hydrogen power generation has the potential to reduce GHG emissions. Hydrogen fuel produces no carbon emissions, making it a clean and sustainable energy source. This transition to low-carbon energy can assist Kenya in achieving its climate goals and transitioning to a more environmentally friendly economy.

1.3. Problem statement

Geothermal power plants in Kenya have the potential to generate surplus electricity. These plants are designed to generate a consistent and reliable source of electricity but sometimes produce excess electricity needed due to low demand in off-peak hours (Ndiritu & Engola, 2020). They serve as standby facilities for variable renewable energy sources. The main issue of concern is the venting of steam from these geothermal plants, which is necessary to control the power output. This is not only wasteful but also detrimental to the environment (Bošnjaković et al., 2019). This issue cannot be overlooked in a world increasingly aware of the importance of environmental sustainability.

Excess electricity could theoretically be stored in Battery Energy Storage Systems (hereafter BESS) to alleviate the issue of overproduction. However, a significant hurdle in implementing this strategy is the substantial capital expenditure (hereafter CAPEX) associated with such systems (Apribowo et al., 2022). The cost of using BESS for large-scale storage (such as 200 MW) is currently high. Moreover, Kenya does not presently possess the infrastructure for pumped storage, a form of large-scale energy storage that could potentially mitigate excess electricity generation. This leaves the nation with a need for alternative solutions.

A promising approach to this problem, which is being increasingly adopted worldwide, is converting surplus geothermal power into hydrogen. Although still in its development stages, the generation of hydrogen power from geothermal sources is a potential game-changer in energy management. By converting excess geothermal power into hydrogen, not only is the issue of waste addressed, but a versatile energy source is likewise created. Hydrogen can be stored and utilized during periods of high demand, thereby mitigating the issue of electricity oversupply during off-peak hours(Nguyen et al., 2019).

The impact of this solution extends beyond merely addressing electricity surplus. By decreasing the wastage and enhancing the effective utilization of geothermal energy, reliance on fossil fuels is also reduced. This contributes to a more sustainable energy landscape, aligning with global efforts to minimize the carbon footprint and tackle climate change. Therefore, the adoption and advancement of geothermal hydrogen power generation presents an intriguing prospect for Kenya's future. It offers an innovative way to harness the nation's geothermal resources more efficiently, paving the way for a sustainable, balanced, and forward-looking energy policy.

Research Questions

The surplus geothermal power generation is an issue of significant importance in Kenya, prompting the need for innovative, effective, and economically viable solutions. As a result of a disproportion between electricity supply and demand coupled with a lack of effective large-scale storage solutions, geothermal energy generation often exceeds the energy demand, particularly during off-peak hours. One potential solution for surplus geothermal generation is a conversion into green hydrogen, which shows promise. However, there are important questions raised about its practical feasibility and policy implication.

1. What is the techno-economic analysis of a geothermal-hydrogen power generation system in Kenya?
2. What policy interventions are needed to enhance the development of geothermal hydrogen power generation for load management in Kenya?

Research Objectives

Geothermal energy generation in Kenya sometimes surpasses the actual energy requirement, specifically during periods of low demand. An emerging strategy to utilize this surplus geothermal power is to convert it into green hydrogen, a concept that holds considerable potential. The primary objective study into geothermal-hydrogen power generation in Kenya will be to assess the practicability of utilizing surplus geothermal energy to create hydrogen. The research goals are summarised as follows:

1. To determine the techno-economic analysis of geothermal-hydrogen power generation in Kenya.
2. To establish policy interventions for developing geothermal hydrogen power generation in Kenya.

1.4. Scope of the study

This research study centres around an evaluation of geothermal data, both historical (2010–2022) and forecasted (2023–2030). The principal aim is to discern the latent excess capacity within the geothermal power sector, which could be channelled toward hydrogen production. A crucial component of this research is examining the underutilized surplus of geothermal energy within the Kenyan context. Interestingly, this surplus, which remains largely untapped when energy demand falls short of the available capacity, accounts for approximately 10% of the overall geothermal generation.

The techno-economic analysis forms a critical component of our methodology. This combined approach integrates technical specifications with economic factors to ascertain the economic feasibility of a system. In view of this study, this method involves a detailed investigation into the technical facets of geothermal hydrogen power generation and technological data. Simultaneously, it delves into the economic implications, including the capital and operational expenditures and the forecasted Levelized Cost of Hydrogen (LCOH).

To further ensure the robustness of our economic model, a sensitivity analysis is employed. This technique aims to discern how input parameter variations can impact a particular model's output uncertainty. As part of this approach, we manipulate the values of several key variables within the model, such as the cost of electricity or geothermal resources and capital and operational expenditures. Observing how these changes influence the model output helps us to identify which variables exert the most profound impact on the economic feasibility of the geothermal hydrogen power generation system. This thesis seeks to provide a robust assessment of the potential for harnessing geothermal energy for hydrogen production in Kenya.

1.5. Thesis structure

This thesis has six chapters. The rest of the research will be as follows.

Chapter 2 provides a retrospective analysis of the nation`s institutional structure in the power sector. It gives an insight into the country`s electricity as it delves into the aspects such as energy generation and capacities per technology for

2022. Consumption patterns are depicted through load curves. Geothermal generation in Kenya will be highlighted in this chapter. A summary to provide an overview of the chapter is presented.

Chapter 3 presents a literature review of the existing body of knowledge on the topic. The pivotal role of green hydrogen in the global energy transition is discussed with a detailed overview of the synergy between geothermal energy and green hydrogen. Different types of electrolyzers and the current hydrogen storage technologies are deliberated, including techno-economic analysis and sensitivity analysis to test the robustness of the model. Further, some research papers specifically discussing hydrogen production from geothermal sources through alkaline water electrolysis are highlighted. The chapter ends with research implications and a chapter summary.

Chapter 4 describes the methodological approach adopted in this study. It discusses the flow charts of the model and the geothermal hydrogen production. It explains the selection of geothermal data and technical analysis of electrolyzers and storage facilities. It presents a techno-economic analysis of the levelized cost of hydrogen (LCOH) and a sensitivity analysis of the variables of LCOH to test their resilience in the model.

Chapter 5 presents the finding derived from the methodology. Explains the results from each scenario as well as a techno-economic analysis of the LCOH and sensitivity analysis of the variable to test their robustness to the model. It assesses the results in light of the existing knowledge and debates in the field, offering a critical perspective on the data obtained.

Finally, Chapter 6 wraps up the study by summarising the key findings, offering a series of policy recommendations, and suggesting areas for future research. It also provides directions for future research in geothermal power and hydrogen production.

1.6. Chapter summary

The introduction chapter highlights the urgency of the global energy transition from fossil fuels to renewable sources, underlining the many drawbacks of fossil fuel dependency. It touches upon Kenya's unique energy scenario, emphasizing that despite its abundant renewable resources, it frequently resorts to fossil fuels due to the intermittency of renewable energy sources. The relevance of geothermal-green hydrogen is underscored, positioning it as a promising frontier in future energy strategies. The problem statement, research questions, and objectives collectively bring out the rationale behind this study, with the scope of the study outlining the methodology applied in this thesis. Finally, the structure of the thesis is highlighted, providing an overview of the content within each chapter.

Chapter II

Status of the Electricity Sector in Kenya

2.1. Policy and Institutional Structure of the electricity sector in Kenya

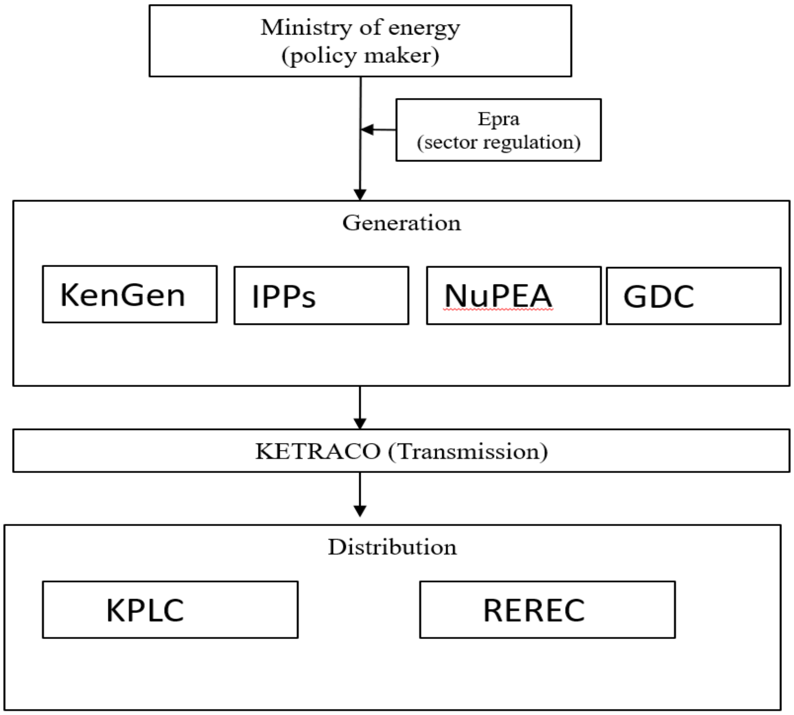
The power sector in Kenya has experienced significant transformations over the years, punctuated by critical policy shifts and institutional restructuring aimed at promoting efficient and sustainable energy production and distribution. The changes can be traced back to the history of the Kenya Power and Lighting Company (KPLC) and its subsequent transition into the Kenya Electricity Generating Company (KenGEn), influenced by various legislative measures and policy documents. KPLC was incorporated in 1922, under the Companies Act (Chapter 486 of the Laws of Kenya), to take over the business of electricity supply in the country from Nairobi Power Company Ltd. For many years, KPLC was the sole entity responsible for electricity generation, transmission, and distribution across the country.

The turn of the century saw a shift in this structure with the introduction of the Energy Act of 2004, which led to the splitting of KPLC's functions. This saw the creation of the Kenya Electricity Generating Company (KenGEn) in 2004, a development that stemmed from the Sessional Paper No. 4 of 2004 on Energy. EKenGEn took over the generation responsibilities, allowing KPLC to focus on the distribution and retailing of electricity. There was also liberalization of the energy sector, permitting independent power producers (IPPs) to participate in power generation. Following this, in 2008, the Kenya Electricity Transmission Company (KETRACO) was established. KETRACO's main mandate was to plan, design, construct, operate, and maintain new electricity transmission lines and associated substations.

Another significant development came in 2008 with the formation of the Geothermal Development Company (GDC). The GDC was established as a Special Purpose Vehicle to accelerate the development of geothermal resources in Kenya. The National Energy and Petroleum Policy of 2015 was a game-changer, marking a paradigm shift in Kenya's energy landscape. It was designed to guide the country towards a diversified and sustainable energy mix and set the stage for further legislative reforms.

The Energy Act of 2019 was a landmark legislation, reflecting the evolution and growth of the energy sector in Kenya. This Act brought significant changes, including the creation of two new regulatory bodies: the Rural Electrification and Renewable Energy Corporation (REREC) and the Nuclear Power and Energy Agency (NuPEA). REREC's role is to enhance the provision of electricity in rural areas of the country and manage renewable energy resources. On the other hand, NuPEA is mandated with promoting and implementing Kenya's nuclear power programme, thus adding a new dimension to the country's energy matrix. The development of the power sector in Kenya has been marked by major legislative and policy shifts, resulting in a more diversified and decentralised energy infrastructure. The overarching aim has consistently been to ensure sustainable, affordable, and reliable energy services for all Kenyans.

Figure 2-1: Institutional structure of the power sector in Kenya



2.2. Current electricity status in Kenya

Kenya's energy generation is diverse and primarily comprises renewable sources which contributed over 90% of the production as stated earlier **Error! Reference source not found.**. Geothermal energy leads, followed by hydro, thermal (oil and gas), wind, and solar power. The country is known for its substantial investment in geothermal power, which has led to a rapid increase in installed capacity over the years.

Table 2-1 shows geothermal power accounted for over 31% of the total electricity supply and has a capacity of 950 MW in 2022. The Olkaria fields are one of the largest geothermal development sites in the world. Hydroelectric power, primarily sourced from dams along the Tana River and the Turkwel Gorge Dam, also forms a significant part of Kenya's power supply. However, due to issues like changing weather patterns and drought, hydro power's contribution has been increasingly erratic and less reliable. Wind power is another important and growing component of Kenya's power mix. The Lake Turkana Wind Power project, which was the largest wind farm in Africa as of 2022, has a capacity of 310 MW. Solar power, while still a small part of Kenya's power mix, 173 MW but is growing rapidly, especially in rural areas where off-grid solar systems are increasingly common. The country also exchanges power with the neighbouring countries Uganda and Tanzania for voltage stabilization.

Table 2-1: Generation capacity and Energy Generation in 2022

TECHNOLOGY	Generation capacity		Energy Generated (GWh)
	Installed	Effective	
Hydro	838	809	3,350
Geothermal	950	871	4,951
Thermal	682	645	1,649
Wind	436	426	2,053
Biomass/ Co-generation	2	2	0
Solar	173	173	313
Imports	-	-	338
TOTAL	3,081	2,926	12,653

Source: Ministry of Energy, Kenya,2022

2.3. Load profiles.

Electricity load profiles are essentially a measure of how much electricity is being used in a certain area at a given time (Proedrou, 2021). An electricity load profile is a graphical representation of the variation in electricity consumption over a specific period, usually a day, week, or month. It is used to understand the patterns of electricity consumption for a specific customer or a group of customers in a specific area.

The load profile typically shows the hourly or half-hourly consumption of electricity, with the horizontal axis representing time and the vertical axis representing the amount of electricity consumed. The load profile is usually presented in the form of a graph or chart, with the highest point on the graph representing the peak demand, and the lowest point representing the off-peak demand.

Understanding the load profile is important for electricity providers as they need to ensure that they have enough capacity to meet the peak demand. It also helps them to plan for future energy generation and distribution needs. For customers, it can help them to identify opportunities to reduce energy usage during peak periods and thus lower their electricity costs.

In Kenya, the electricity load profile is likely to vary depending on a number of factors, including the time of day, location, and economic activity in the area (Deepak Sharma & Singh, 2014). For example, during the day, when people are at work and businesses are operating, the electricity load is likely to be higher than at night, when many people are at home and using less electricity. Similarly, during the hot season, when people are using air conditioning and other appliances that use a lot of electricity, the load is likely to be higher than during the cooler months (Hart & Wright, 2016).

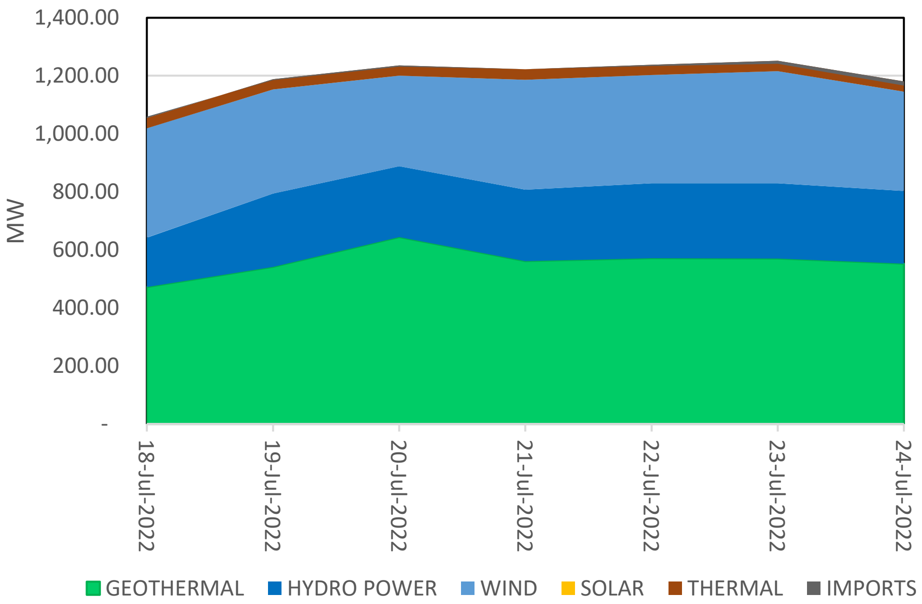
The daily load curve of Kenya, Figure 2-2 which is a graphical representation of the variation in electrical load over 24 hours, can be divided into three distinct sections: off-peak, mid-peak, and on-peak.

The off-peak period usually occurs during the late night to early morning hours when the overall electricity demand is at its lowest. During this time, most businesses are closed, and many residential consumers are asleep, leading to reduced consumption. This is the period when the cost of electricity is typically at its lowest due to the lower demand.

The mid-peak period generally happens in the late morning to early afternoon. At this time, there's an increase in electrical demand as businesses start their operations and residential activities increase. However, this period doesn't coincide with the highest demand of the day. The cost of electricity during this period is generally higher than during the off-peak period but lower than the on-peak period.

The on-peak period is typically in the late evening. This is when electricity demand is at its highest, as it's the time when both residential and commercial consumption peaks. Many people are returning home from work, turning on appliances, lights, and electronics, and businesses are often still operating. Due to the high demand, the electricity cost during the on-peak period is typically the highest. Understanding these daily load curve sections is crucial for power planning. It informs decisions on when to generate more or less electricity, helping to balance supply with demand and maintain grid stability.

Figure 2-2: Daily load curve 2022



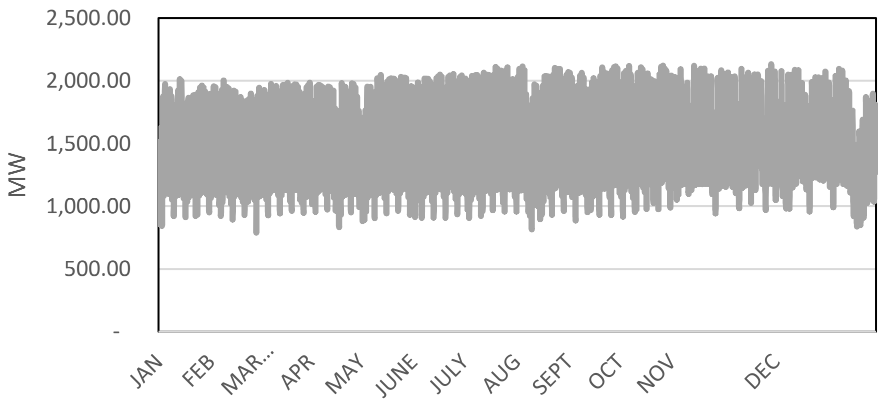
Source: Ministry of Energy, Kenya, 2022

Kenya's annual load curve for 2022 Figure 2-3, much like its daily load curve, reveals the fluctuations in electricity demand throughout the different months of the year, indicating periods of off-peak, mid-peak, and on-peak consumption.

An annual load curve Figure 2-3 takes into account broader seasonal variations influenced by factors such as climate, cultural events, school terms, and industrial activity cycles, among others. Nonetheless, it also carries within it the daily cycle of off-peak, mid-peak, and on-peak periods, which recur consistently throughout the year.

The presence of off-peak periods, where electricity demand is lower, indicates that there are times in the day when the power generated can exceed the demand. These periods represent opportunities for innovative energy management strategies, such as the storage of excess power or its use in applications like the production of green hydrogen, which can contribute to improved energy efficiency and sustainability.

Figure 2-3: Annual load curve 2022

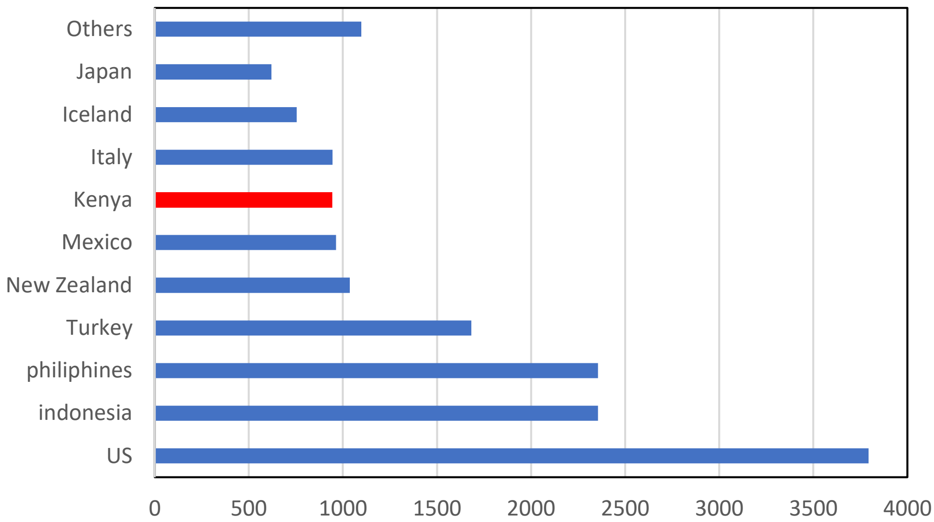


Source: Ministry of Energy, Kenya,2022

2.4. Geothermal power generation in Kenya.

Geothermal power generation is a process by which electricity is produced from the heat of the Earth's crust. The heat is harnessed through the use of geothermal power plants, which typically consist of a power generation unit, a heat exchanger, and a fluid circulation system. The most common type of geothermal power plant is the dry steam power plant, which uses steam from geothermal reservoirs to turn turbines that generate electricity. Another type is the binary cycle power plant, which uses hot water from geothermal reservoirs to heat a secondary fluid with a lower boiling point, which is then vaporized to turn the turbines. According to IRENA, 82 countries benefit from using geothermal power. 26 countries apply geothermal energy production. 8.3% of total electricity generation is from geothermal generation. Global geothermal leader countries are as follows Figure 2-4: Global geothermal production.

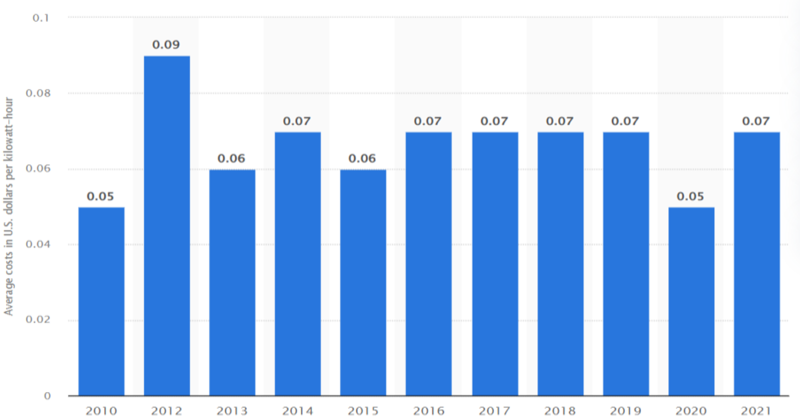
Figure 2-4: Global geothermal production



Source: International Renewable Energy Agency, IRENA, 2021

According to the International Renewable Energy Agency, IRENA, the levelized cost of electricity (LCOE) from geothermal Figure 2-5 was between USD 0.05 and USD 0.09 per kWh between 2010 and 2020. This cost varies depending on the location and specific project, as some geothermal resources are more expensive to develop than others. The cost also changes over time with advancements in technology and economies of scale.

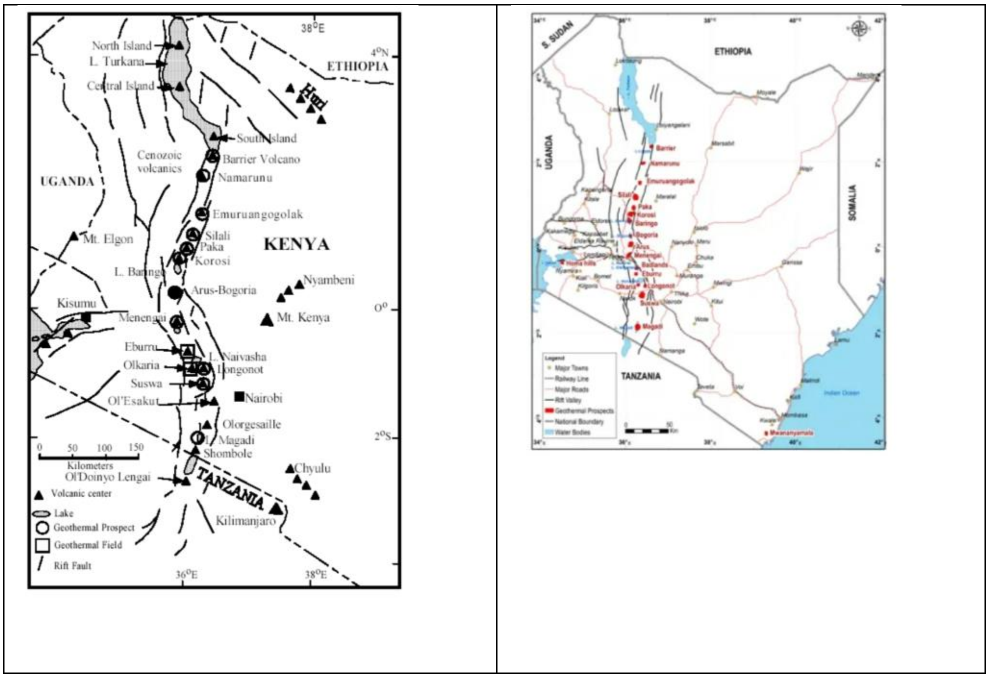
Figure 2-5: Levelized cost of energy -geothermal



Source: International Renewable Energy Agency, IRENA, 202)

Geothermal power is well-suited to be used as a baseload power source, which refers to a source of power that is consistently available to meet the minimum power needs of a region (Barasa Kabeyi & Olanrewaju, 2022). This is because geothermal power plants can operate consistently and reliably, providing a steady stream of electricity. In Kenya, geothermal power is increasingly being dispatched as a baseload power source, particularly in the Olkaria geothermal fields.

Figure 2-6: geothermal fields locations in Kenya



(Olkaria Geothermal | OpenStreetMap, n.d.)

2.4.1. Geothermal Technologies in Kenya

In Kenya, three main types of geothermal technologies are utilised: Single Flash Technology, Binary Cycle Technology, and Wellhead Technology.

Single Flash Technology: This is the most commonly used technology in geothermal power generation worldwide, and it is extensively used in Kenya. In a single flash geothermal power plant, high-pressure hot water from the geothermal reservoir is allowed to rapidly depressurise or 'flash' into steam upon reaching the lower pressure at the surface (Chamorro & Mondejar, 2022). The resulting steam is then used to drive a turbine connected to a generator to produce electricity. The remaining hot water and condensed steam are injected back into the reservoir. This method is effective but works best with high-temperature geothermal resources (above 180°C).

Binary Cycle Technology: The plants operate on lower temperature geothermal resources ranging between 100°C and 180°C. These power plants work on the principle of heat exchange. In these systems, the geothermal water is passed through a heat exchanger where it heats a secondary fluid with a lower boiling point, like isopentane or isobutane (Bett & Jalilinasrabady, 2021). This secondary fluid vaporises and drives the turbine to generate electricity. The advantage of this technology is that it can exploit lower-temperature geothermal resources, which are more prevalent, and it results in virtually zero emissions since the geothermal fluid is entirely re-injected back into the reservoir.

Wellhead Technology: Wellhead geothermal power generation is a relatively recent approach to geothermal power production that has been adopted in Kenya. A wellhead generator unit is essentially a small, self-contained power plant installed at the wellhead of a productive geothermal well (Kipyego & Kiptanui, 2016). These plants can start generating electricity soon after the well is tested and confirmed to be productive, thus enabling faster monetisation of the geothermal resource. The generated power can be used for internal plant operations or fed into the grid. This approach allows for incremental development of a geothermal field and can be a cost-effective way of rapidly increasing power generation capacity.

By employing these technologies, Kenya has been able to tap into its vast geothermal potential, making it one of the leading producers of geothermal power globally Figure *2-4*. Each of these technologies has its advantages and suitability depending on the characteristics of the geothermal resource, and the careful selection and use of these technologies is an important aspect of Kenya's geothermal development strategy.

2.5. Chapter summary

This chapter provides an overview of the institutional structure of the power sector in Kenya, with particular emphasis on the country's energy supply and demand dynamics. It presents an in-depth examination of the diverse energy technologies utilised in Kenya, along with an assessment of their capacities. Furthermore, the chapter explores daily and annual energy consumption patterns, as depicted by load curves, to offer a detailed understanding of the nation's energy demand. It also reviews the current status of geothermal power generation on a global scale. Lastly, the chapter explores the variety of geothermal technologies applied in Kenya, providing a comprehensive review of the country's energy landscape.

Chapter III

Literature Review

3.1. General review

The global energy transition from fossil fuels to renewable energy is a fundamental aspect of contemporary energy discourse. This shift is driven by a myriad of factors including concerns about climate change, pollution, and the need for energy security(Colgan & Hinthorn, 2022). Fossil fuels such as oil and gas, and coal are the dominant sources of energy, however, they are finite resources and are increasingly becoming depleted (IEA- World Energy Outlook 2022). The sharp rise in demand for electricity specifically and energy generally, for sustainable and affordable energy supply(Bogdanov et al., 2021). Energy security serves as a significant driver in the shift towards renewables. Global energy supplies are often destabilised due to international disputes, leading to a cascade effect of escalating fuel prices and subsequent energy poverty (San-Akca et al., 2020) The international energy crisis has thus catalysed a surge in the growth of renewable energy. Many nations, as a result, have bolstered their renewable energy policies. As a domestically available and nearly inexhaustible energy source, renewable energy can contribute significantly to a nation's energy security by reducing reliance on imported fuels. Meanwhile, higher fossil fuel prices globally have improved the competitiveness of solar photovoltaic (PV) and wind power generation in comparison to other fuel sources.

Renewable energy resources such as wind, solar, and geothermal have risen to the forefront of this transition. There is already a shift away from conventional fossil fuels. In 2022, renewable energy resources accounted for 90% of the new power capacity added globally, while coal accounted for 1% (IEA-Renewables 2022). this trend is expected to continue, by 2025, renewables are forecasted to surpass coal as the most dominant source of global electricity generation. Over the projected period, the renewables percentage in the power mix is expected to increase by 10% to 37% by 2027. In the same period, there will be a concurrent decrease anticipated for coal, nuclear, oil and gas generation. Electricity from Solar (PV) and wind sources are projected to more than double, accounting for almost 20% of worldwide power generation. These variable technologies are expected to make up for 80% of the increase of the global increase in renewable energy production. The dispatchable renewable energy sources such as hydropower, biomass, concentrated solar power and geothermal are predicted to remain constricted due to various reasons such as resource availability, environmental concerns, technological constraints, and financial viability.

The challenge of intermittency indeed stands as one of the most significant hurdles in the energy transition. Variable Renewable Energy technologies such as wind and solar are contingent on weather patterns and natural conditions, meaning that their energy output is not constant but fluctuates with the availability of sunlight and wind. This implies that they cannot deliver a constant and reliable energy supply, in contrast to traditional fossil fuels, which can be dispatched at will. The variability of wind and solar means the generation levels change widely(Ruggles & Caldeira, 2022). Sunlight and wind speech can fluctuate due to weather conditions, time of day and seasons resulting in overproduction or underproduction of electricity. These resources can't be solely relied upon to meet the electricity demand. this poses a challenge to maintaining the power grid and reliability. The dispatchable sources can provide adjustable power generation to balance the variable of wind and solar PV to improve the reliability and stability of the power supply.

Furthermore, there is a need for investment in advanced energy storage solutions and grid infrastructure development to accommodate the increasing renewable energy share. These measures can significantly enhance the flexibility of power systems, ensuring a smooth transition towards a low-carbon future. Energy storage systems such as batteries, pumped hydro storage and green hydrogen can store excess power during periods of overproduction and then dispatch it in peak demand. Grid infrastructure development such as smart grid technologies, will facilitate the variable renewables integration and improve the stability and resilience of the power system. Decreasing costs and technology advancements are expected to play a vital role in the global energy mix.

Battery energy storage systems (BESS) are presently the most prevalent form of energy storage technology and have witnessed substantial expansion in recent years. Such systems involve linking several batteries together to create a network, capable of harmonising the grid. This is achieved by absorbing surplus energy during periods of high-power generation and then discharging it during instances of low production. Lithium-ion batteries are the dominant force in this sector, attributed to their superior energy density.

Pumped Storage Hydropower (PSH) plays an integral role in providing flexibility and reliability to the grid(Canales et al., 2021). It is recognised as a pivotal component in the energy transition, given the rising integration of variable renewable energy sources such as wind and solar power. During instances of low electricity demand or surplus generation, electrical power is employed to pump water from the lower to the upper reservoir, effectively storing energy in the form of gravitational potential energy. Conversely, during periods of high electricity demand, the stored water is allowed to flow back downwards through turbines, thereby converting the potential energy back into electrical energy(Bhattacharjee & Nayak, 2019). The capability of PSH to offer both generation and absorption capacities makes it a vital technology for grid balancing and frequency regulation. It can help to iron out discrepancies between power supply and demand(Jayachandran et al., 2022).

Green hydrogen is another promising energy storage solution that has gained attention in recent years. Green hydrogen is produced from water using renewable energy sources such as geothermal, solar and wind power. The hydrogen can then be stored and used to generate electricity when needed, providing a carbon-neutral energy source. The use of green hydrogen as an energy storage solution could significantly reduce the reliance on carbon-intensive fossil fuels and help accelerate the transition to a more sustainable energy future.

Geothermal energy, as a renewable, abundant, and constant source, plays a crucial role in the energy transition. It can be utilized to produce hydrogen. Geothermal-hydrogen power generation has emerged as a potentially important technology combining the benefits of renewable energy sources with the versatility of hydrogen—a carbon-free and high-capacity energy carrier— by electrolysis or thermolysis. This approach eradicates the carbon emissions that are typically associated with the conventional production methods of both blue and grey hydrogen which typically involves fossil fuel sources and thus contributes to GHG emissions (Qureshi et al., 2022).

Looking towards the future, green hydrogen represents a versatile, scalable solution to decarbonising sectors that are difficult to electrify, such as heavy industry and long-haul transport. The use of geothermal energy for green hydrogen production is, therefore, a promising avenue for achieving deeper decarbonisation and advancing the energy transition. However, despite the potential of geothermal hydrogen power generation, several challenges must be addressed, including the high initial capital costs and the need for advancements in electrolysis technology. Furthermore, the environmental impacts associated with geothermal exploration and development must also be carefully managed to ensure sustainable deployment (IEA 2021-Global Hydrogen Review)

As of 2022, green hydrogen is more expensive than hydrogen produced from fossil fuels, termed grey or blue hydrogen (Yu et al., 2021). However, the levelized cost of hydrogen (LCOH) from renewable resources is expected to decrease as the technology matures and economies of scale kick in, making green hydrogen economically competitive. Looking ahead, geothermal hydrogen power generation offers significant potential for energy security and the advancement of green hydrogen, constituting a crucial part of this transition.

3.2. Review of Green Hydrogen electrolysers

The types of electrolysers mainly used for this process include Alkaline Electrolysers (AWE), Proton Exchange Membrane Electrolysers (PEME), Solid Oxide Electrolysers (SOE), and Anion Exchange Membrane Electrolysers (AEME).

In terms of technical performance, Alkaline Water Electrolyser operates with high efficiency at a significantly large scale. It provides a good hydrogen production rate, making it favourable for large-scale geothermal hydrogen power generation. AWE systems exhibit an overall efficiency ranging between 60-80%, with the potential to reach up to 85% at optimal operating conditions. This high efficiency reduces the amount of electrical energy required per unit of hydrogen produced, thereby minimizing the operational costs of geothermal hydrogen power generation.

The initial capital cost of AWE systems is a critical factor in techno-economic analysis. Generally, AWE is considered to have a lower capital cost than other electrolysis methods such as Proton Exchange Membrane (PEM) electrolysis (Bertuccioli et al., 2014). This lower capital cost is primarily attributed to the simplicity of the cell design and the usage of inexpensive materials in the electrode and electrolyte.

Operating expenses, mainly associated with electricity usage and maintenance, are critical components in the techno-economic analysis of geothermal-AWE systems. While the electricity cost is relatively low given that it's provided by the geothermal power plant, the maintenance cost can be high due to the corrosive nature of the alkaline electrolyte, leading to electrode degradation over time (Nielsen et al., 2017). This necessitates regular replacement of components, thereby increasing the overall operational costs.

Advanced Water Electrolysis (AWE) presents significant potential as a technically feasible and economically viable method for hydrogen production within the scope of geothermal hydrogen power generation. Despite the inherent challenges, AWE is emerging as a sustainable energy solution which offers higher efficiencies compared to conventional water electrolysis techniques.

3.3. Review of Hydrogen Storage Technologies

Hydrogen storage is a critical component of a hydrogen-based energy system, enabling the efficient and reliable storage of hydrogen gas for various applications such as energy storage, fuel cells and transportation. There are different types of compressed gas air storage (Erdemir & Dincer, 2023), cryogenic liquid storage(Kanoglu et al., 2007), metal hydride storage (Gkanas, 2018) chemical hydride storage, carbon-based materials, and underground storage (Andersson & Grönkvist, 2019).

Compressed gas storage is a widely studied method for storing hydrogen gas, which involves storing hydrogen under high pressure in specially designed tanks. It also has advantages that make it a preferred option compared to other forms of storage in certain applications. While hydrogen gas has a low energy density per unit volume, compressed gas storage allows for higher energy densities compared to other storage methods such as cryogenic liquid storage or chemical storage. By compressing the gas, a significant amount of hydrogen can be stored in a relatively small volume, which is advantageous in applications where space is limited.

Compressed air energy storage (CAES) offers versatility and flexibility in terms of its applications. It can be used for various purposes, including stationary power generation, portable power, and transportation. This adaptability makes it suitable for a wide range of industries and sectors. Compressed gas storage provides ease of handling, especially when compared to cryogenic liquid storage. It eliminates the need for extremely low temperatures and specialized handling equipment required for cryogenic systems. This simplifies storage and transportation logistics, reducing complexity and associated costs. Lastly, this technology has a good safety record and benefits from well-established safety protocols and regulations for handling and storage of compressed gases. The industry has developed robust standards and guidelines to ensure the safe storage and transportation of compressed hydrogen gas. Suitable materials applied applicable to this technology include stainless steel, aluminium and copper alloys (Elberry et al., 2021a).

There are some demerits associated with technology. Compressed air energy storage (CAES) tanks have limited storage capacity compared to other energy storage technologies such as pumped hydro storage or battery storage. The storage capacity of compressed air is dependent on factors like tank size, pressure, and the compressibility of air. Achieving large-scale storage capacity with compressed air can be challenging. Compressed air technology experience energy losses due to heat transfer during the compression and expansion processes. Constructing and maintaining CAES tanks can involve high capital costs. This CAES technology relies on underground storage, identifying suitable geological formations for the construction of these reservoirs can be challenging

3.4. Techno-economic analysis of geothermal-hydrogen power generation

Techno-economic analysis (TEA) is an important instrument in the energy sector in the evaluation of renewable energy technologies such as geothermal and hydrogen power generation (Spataru et al., 2015). It is a hybrid system that can offer valuable insights to industry leaders, policymakers, and researchers, to promote the uptake and development of renewable energy sources. Studies have been conducted on these technologies exploring the technical dynamics, economic feasibility, and environmental implications.

The techno-economic analysis provides a critical perspective into the feasibility, scalability, and profitability of geothermal hydrogen power generation.

performed a techno-economic analysis of geothermal-based hydrogen production, considering parameters such as initial capital investment, operational costs and electrolyser efficiency. Despite the high initial investment, geothermal hydrogen power generation could potentially offer competitive energy prices, depending on the electricity market and geological location(Alirahmi et al., 2022).

The overall efficiency of geothermal hydrogen power generation is a key factor that dictates its economic viability. (Brauns & Turek, 2020) proposed alkaline water electrolysis (AWE) for hydrogen production. They argued that this system offers higher overall efficiency compared to standalone geothermal power plants or hydrogen production facilities. (Ulleberg, 2003) discussed that AWE has a lower capital cost than other electrolysis methods such as Proton Exchange Membrane (PEM) electrolysis(Shiva Kumar & Himabindu, 2019) This lower capital cost is primarily attributed to the simplicity of the cell design and the usage of inexpensive materials in the electrode and electrolyte.

Capital and operational costs are central aspects of techno-economic analysis. For this study, the geothermal hydrogen production plant's economic viability primarily depends on the cost of the electrolyser. According to (Chitsaz et al., 2019) the generated hydrogen can be efficiently stored and transported, and it can serve as a tradable commodity, creating an additional revenue stream apart from electricity generation. Moreover, potential revenues from carbon credits due to its low carbon emissions could also improve the project's economic viability.

3.5. Review of sensitivity analysis

Sensitivity analysis, a widely adopted practice in decision sciences and systems modelling, has been extensively applied to energy system analyses to comprehend and predict the impacts of uncertainties. Recently, its application in geothermal hydrogen power generation has garnered significant interest, in line with the increasing recognition of hydrogen as a key element in decarbonising our energy systems and the potential role of geothermal energy in sustainable hydrogen production. The economics of geothermal hydrogen power generation is significantly influenced by various input parameters (Niknam et al., 2021). Therefore, conducting a sensitivity analysis to understand the influence of these variables on the Levelized Cost of Hydrogen (LCOH) is a fundamental step in optimizing the system (Niknam et al., 2021)

Electricity cost is a pivotal factor in geothermal hydrogen power generation (Buffo et al., 2019). Hydrogen is an energy carrier, not a primary energy source, implying that it must be produced from other energy sources (Yue et al., 2021b). The predominant method of hydrogen production is electrolysis, where water is split into hydrogen and oxygen using electricity. Therefore, the cost of electricity directly influences the cost of hydrogen production. In a geothermal hydrogen power generation setup, electricity derived from geothermal energy is typically used for the electrolysis process. This creates an inherent linkage between the cost of geothermal electricity production and the cost of hydrogen production.

Lee (2016a) argued the capital costs and plant efficiency were identified as the two most significant factors influencing the LCOH. The capital costs and the electrolysis process for hydrogen generation.

Electrolysis is an energy-intensive process, and as such, the efficiency with which electrical energy is converted into chemical energy stored in hydrogen significantly affects the levelized cost of hydrogen (LCOH). High electrolysis efficiency implies less electricity is required to produce a given quantity of hydrogen (Yilmaz et al., 2015). Therefore, improved conversion efficiency results in reduced energy demand and, consequently, a lower LCOH, making hydrogen production more cost competitive. Conventional alkaline electrolysis has an energy efficiency between 60-80%, while newer technologies like polymer electrolyte membrane (PEM) electrolysis can potentially achieve efficiencies above 80% (Chitsaz et al., 2019). Solid oxide electrolyser cells (SOECs) (Mohammadi & Mehrpooya, 2018), despite being at a more experimental stage, promise even higher efficiencies, up to 90%, at high temperatures.

Operational Expenditure (OPEX) represents a significant portion of the total costs involved in geothermal hydrogen power generation. OPEX is a key determinant of the financial sustainability of such projects, given that it encompasses ongoing expenses incurred during the operational lifetime of the plant. These include costs associated with maintenance, insurance, labour, fuel, and depreciation of the plant's infrastructure and equipment. The sensitivity of OPEX to these variable costs has been substantially highlighted in the literature. (Dokhani et al., 2023) discussed how labour costs, which encompass salaries, benefits, and training expenses, also significantly influence OPEX.

3.6. Relevant previous studies

Globally, there have been several studies conducted on the potential for using geothermal energy for hydrogen production. found that geothermal energy could be used to produce hydrogen through the process of electrolysis, which involves splitting water molecules into hydrogen and oxygen using electricity. A geothermal-hydrogen power generation is a viable option for energy load (Alirahmi et al., 2021b) in countries with abundant geothermal resources and growing electricity demand.

Turkey

Yilmaz et al.(2012a) developed a methodology for the economic analysis of the models, estimating the cost of hydrogen production and liquefaction to range between 0.979 $/kg H2 and 2.615 $/kg H2, depending on the model. The analysis revealed that geothermal water temperature significantly affects the cost of hydrogen production and liquefaction. Specifically, as the geothermal water temperature increases, the cost of hydrogen production and liquefaction decreases. The study also found that the capital costs for models involving hydrogen liquefaction are higher than those solely involving hydrogen production. Thus, this research provides critical insights into the economics of geothermal-based hydrogen production and liquefaction, indicating potential areas for cost optimization and efficiency improvement.

Yilmaz (2020) presents an innovative approach to the study of geothermal energy, incorporating a hydrogen production and liquefaction storage system. This integrated system's main feature is its ability to generate a geothermal power of 7856 kW, alongside a hydrogen liquefaction rate of 0.05 kg/s. The paper employs Aspen Plus software for simulating the integrated hydrogen energy system under varied thermodynamic conditions. The author also incorporates a life cycle cost analysis, which significantly broadens the work's relevance and applicability. This coupling of dynamic simulation with economic analysis differentiates this study from previous research in the field. Central to the paper is the concept of an integrated system wherein hydrogen production and liquefaction are achieved by a geothermal source. The geothermal power plant provides the electrical power needed for both the electrolysis unit and the liquefaction cycle, ensuring the high efficiency and sustainability of the proposed system. The author further calculates the work required for the generation of unit hydrogen, considering the effects of preheating in the electrolysis process. The results depict a work consumption of 43.57 kW h/kg H2. Notably, the author's analysis shows an actual work consumption of 8.98 kW h/kg LH2 to hydrogen liquefaction, indicating the system's effective use of energy. One of the critical outcomes of the paper is the estimation of unit costs of hydrogen and the system payback period. The author calculates a unit cost of 2.154 $/kg LH2, with a system payback period of 6.17 years. These results highlight the potential economic viability of such integrated systems for geothermal power and hydrogen production.

South Korea

Jang et al. (2022) presented an insightful techno-economic analysis of green hydrogen production from various water electrolysis technologies. The paper delved into the examination of four distinct water electrolysis technologies: alkaline water electrolysis (AWE), proton exchange membrane electrolysis (PEMEC), solid oxide electrolysis with electric heaters (SOEC (E.H)), and solid oxide electrolysis combined with a waste heat source (SOEC (W.H)). The authors applied a robust combination of net present value calculation, sensitivity analysis, and the Monte Carlo method to these four cases, leading to rigorous and comprehensive results. The authors computed the unit hydrogen production costs as 7.60, 8.55, 10.16, and 7.16 $/kgH2 for AWE, PEMEC, SOEC (E.H), and SOEC (W.H), respectively. From these figures, it is evident that the SOEC (W.H) technology emerges as the most competitive option due to its sensible heat energy saving and higher stack efficiency.

Germany

Kuckshinrichs et al. (2017a) focused on the economic analysis of improved alkaline water electrolysis (AWE) technology, particularly advanced AWEs based on novel polymer-based membrane concepts. The paper highlighted the importance of developing new configurations and technical and economic key process parameters for advanced AWEs. They emphasized the need for comprehensive economic assessments that go beyond cost analysis and include financial metrics to evaluate the attractiveness and supply/market flexibility of the technology from an investor's perspective. The financial analysis was based on cash flow (CF) analysis and included several key performance parameters. The metrics used for evaluation comprise the levelized cost of energy or levelized cost of hydrogen (LCOH) for cost assessment, net present value (NPV) for attractiveness analysis, and variable cost (VC) for market flexibility analysis., the levelized cost of hydrogen (LCOH) was estimated to be 3.2 €/kg.

Djibouti

Awaleh et al. (2022a) explore the economic feasibility of green hydrogen production in the Asal-Ghoubbet Rift of the Republic of Djibouti, marking a pioneering effort in Africa to compare the costs of green hydrogen production by wind and geothermal energy from a single site. The paper builds on the premise that Djibouti holds substantial untapped renewable energy resources, including geothermal, wind, and solar energy. In this light, the study serves as a crucial step in realizing the potential of these resources for sustainable hydrogen production. A key finding of the study is that the unit cost of electricity produced by the wind turbine (0.042 $/kWh) is more competitive than that from a dry steam geothermal plant (0.086 $/kWh). This comparison offers a significant contribution to the discourse on renewable energy production and use, as it provides a clear cost advantage for wind energy over geothermal energy in the country.

Kenya

A baseline study on hydrogen in Kenya (*Report et al., n.d.*) explored the potential of employing geothermal-hydrogen power generation in the Olkaria fields for grid-connected applications. The study concluded that geothermal-hydrogen power generation could serve as a reliable and cost-effective electricity source, potentially contributing to the diversification of Kenya's energy mix. The report underlines the existence of excess energy in the current geothermal power generation system. It estimates that approximately 10% of the total geothermal energy, equating to around 400 GWh out of the total 4,000 GWh per year, is not currently utilised.

3.7. Research implications

This paper has significant implications and presents a novel approach to addressing the challenges posed by intermittent renewable energy sources and reducing reliance on fossil fuels. By utilizing excess geothermal energy to produce hydrogen power, the study proposes a sustainable solution for load management in the Kenyan context. The novelty lies in the integration of geothermal energy and hydrogen production, which enables the storage and utilization of excess energy during periods of low demand. This approach not only helps stabilize the grid but also provides an opportunity to store renewable energy for later use, thereby reducing the need for conventional fossil fuel-based power generation. Furthermore, the paper highlights the importance of sensitivity analysis, which allows for an assessment of the project's economic viability under various scenarios and changing input variables. By conducting sensitivity analysis, the study aims to evaluate the robustness and potential risks associated with the proposed geothermal-hydrogen power generation system, providing valuable insights for policymakers, investors, and stakeholders interested in renewable energy deployment and load management strategies.

3.8. Chapter summary

This literature review chapter provides a comprehensive examination of geothermal hydrogen power generation from various perspectives. It mentions the importance of transitioning from traditional fossil fuels to sustainable renewable energy, acknowledging the necessity for backup or storage solutions to support these variable resources. Green hydrogen emerges as a promising candidate in this context. The chapter dissects multiple facets of this topic, including the various types of electrolysers, hydrogen storage technologies, a techno-economic analysis, sensitivity analysis, and a review of previous studies, all contributing to a holistic understanding of the subject. Notably, sensitivity analysis is identified as being crucial to understanding the economic viability of geothermal hydrogen power generation, with technical and economic sensitivities playing key roles. However, it also recognises the growing need for a more comprehensive approach. Ultimately, this chapter highlights the implications of the study and brings the novel aspects of the paper to the forefront, thereby paving the way for future research in this field.

Chapter IV

Methodology and Data

4.1. Methodology and analysis approach

This study investigates the techno-economic analysis of geothermal hydrogen power generation in Kenya. The country has one of the most substantial geothermal resources globally, and this study aims to understand the potential of using this geothermal energy to produce hydrogen. It employs a techno-economic analysis of geothermal hydrogen power generation in Kenya, intertwined with a sensitivity analysis to test the robustness of the economic model.

This study involves an assessment of geothermal data, historical data from 2010-2023 and future data from 2023 to 2030, to identify the excess geothermal power capacity that could potentially be harnessed for hydrogen production. Central to this investigation is the appraisal of surplus geothermal energy in Kenya. This surplus energy, largely unexploited during times when the demand dips below capacity, constitutes about 10% of total geothermal generation.

The techno-economic analysis is a method that combines the technical characteristics and economic factors of a system to assess its economic viability. In the context of this study, involves analysing the technical aspects of geothermal hydrogen power generation, including the design, performance, and operating conditions, along with the economic aspects such as capital and operational costs, and projected levelized cost of hydrogen (LCOH).

Sensitivity analysis is a method used to determine how the uncertainty in the output of a model can be attributed to different sources of uncertainty in its inputs. It is used to test the robustness of the economic model. This involves changing the values of the variables in the model such as electricity cost or geothermal cost, capital cost and operational cost to see how these changes affect the output. It helps to identify which variables have the most significant impact on the economic viability of the geothermal hydrogen power generation system.

The integration of techno-economic analysis with sensitivity analysis provides a comprehensive assessment of the geothermal hydrogen power generation system. It not only reveals the system's economic viability under current conditions but also offers insights into how changes in key variables could impact its economic viability in the future. Such an approach is essential in guiding decision-making processes related to the design, operation, and potential investment in geothermal hydrogen power generation systems.

4.1.1. Analysis software and tools

In this study, the process of developing the Levelized Cost of Hydrogen (LCOH) model and conducting the sensitivity analysis, Microsoft Excel was utilised. Simulations were executed using the RStudio software. This probabilistic technique was ideal for assessing the potential variability in the LCOH model outputs given the randomness in input parameters. Therefore, this combination of Excel for model development and sensitivity analysis, and RStudio for uncertainty modelling and graphical representation, provided a comprehensive toolset for this research.

4.2 Methodology framework

Figure 4-1: Flow chart of Geothermal hydrogen production

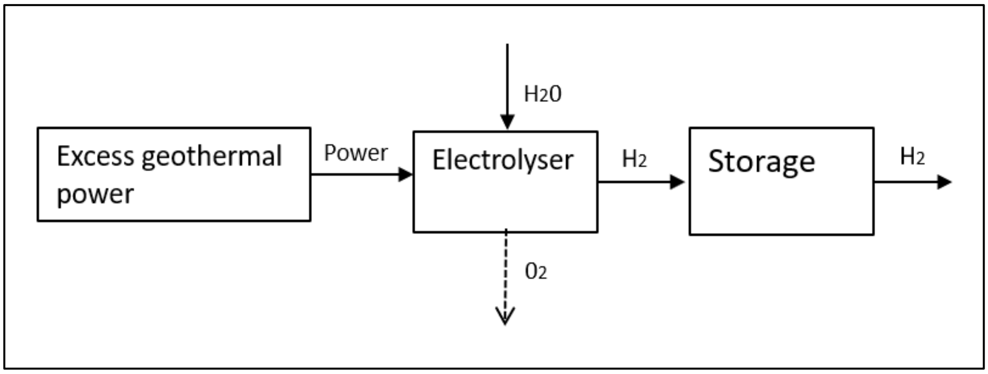
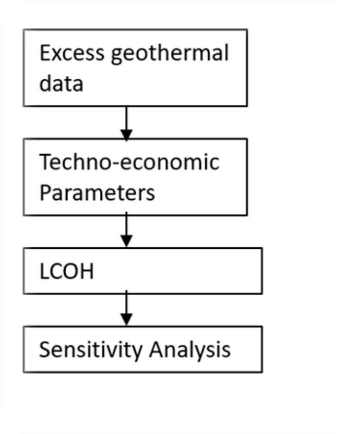


Figure 4-2: Flow chart of the model



The geothermal hydrogen generation production chart Figure 4-1 begins with the utilization of electricity from the geothermal power plant, it applied to produce hydrogen by electrolysis process. The chart depicts the hydrogen storage facility. It is pivotal in the hydrogen economy as it serves as a reservoir. The storage tank specifications are evaluated, this includes size analysis, maximum pressure, construction material and energy consumption, after which it is dispatched for other functions such as electricity generation.

Flow chart of the model Figure 4-2 begins with an analysis of the excess geothermal data collected over a span of 20 years from Kenya. This data provides insights into the availability of surplus geothermal power, which is the energy that exceeds the current demand during non-dispatchable periods. By examining the historical trends and patterns in geothermal energy generation, the chart showcases the magnitude and variations in this excess energy over time. This information is crucial for understanding the potential for utilizing this surplus energy for hydrogen production.

Following the analysis of excess geothermal data, the chart moves on to explore the techno-economic parameters involved in geothermal hydrogen production. Firstly, the selection of an appropriate electrolyser is considered. Factors such as the electrolyser type (e.g., alkaline, PEM, solid oxide) and the required technical specifications for its operation are evaluated. These specifications may include electrolyser capacity, operating temperature and pressure, efficiency, and durability.

The next aspect covered in the chart is the examination of the economical parameters required for geothermal hydrogen production. This includes the cost of the electrolyser itself, as well as additional costs associated with the process, such as electricity costs, hydrogen storage costs and other operational expenses. The chart emphasizes the significance of considering these factors to evaluate the economic viability and sustainability of geothermal hydrogen production.

To calculate the levelized cost of hydrogen, the chart incorporates the techno-economic parameters identified earlier. The levelized cost of hydrogen represents the average cost of producing hydrogen over the entire project lifetime, considering factors like capital costs, operational and maintenance costs, and the quantity of hydrogen produced. By quantifying the levelized cost, the chart provides an essential metric for assessing the cost competitiveness of geothermal hydrogen production compared to other energy sources or hydrogen production methods.

Additionally, the chart highlights the importance of conducting sensitivity analysis to test the robustness of the model used for the techno-economic assessment. Sensitivity analysis involves varying the input parameters within a certain range to evaluate the impact on the levelized cost of hydrogen. This analysis helps identify the key factors that significantly influence the economic viability of geothermal hydrogen production and provides insights into the uncertainties and risks associated with the project.

4.3. Data requirements and assumptions

The data required for this study encompasses several key elements related to geothermal energy generation and electricity tariffs in Kenya. The data collection involves historical and forecasted geothermal generation from 2010 to 2030, including information on the installed and effective capacities of geothermal plants. Additionally, data on other energy technologies such as wind, solar PV, hydropower, and thermal plants is also necessary. The annual discount rate of 9% was assumed for the Levelized cost of Hydrogen calculation in the study. Regarding the electrolyser technical data, it is sourced from previous studies (Fragiacomo & Genovese, 2020a), (Müller et al., 2023a), (Abdin et al., 2022) and (IRENA

(International Renewable Energy Agency), 2022). This data forms an essential component for conducting a comprehensive techno-economic assessment of hydrogen production through alkaline water electrolysis (AWE), allowing for the evaluation of the feasibility, sustainability, and economic viability of the process.

4.3.1. Geothermal curtailment data

The study incorporates an evaluation of the surplus geothermal energy available in Kenya. This surplus energy amounts to approximately 10% of the total geothermal generation but remains unutilized during periods when demand is lower than capacity. As demand grows, it is anticipated that the surplus will decrease, although the addition of new geothermal plants may increase excess energy availability.

Geothermal energy is regarded as the most cost-effective option for Kenya's power system, and the surplus energy is accounted for in the Long-Term Least Cost Power Development Plan 2020-2040 (LCPDP 2021, n.d.) of the country. This excess energy holds the potential to support the implementation of alternative technologies, such as green hydrogen (H2) production. The fluctuation of this excess energy throughout the day and week is influenced by demand fluctuations, and it exhibits medium to long-term upward and downward trends. Additionally, consideration is given to the ownership aspects of this surplus energy.

The study acknowledges the presence of surplus geothermal energy in Kenya and recognizes its significance for the power system. Leveraging this excess energy can facilitate the adoption of innovative technologies like green hydrogen production while considering its varying patterns and ownership considerations.

Table 4-1: Kenyan energy generation data

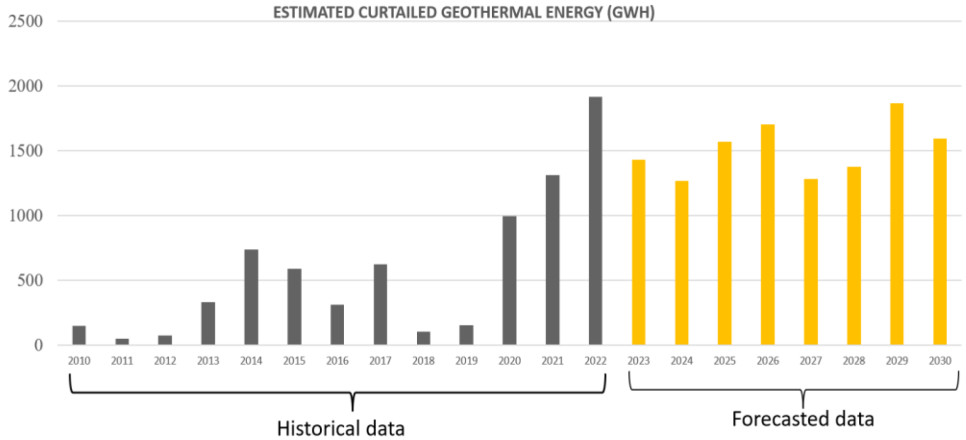
YEAR	INSTALLED CAPACITY (MW)	EFFECTIVE CAPACITY (MW)	PEAK DEMAND (MW)	GEOTHERMAL CAPACITY-INSTALLED (MW)	GEOTHERMAL CAPACITY-EFFECTIVE (MW)	POTENTIAL GEOTHERMAL GENERATION (MW)	ACTUAL GEOTHERMAL GENERATION GWH	ESTIMATED EXCESS GEOTHERMAL ENERGY (GWH)
2010	1,473	1,416	1,107	198	189	1,490.08	1,339.03	151.04
2011	1,593	1,479	1,194	198	191	1,505.84	1,453.82	52.03
2012	1,691	1,636	1,236	210	200	1,573.65	1,498.12	75.53
2013	1,765	1,652	1,354	250	245	1,931.11	1,599.19	331.92
2014	1,885	1,805	1,468	363	348	2,743.63	2,007.65	735.98
2015	2,299	2,228	1,512	598	590	4,651.56	4,059.70	591.86
2016	2,341	2,270	1,609	632	624	4,919.62	4,608.86	310.75
2017	2,333	2,259	1,768	652	644	5,077.30	4,450.92	626.38
2018	2,351	2,273	1,802	662	654	5,156.14	5,053.00	103.14
2019	2,741	2,630	1,882	684	658	5,187.99	5,033.00	154.99
2020	2,840	2,708	1,926	863	805	6,348.99	5,352.00	996.99
2021	2,984	2,852	1,994	863	805	6,346.62	5,035.00	1,311.62
2022	3,081	2,926	2,132	950	871	6,866.96	4,951.00	1,915.96
2023[1]	3,151	2926	2,233	950	879.4	6,933.19	5,855.6	1,640.00
2024	3,386	2,926	2,268	1000	879.4	6,933.19	6,015.6	1,268.45
2025	3,570	2,926	2,353	1,017	1017.4	8021.81	6,857.5	1,569.49
2026	3,765	2,986	2,441	1,017	1017.4	8,021.18	6721.5	1,705.51
2027	4,022	3,144	2,585	973	972.8	8,021.18	6,777.0	1,280.59
2028	4,227	3,232	2,737	1,033	1032.8	7,669.56	7,178.2	1,376.43
2029	4,441	3,413	2,912	1,212	1211.8	8,142.60	8,171.2	1,866.04
2030	4,765	3,609	3,099	1,212	1211.8	9,553.83	8,445.5	1,591.79

[1] data similarity in 2022,2023,2024 indicates actual development might have exceeded the forecasted data.

Table 4-1 presents the historical data for the period spanning 2010 to 2022, focusing on geothermal energy generation. Within this table, an important metric highlighted is the estimated excess geothermal energy. This value is calculated by taking the potential geothermal energy generation and subtracting the actual geothermal generation during each year. The resulting difference represents the surplus or excess geothermal energy available beyond the current demand. The historical data reveals that, on average, there have been approximately 500 gigawatt-hours (GWh) per year of excess geothermal power in Kenya. This means that each year, geothermal generation exceeds the immediate demand by an average of 500 GWh. This excess geothermal energy, when not utilized, represents an untapped resource that can potentially be harnessed for various applications.

Looking ahead to the forecasted years from 2023 to 2030, Table 4-1: Kenyan energy generation data shows a significant increase in the estimated excess geothermal power. The forecast indicates that the surplus geothermal energy is expected to reach approximately 2,691 Gwh. This considerable rise can be attributed to the role that geothermal energy will play as a spinning reserve, providing support to balance the variable generation from solar, wind, and hydropower sources. Figure 4-3 highlights the curtailed geothermal energy for both historic and forecasted periods.

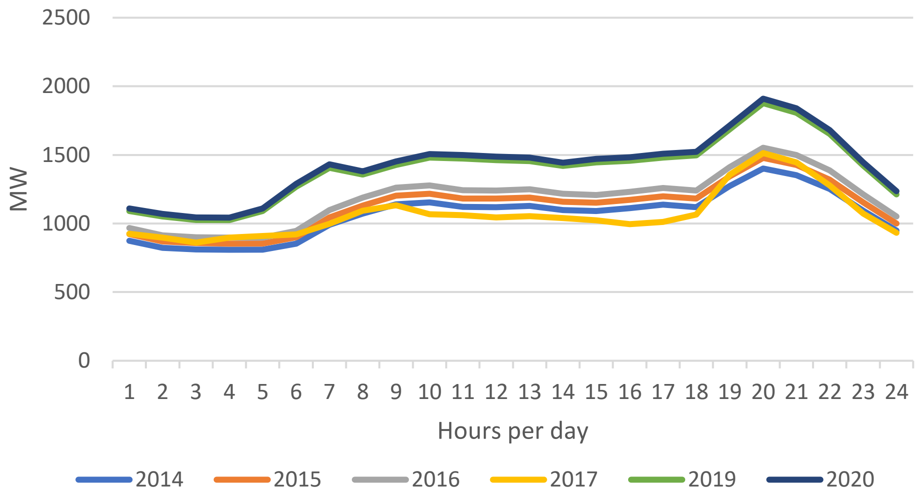
Figure 4-3: Estimated curtailed geothermal energy



Source: Ministry of Energy, Kenya, 2022

Figure 4-4 shows an analysis of historical average annual load curves from 2014 to 2020 reveals a consistent pattern in electricity consumption. These patterns, provide vital insights into the daily demand dynamics in Kenya's power sector. The load curves distinctly segment the day into three primary intervals - off-peak, mid-peak, and peak hours. Each period corresponds to a specific level of power consumption, predominantly dictated by human activities and societal routines.

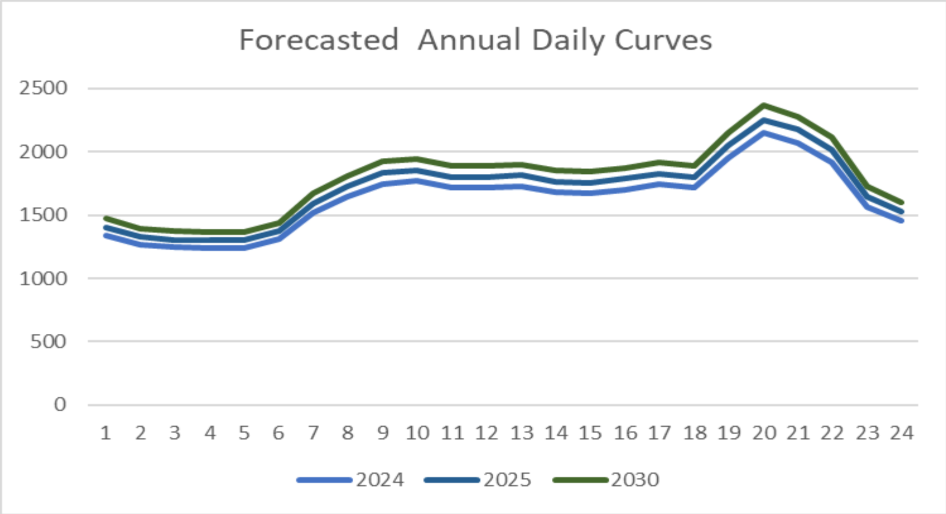
Figure 4-4: Historical annual load curves



Source: Ministry of Energy, Kenya, 2022

Off-peak hours extend from midnight to the early morning (8 am). During this time, the electricity demand is generally low. This period typically correlates with the least intensive part of the day, when most people are asleep, and businesses and industrial activities are minimal or inactive. Mid-peak hours commence from 8 am and continue until 5 pm. This period represents a moderate level of power consumption. It correlates with regular business hours when commercial and some industrial activities are operational, but residential power usage is still relatively low. Peak hours extend from 6 pm to 11 pm, representing the timeframe with the highest electricity demand. This period coincides with the evening when most people return home from work. Residential activities such as cooking, the use of heating or cooling systems, and entertainment contribute to a surge in power consumption. It's during these hours that the power grid is under the most strain, and fossil fuels are injected to meet the high demand.

Figure 4-5: Forecasted Average Daily Curves

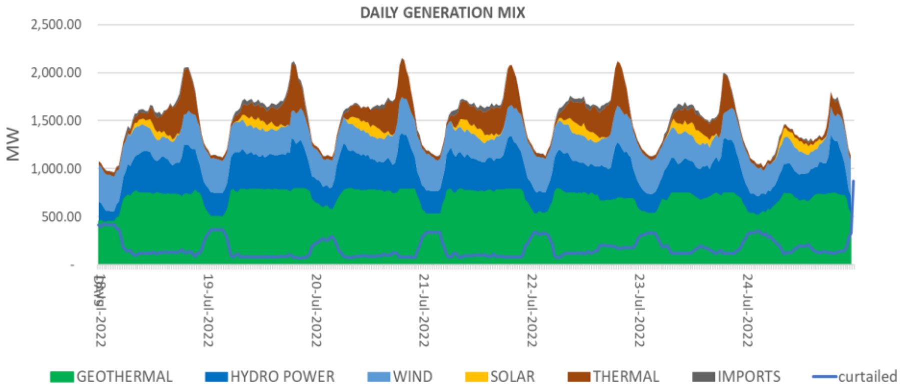


Source: Ministry of Energy, Kenya, 2022

Figure 4-5 projection from 2024 to 2030 indicates that while the general trend of electricity consumption during off-peak, mid-peak, and peak hours remains consistent, there is an observable increase in overall power demand. This upward trend in electricity consumption can be attributed to various factors such as economic growth, increased industrial activity, population growth, and the proliferation of electrical appliances in residential and commercial settings.

Figure 4-6 showcases the daily load curve, illustrating the distribution of various energy technologies, namely geothermal, hydropower, wind, solar, and thermal power. It includes a line graph specifically focusing on the excess geothermal power. In the load curve, each energy technology's contribution to the total electricity demand throughout the day is represented. The curve provides a visual depiction of how the electricity load varies over 24 hours, showing the relative shares of geothermal, hydropower, wind, solar, and thermal power in meeting the demand.

Figure 4-6:Daily Dispatch by source



Source: Ministry of Energy, Kenya, 2022

Within the figure, a line graph specifically focuses on the excess geothermal power. This excess power arises due to the geothermal capacity exceeding the actual demand during specific periods, such as night-time and when non-dispatchable renewable energy plants are operational. The line graph highlights the consistent availability of surplus geothermal power that can be harnessed for alternative applications. Moreover, it reveals that the excess geothermal power reaches higher levels during weekends when the electricity demand tends to be lower, presenting even greater potential for utilization. The figure underscores the importance of geothermal energy as a reliable and continuous energy source. It emphasizes the significant opportunity to utilize the excess geothermal power for other purposes, thereby maximizing the use of renewable resources. By tapping into this surplus energy during periods of low demand, the figure highlights the potential to optimize energy utilization and contribute to a more sustainable and efficient energy system.

Overall, the figure's representation of the daily load curve and its specific emphasis on excess geothermal power highlight the role of geothermal energy as a dependable source and emphasize the possibilities for utilizing surplus geothermal power to meet additional energy needs. This visualization contributes to a better understanding of the dynamic nature of electricity demand and the potential for leveraging geothermal energy to create a more sustainable energy landscape.

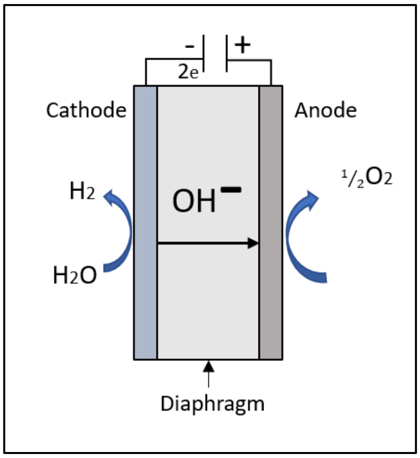
4.3.2. Electrolysers Technical Data

An electrolyser is a device that utilizes electrical energy to perform electrolysis, a chemical process that splits water or other compounds into their constituent elements. Specifically, it breaks down water molecules (2 H_2O) into hydrogen gas (2 H_2) and oxygen gas (O_2). Electrolysis is achieved by passing an electric current through a liquid or solid electrolyte, causing the oxidation of water at the anode and the reduction of water at the cathode (Eichman et al., 2014).

There are different types of electrolysis technologies, each with its unique characteristics and operational principles. Three prominent types are commonly studied:

Alkaline Water Electrolysers (AWE): These electrolysers employ two electrodes operating in a solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH) (Ding et al., 2022) AWEs typically operate optimally within a temperature range of 20-80 °C. They are widely deployed for commercial hydrogen production due to their established technology and commercial viability (Brauns & Turek, 2020). The reactions are as follows:

Figure 4-7: Alkaline Water Electrolyser



Cathode:	$\mathbf{2H_2O + 2e^- \rightarrow H_2 + 2O\overline{H}}$	**(1)**
***Anode*:**	$\mathbf{2H_2O + 2e^- \rightarrow {}^1/_2\, O_2 + H_2O + 2e^-}$	**(2)**
Total:	$\mathbf{2H_2O \rightarrow O_2 + 2H_2}$	**(3)**

Proton Exchange Membrane Electrolysis (PEMEC): This type of electrolysis takes place in a cell equipped with a solid polymer, which allows for the selective transport of protons. The reaction involved is the electrolysis of water. PEMEC operates optimally at a temperature range of 20-200 °C. It offers the advantage of high efficiency and rapid response time, making it suitable for various applications(Maric et al., 2018). The reactions are as follows:

Anode: $H_2O \rightarrow 2H^{+} + {}^{1}/_{2}\, O_2 + 2e^{-}$ **(4)**

***Cathode*:** $2H^{+} + 2e^{-} \rightarrow H_2$ **(5)**

Total: $2H_2O \rightarrow {}^{1}/_{2}\, O_2 + H_2$ **(6)**

Anion Exchange Membrane Electrolysis (AEM): AEM electrolysis also utilizes a membrane as an electrolyte but allows for the transport of both cations and anions (Xiang et al., 2022). AEM electrolysis is an emerging technology with potential advantages such as enhanced selectivity, lower operating costs, and improved durability(Santoro et al., 2022). The reactions are as follows:

Anode: $4OH + O_2 + 2H_2O + 2e^{-}$ **(7)**

Cathode: $4H_2O + 4e \rightarrow O_2 + 2H_2O + 4e^{-}$ **(8)**

***Overall Reaction*:** $2H_2O \rightarrow O_2 + H_2$ **(9)**

Additionally, there is Solid Oxide Electrolysis, which employs a ceramic solid oxide electrolyte membrane. This type of electrolysis combines thermal energy from heat and electrical energy from an electric current to synthesize hydrogen. (Jang et al., 2022) Solid Oxide Electrolysis operates at high temperatures typically ranging from 600 to 1000 °C. It offers the advantage of high conversion efficiency and the potential for integration with high-temperature heat sources. The reactions are as follows:

Anode: $4OH \rightarrow {}^{1}/_{2}\, O_2 + 2e^{-}$ **(10)**

Cathode: $H_2O + 2e^{-} \rightarrow H_2 + O2^{-}$ **(11)**

***Overall Reaction*:** $H_2O \rightarrow {}^{1}/_{2}\, O_2 + H_2$ **(12)**

Among these technologies, alkaline electrolysis has been widely adopted for commercial hydrogen production due to its technical maturity, reliability, established infrastructure, and economic viability. PEMEC is still in the early stages of commercialization. AEM which is a hybrid of both PEMEC and AWE is still under development as well as the SOE. Table 4-2 illustrates the differentiation between the two most advanced technologies within the electrolyser domain, specifically Alkaline Water Electrolysis (AWE) and Proton Exchange Membrane Electrolysis Cell (PEMEC).

Table 4-2: Comparison of AWE and PEMEC

TECHNOLOGY	UNIT	AWE 2020	2025	PEMEC 2020	2025
System Lifetime	Years	20-30	20-30	20	20
Efficiency (system)	kWh/kgH2	51	50	58	52
Cell Pressure	Bar	30	15	30	60
Temperature	Celsius	20–80 °C	20–80 °C	20–200 °C	20–200 °C
Electrolyte		NaOH/ KOH solution		PEM	
CAPEX	(US$/KW)	750	480	1,200	700
Voltage efficiency (System efficiency)	%	60-84%	80-90%	50-80%	45%
STACK Lifetime	Operating hours	60,000	80,000	40,000	50,000
STACK REPLACEMENT	(US$/KW)	300	200	420	200
OPEX	% of the CAPEX	2%	2%	2%	2%
System Lifetime	Years	20	20	20	20
Efficiency (system) Higher Heating Value	kWh/kgH2	51	40	58	52
Lifetime system	Years	20-30	20-30	10-20	10-20
Application		Mature	Mature	Near commercialization	commercialization
Advantages		Low capital cost Advanced technology Long-term stability Long term stability Non-noble material		Compact design Fast response. Dynamic operation Dynamic operation Design simplicity	
Disadvantages		Corrosive electrolyte, Gas crossover, Low efficiency Slow dynamics		High costs, Noble metals Corrosion environment Low durability	
Electrolysers integrable to RE in Kenya.	Geothermal	✓		✓	
	Hydropower	✓			
	Solar PV	✓			
	Wind power	✓			

Source: www.irena.org 2022

4.3.3. Hydrogen Storage technical data

Hydrogen storage technology is key in the energy sector or hydrogen economy as a key enables the efficient and effective utilization of hydrogen as an energy carrier. Once produced, hydrogen needs to be safely stared for later use, ensuring a reliable and continuous supply of hydrogen for various energy applications. Hydrogen gas is highly flammable and risky. Therefore, the importance of hydrogen storage technology lies in its ability to overcome such limitations as well as low density. Efficient storage methods enable the storage of large quantities of hydrogen compactly and safely, allowing for flexible deployment and utilization across different sectors. Hydrogen has the potential to play a significant role in the global energy transition by offering a clean and sustainable alternative to fossil fuels. Hydrogen storage systems can be a solution to grid stability by addressing the intermittency of renewable energy sources (Andersson & Grönkvist, 2019), supporting peak energy demand, and enhancing grid flexibility. By storing excess renewable energy during periods of low demand and releasing it during high demand, hydrogen storage contributes to a more stable and reliable energy supply. Effective hydrogen storage enables the integration of hydrogen-based technologies such as fuel cells and hydrogen-powered vehicles, facilitating the decarbonization of various sectors, including transportation, power generation, and industrial processes.

There are different types of hydrogen storage technologies as described in Table Figure 4-3.

Table 4-3: Classification of hydrogen technologies

Classification	Type	Description	Comments
High-pressure storage	Compressed Air Gas Storage	High efficiency, low energy consumption, simple equipment structure	High material cost, Long-run affordability
Liquid hydrogen storage	Cryogenic liquid Storage	High-quality hydrogen storage density	High energy consumption and complex equipment
Chemical hydrogen storage	Metal hydride Storage Chemical Hydride Storage	High safety, high purity, and high hydrogen storage density.	The high cost of hydrogen storage and the chemical reaction process is difficult
Adsorption storage	-Porous materials:	High hydrogen storage density	Ultra-low temperature,

Classification	Type	Description	Comments
	-Liquid Organic Hydrogen Carriers -Underground storage		Complex equipment structure

Compressed Air Gas Storage is a well-established technology. Hydrogen is stored under high pressure in specially designed tanks. It is widely used in various sectors, including stationary power, industrial processes, and mobility. Compressed gas storage offers simplicity, reliability, and compatibility with existing infrastructure. Table 4-4 illustrates the difference between the most commonly used hydrogen storage technologies.

Table 4-4: Comparison between compressed hydrogen and liquified hydrogen

Properties	Unit	Compressed Hydrogen	Liquified Hydrogen	Reference
Cost	$	1500	2500	(Yin & Ju, 2020)
Temperature	ºC	25 (room)	-252.9	(Bartela, 2020)
Storage Pressure	MPa	69	0.1	(Yun, 2011)
Energy consumption kWh/kg	Kwh/kg	5	15	(Bartela, 2020)
Gravimetric energy density (LHV)	Mj/kg	120	120	(Schoenung, 2011)
Density	Kg/m^3	39	70.8	(Elberry et al., 2021b)
Hydrogen release	-	Pressure release	Evaporation	(Elberry et al., 2021a)
Energy to extract hydrogen	Kj/mol-H2	-	0.907	(Al Ghafri et al., 2022)

4.4. Economic Analysis

The Levelized Cost of Hydrogen (LCOH) is an economic assessment that calculates the cost of producing hydrogen over a system's lifetime and it is an essential metric for gauging the economic viability of geothermal hydrogen power generation. Several factors influence the LCOH, including capital costs, operation, and maintenance (O&M) costs, energy conversion efficiency, and plant lifetime, among others(*The Future of Hydrogen – Analysis - IEA*, n.d.). Levelized Cost of Hydrogen (LCOH), of which unit is $/kg(Abdin et al., 2022). In this research, the LCOH is ascertainable through the given equation (13). Here the C is capital expenditure ($) invested in the first year, Ot is the operating expenditure ($) in the corresponding years, Ht is the total hydrogen produced (kg), and r is the discount rate of 9% (Nicita et al., 2020).

$$LCOH = \frac{capital\ cost + NPV(OPEX)}{NPV(Total\ H2\ produced)}$$

$$\boldsymbol{LCOH} = \frac{\mathbf{C}+\sum_{\mathbf{t=20}}^{\mathbf{n}} \frac{\mathbf{O_t}}{\mathbf{(1+r)^t}}}{\sum_{\mathbf{t=20}}^{\mathbf{n}} \frac{\mathbf{H_t}}{\mathbf{(1+r)^t}}} \quad \textbf{(13)}$$

To calculate the Levelized Cost of Hydrogen (LCOH), an Excel model was developed and assumptions on the electrolyser requirements and design from previous literature were established. The size of the water electrolysis plant is determined by the power load required for the electrolyser. For our calculations, we assume the annual operating hours to be 7884 hours per year, which is 90% corresponding to the geothermal capacity factor, and the system's operational lifespan to be 20 years, a common duration for AWE Electrolysers (Xia et al., 2023).

The total project capital expenditure (CAPEX) is derived from the unit price and size of the water electrolysis facility, which includes the electrolyser capex, power supply unit and the balance of plant (BOP) (Jang et al., 2022). Operating expenditures (OPEX) are determined by the unit price of water and electricity cost. To account for maintenance, labour costs other consumables costs, a factor of 5% to the total capex is applied. The parameters employed for determining the LCOH are summarized in Table 4-5

Table 4-5: Levelized cost of hydrogen parameters

Electrolyser Inputs	SCALE	UNIT	Description	Reference
Base year for evaluation	2023	year		
Project Life	20	years	Project life span	
Discount rate	9	%	Discount rate	*Kenya Interest Rate - 2023 Data - 1991-2022.)*
Electrolyser Nominal Power	1,000	kW	Electrolyser capacity of the system being modelled	*(IRENA, 2020)*
Electrolysis system requirements			System requirement	*Table 4-2*
Capex at 1MW scale	780	$/kW at 1MW scale	Capital expenditure	*(Stoll et al., 2017)*
Electrolyser Capex Scaling Factor	0.9		The variation in capital expenditure	*(Global Hydrogen Review 2021 – Analysis - IEA, n.d.)*
Water Cost	5	$/KL	Water cost	*(Syed, 2021)*
Water requirement	10	L/kg	Litres of water required to produce each kg of H2	*(Glenk & Reichelstein, 2019)*
Stack replacement time	60,000	Hours	Hours of operation before stack replacement.	*(Xiang et al., 2022)*
Stack replacement cost	50% of the CAPEX	$/kW	Proportion of total electrolyser capex	*(The Future of Hydrogen – Analysis - IEA, n.d.)*
Operational cost	5% of the CAPEX	$/W/year	non-stack replacement OPEX	*(Yilmaz et al., 2012b)*
Electrolyser Conversion Efficiency	**80%**	**%**	**Conversion efficiency (electricity to hydrogen)**	
Electricity Consumption	50	kWh/H2 Kg	Electricity required to produce each Kg of H2	*(Alirahmi et al., 2021c)*
Geothermal Inputs				
Geothermal capacity factor	%	90%	Availability of geothermal power plant per year	
Geothermal tariff in Kenya	0.060	$/kWh	Geothermal cost in Kenya	*(Kenya Energy Outlook – Analysis - IEA, n.d.).*

4.4.1. Discount rate

The discount rate plays a crucial role in calculating the levelized cost of hydrogen. The levelized cost of hydrogen represents the average cost of producing hydrogen over the entire project lifetime, accounting for the time value of money. The discount rate is used to convert future costs and revenues into their present value equivalents, reflecting the preference for present consumption and the opportunity cost of capital.

By applying a discount rate, the future costs of hydrogen production are discounted to their present values. This allows for a fair comparison of costs and revenues that occur at different points in time. The discount rate reflects the desired rate of return on investment and the risk associated with the project. It represents the rate at which future cash flows are adjusted to reflect their present value. This enables a comprehensive evaluation of the economic feasibility and profitability of hydrogen production projects over their expected lifespan.

4.4.2. Electrolyser Capital cost

In this study, the capital cost of an alkaline water electrolyser (AWE) can vary depending on several factors, such as the electrolyser's capacity, technology type, and scale of production. Generally, the capital cost of an AWE electrolyser is estimated to range between $480 and $780 per kilowatt (kW) *Table 4-2***.** These estimates are approximate and subject to change based on market conditions, technological advancements, and economies of scale. For this particular case, it is determined that the highest estimated capital cost for an AWE electrolyser is $780 per kilowatt (kW). This selection considered specific considerations such as the technology employed, and any additional costs associated with the site location.

Capital Expenditure scaling factor

The capital expenditure scaling factor refers to a multiplier used to adjust or scale the capital cost of a project based on its size or capacity. It accounts for the economies or diseconomies of scale that arise when increasing or decreasing the size of a project (Yates et al., 2020). By applying a capital scaling factor of 0.8, the total capital cost of the project is adjusted downwards to account for these economies of scale. This adjustment is crucial for accurately estimating the capital investment required and determining the financial viability of the project. It helps ensure that the cost projections align with the economies achieved at different project sizes

4.4.3. Energy Cost

The energy is critical in the electrolysis process. Therefore, energy cost is important in the techno-economic analysis of hydrogen production. Geothermal energy consists of various factors, including the unit cost of geothermal energy generation, the capacity factor, and the efficiency of the electrolysis process. By considering the energy consumption and efficiency of the electrolysis process, the total energy cost for geothermal hydrogen power production can be evaluated, contributing to the overall techno-economic assessment of the system.

For this study, we considered the electrolyzer system, 80%, **Table 4-2**, voltage or higher heating value (HHV) of hydrogen 50kw/kg, in table 3, and the electricity (kW), geothermal capacitor factor 90%, hours per year and the unit cost of the geothermal energy.

$$\mathbf{nH_2 = \frac{P_{el}}{HHV} nel} \tag{14}$$

In the equation, nH_2 represents the amount of hydrogen generated per hour in kilograms (kg), nel denotes the efficiency of the electrolyser system, PEL represents the power input in kilowatts (kW), and HHV represents the higher heating value of hydrogen in kilowatt-hours per kilogram (kWh/kg). The system efficiency considered in this study is set at 80%(Xia et al., 2023), considering the current technology level. In this thesis, the levelized cost of electricity, and geothermal energy unit cost is 0.06$/kwh(*Kenya Energy Outlook – Analysis - IEA*, n.d.).

4.4.5. Stack replacement

To calculate the stack replacement cost for alkaline water electrolyser (AWE) systems, several factors should be considered. The stack lifespan is a crucial consideration, representing the durability and operational life of the stack(Xia et al., 2023). In this case, the stack lifespan is specified as 80,000 hours, as indicated in Table 4-2

To determine the replacement frequency, the project lifetime is divided by the stack lifespan. This calculation provides insights into how often the stack will need to be replaced during the project's lifespan. The formula for calculating the replacement frequency is as follows:

Replacement frequency = Project life (hours) / Stack lifetime (hours).

Electrolyzer capital cost (Ecapex), power supply capital expenditure (Pcapex), and stack replacement cost (Scapex) are categorized as components of total project cost expenditure.C.

$$\boldsymbol{E}\mathbf{capex} + \mathbf{Pcapex} + \mathbf{Scapex} = \mathbf{C} \quad \mathbf{(15)}$$

4.4.6. Water cost

The electrolysis process used for hydrogen (H2) production typically requires an average of 10 litres of water per kilogram of hydrogen produced. In this study, it is proposed that the water required for electrolysis would be sourced from Lake Naivasha, a nearby freshwater lake situated close to the Olkaria geothermal fields. Water quality plays a significant role in electrolysis processes. To ensure efficient operation and optimal results, the electrolysis process necessitates the supply of purified and deionized process water, as This implies that the water sourced from Lake Naivasha would need to undergo purification and deionization treatments to meet the required quality standards for electrolysis.

The capital cost associated with water usage includes the expenses related to pumps, pipes, and other necessary infrastructure to facilitate the extraction and delivery of water from Lake Naivasha to the electrolysis facility. The total cost of water includes not only the volume of water required for the electrolysis process but also the costs associated with the purification and deionization processes (Müller et al., 2023a). By considering the water requirements, quality considerations, and associated costs, this study aims to provide a comprehensive assessment of the feasibility, sustainability, and economic viability of using Lake Naivasha as the water source for hydrogen production through electrolysis. To produce 1 kg of hydrogen, the electrolyser system required approximately 10 litres of water. The water was sourced externally and incurred a cost of $5 per kilolitre (Ulleberg, 2003). The overall water consumption was calculated based on the hydrogen production rate and accounted for in the cost analysis. Figure 4-8: shows the proximity of the geothermal power plants to Lake Naivasha, which will be the water source.

Figure 4-8: Site location -Lake Naivasha- Kenya.

(Olkaria Geothermal | OpenStreetMap, n.d.)

4.4.7. Operational costs

Operational costs are ongoing expenses incurred during the operation and maintenance of the hydrogen production system. It encompasses various costs associated with the regular operation of the system to produce and deliver hydrogen. The operation cost includes factors such as insurance costs, labour costs, maintenance and repair cost and administrative costs.

By considering the operation cost along with other factors such as capital costs and energy. the levelized cost of hydrogen can be determined. The levelized cost of hydrogen represents the average cost of producing hydrogen over the entire project lifetime, considering both capital and operational expenses. For this study, operational expenses are 5% of the capital expenses. It is important to note, the energy cost has been declassified for hydrogen generation.

4.5. Sensitivity analysis

In the sensitivity analysis of geothermal hydrogen power generation, considering various factors such as capital expenditure (Capex), energy costs (specifically the electricity unit cost), higher heating value, stack replacement costs and operation costs. The objective of this analysis is to evaluate how these variables influence the levelized cost of hydrogen (LCOH).

Capital Expenditure (Capex): Capex represents the initial investment required for setting up the geothermal hydrogen power generation system. The sensitivity analysis focuses on assessing the impact of variations in Capex on the LCOH. This analysis helps understand how changes in the initial investment affect the overall cost of hydrogen production. By evaluating different Capex scenarios, decision-makers can determine the feasibility and profitability of the project.

Energy Costs (Electricity Unit Cost): Energy costs, specifically the electricity unit cost, play a crucial role in the economic analysis of geothermal hydrogen power generation. The sensitivity analysis considers different electricity unit cost scenarios to evaluate their influence on the LCOH (Scott, 2019) (Ulleberg, 2003). Higher electricity costs increase operational expenses, resulting in a potentially higher LCOH. Conversely, lower electricity costs can lead to a reduced LCOH. Assessing the sensitivity of the LCOH to changes in electricity costs helps identify the impact of energy prices on the economic viability of the project.

Higher Heating Value: In the context of sensitivity analysis for geothermal hydrogen power generation, the higher heating value refers to variations in the energy required to produce hydrogen per kilogram(Xia et al., 2023). By assessing the sensitivity of the levelized cost of hydrogen (LCOH) to changes in the higher heating value, we can understand the impact of variations in the energy content of hydrogen on the overall cost. It is important to consider the higher heating value as a factor in sensitivity analysis because it directly affects the energy efficiency and cost-effectiveness of hydrogen production. By examining the sensitivity of the LCOH to changes in the higher heating value, we can gain insights into how variations in the energy content of hydrogen impact the overall cost of hydrogen production in the geothermal hydrogen power generation system.

Stack Replacement Costs: The stack replacement cost refers to the expenses associated with replacing or refurbishing the electrolyser stack. (Ghazvini et al., 2019b). By assessing the sensitivity of the LCOH to changes in stack replacement costs, the analysis evaluates their impact on the overall cost of hydrogen production. Higher stack replacement costs contribute to increased total present costs, which can result in a higher LCOH. Understanding the sensitivity to stack replacement costs helps identify potential risks and expenses associated with the system's maintenance and longevity.

Operational Costs: Operational costs encompass expenses related to maintenance, personnel, and ongoing operations throughout the geothermal hydrogen power generation system's lifetime Oner & Khalilpour, 2022), (Kojima et al., 2023). The sensitivity analysis examines variations in operational costs to assess their influence on the LCOH. Higher operational costs lead to increased total present costs and, subsequently, a higher LCOH. Evaluating the sensitivity of the LCOH to changes in operational costs aids in understanding the economic implications of ongoing expenses.

Conducting a comprehensive sensitivity analysis considering these factors provides valuable insights into the cost dynamics of geothermal hydrogen power generation. By assessing different scenarios and varying the input factors, the sensitivity analysis aids in identifying the most influential parameters and optimizing the project's economic performance.

4.6. Chapter summary

This chapter delves deep into describing the methodology and analysis approach used in the study. The main tools utilized are Microsoft Excel and RStudio, which facilitate the computation of the Levelized Cost of Hydrogen and allow for the execution of sensitivity analysis simulations. A comprehensive overview of techno-economic parameters essential to electrolyser operation is presented, along with a discussion of the assumptions applied within the model. The final section delves into sensitivity analysis, exploring how potential changes in key variables can impact outcomes.

Chapter V

Results and Analysis

5.1. Levelized cost of hydrogen Results and Analysis

The LCOH value we obtained is $3.35 per kg in Table 5-6. This represents the average cost of producing one kilogram of hydrogen over the 20-year project lifetime, considering the capital expenditures (CAPEX). Discounted cost for all the recurrent expenses such as operating expenditures (OPEX), insurance cost, stack replacement cost, electricity costs, and water costs was considered.

Table 5-6: Estimated Levelized cost of Hydrogen

Alkaline Water Electrolyser			
	INPUT	**UNITS**	**$**
Economic factor	Discounting rate	%	9%
Geothermal Inputs	Tariff /unit cost	$/kWh	0.06
	Capacity factor	%	90%
Capital cost	Project life	Year	20
	Plant size	KW	1,000
	Electrolyser	$	780,000
	Stack replacement cost	USD	179,152
Operating Cost	OPEX[2]	$	356,013
	Water cost	$/KL	64,336
	Energy cost	kwh/$	3,449,235
TOTAL COST		**%**	4,828,736
H2 Produced		Kg	1,442,716
	LCOH	$/kgH2	3.347
	LCOE	kwh/$	0.1004

CAPEX: The initial capital expenditure for the electrolyser is $780,000, which accounts for the purchase and installation of the equipment. This cost is incurred at the start of the project and remains constant throughout its lifetime. It contributes to the overall cost of hydrogen production.

[2] OPEX and insurance costs were combined for sensitivity analysis.

OPEX: The annual operating expenditure is estimated to be 5% of the CAPEX, which amounts to $39,000 per year. OPEX covers the regular operational and maintenance costs associated with running the electrolyzer system. These costs are spread evenly over the project lifetime and contribute to the levelized cost.

Stack Replacement Cost: At the end of year 10, the electrolyser's stack needs replacement, which incurs a cost of 50% of CAPEX. With a capacity of 1,000 kW, the stack replacement cost totals $179,152 This cost is incurred once during the project and impacts the levelized cost accordingly.

Electricity Costs: The geothermal power plant supplies the energy required for electrolysis, with a capacity factor of 90%. Considering the electrolyser efficiency of 80%, the annual average electricity consumption for hydrogen production amounts to 6,247,639.59 kWh. The cost of electricity, estimated at $0.06/kWh, contributes to the overall levelized cost.

Water Costs: Water is necessary for the electrolysis process, with a consumption rate of 10 litres per kilogram of hydrogen produced. The annual water consumption is approximately 2 million litres, resulting in a total cost of $70,185. This cost, incurred throughout the project's lifetime, is factored into the levelized cost.

Taking all these factors into consideration, we arrive at the levelized cost of hydrogen (LCOH) of $3.3 per kg. This represents the average cost of producing hydrogen over the project lifetime, considering all the operational and capital expenses, as well as the specific parameters and assumptions outlined.

5.2. Sensitivity analysis results and analysis.

5.2.1. Electricity unit cost analysis ($/kwh).

Hydrogen is an energy carrier and is dependent on the transformation of another energy form, hence its generation is fundamentally influenced by energy costs. This particularly holds when hydrogen is produced through electrolysis. Therefore, the cost of energy becomes a principal factor that significantly shapes the overall economic feasibility of hydrogen production (Nicita et al., 2020). Indeed, the cost-effectiveness of generating hydrogen via electrolysis is intimately tied to the cost of the energy consumed in the process.

Figure 5-9:Sensitivity analysis of unit electricity cost

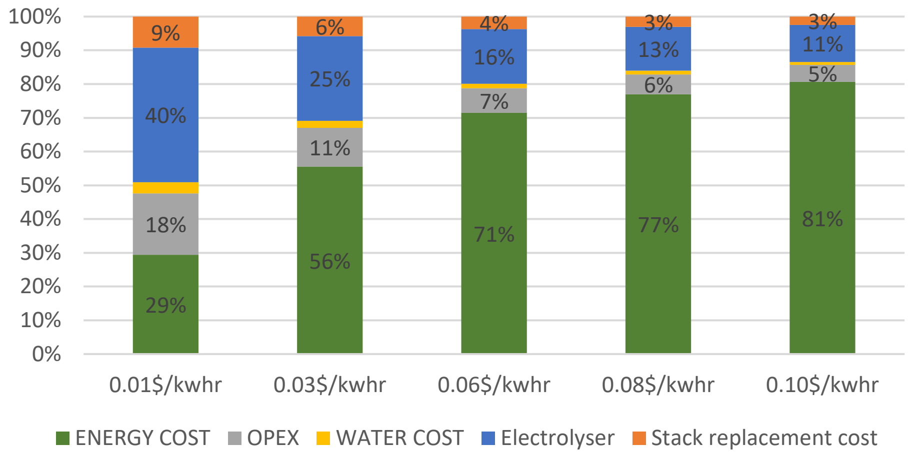


Figure 5-9 depicts a case analysis of variation in unit cost of electricity, for this study geothermal energy cost. Firstly, at $0.01 per kWh, the energy cost constitutes 29% of the LCOH, with the electrolyser capital expenditure (capex) at 40%, and operational costs making up 18%. The stack replacement cost, a critical component of electrolysis maintenance, stands at 9%. However, as the unit cost of electricity ascends to $0.03 per kWh, the energy cost fraction considerably escalates to 56%. Correspondingly, the capex contribution markedly descends to 25% and operational expenditure (OPEX) reduces to 11%. The stack replacement cost diminishes to 6% under this scenario.

At a presumed geothermal energy unit cost of $0.06 per kWh, the energy cost fraction swells to 71%, with the capex proportion at 16% and Opex at 7%. When the unit cost of electricity amplifies to $0.10 per kWh, the energy cost component of the overall hydrogen production cost increases to 81%.

The analysis underscores that the unit cost of electricity is a pivotal factor in determining the viability and competitiveness of hydrogen production. It exhibits a direct impact on the LCOH, which represents the average cost of generating hydrogen throughout the project's lifespan. By effectively managing and optimising the unit cost of electricity, hydrogen production can potentially be more economically feasible and efficient (Ghazvini et al., 2019a).

5.2.2. Sensitivity to Higher heating value (kwh/kg)

The higher heating value (HHV) of hydrogen plays a crucial role in determining the levelized cost of hydrogen (LCOH). It represents the amount of electrical energy required to produce one kilogram of hydrogen via electrolysis, the predominant method of green hydrogen production. Which is essentially the amount of electrical energy required to produce a kilogram of hydrogen via electrolysis.

Figure 5-10: Sensitivity analysis of the higher heating value

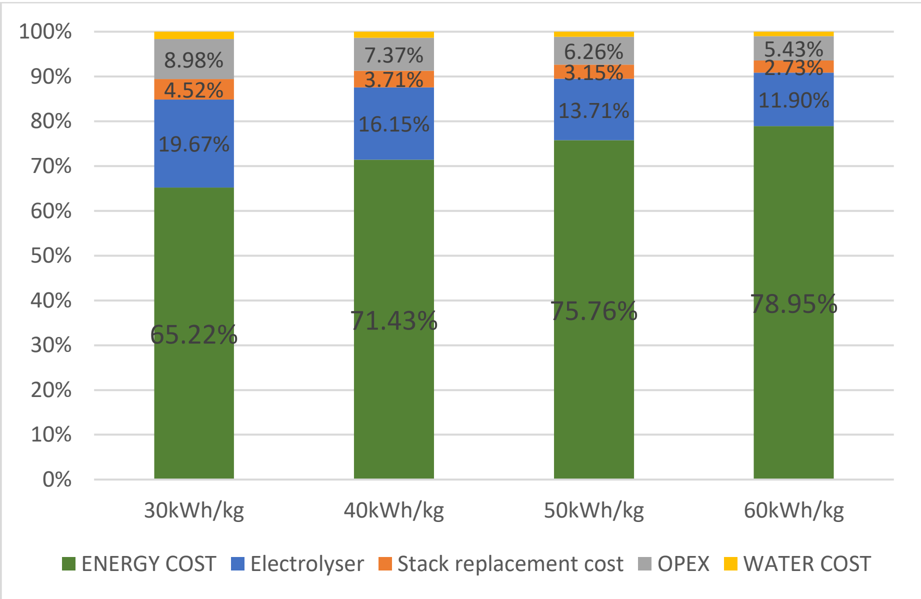


Figure 5-10 where the energy consumption is at 30kWh/kg, the energy cost significantly contributes to the Levelized Cost of Hydrogen (LCOH), making up 65% of the total. The Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) make up 19% and 9% respectively, while the cost for Electrolyser stack replacement stands at 4.5%.

However, if the energy consumption rises to 40kWh/kg, a noticeable shift can be observed in the components contributing to the LCOH. The percentage contribution of the energy cost escalates to 71.43%. The proportion of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) decrease to 16.15% and 7.37% respectively. Meanwhile, the cost allocated for Electrolyser stack replacement diminishes to 3.7%.

With the electrolyser's higher heating value at 50 kWh/kg, the composition of the Levelized Cost of Hydrogen (LCOH) becomes significantly influenced by energy cost, accounting for 75.76% of the total. In comparison, capital expenditure contributes 13.67%, operational expenditure is 6.9%, and the cost of electrolyser stack replacement stands at 3%. Should the lower heating value rise to 60 kWh/kg, an increase in energy cost's contribution to 79% of the total (LCOH) is observed, while capital expenditure, operational expenditure, and stack replacement cost reduce to 11.9%, 5.3%, and 2.7% respectively.

These findings emphasise the direct correlation between the energy cost and lower heating value in hydrogen production. Electrical energy in this context is usually derived from renewable sources like geothermal, wind, solar, or hydropower. As the energy cost constitutes a considerable portion of the overall Levelized cost of Hydrogen (LCOH), reducing the required kWh per kg of hydrogen could potentially enhance the economic viability of green hydrogen production.

5.2.3. Sensitivity to electricity cost and energy consumption

As analysed above higher heating value (HHV) in kWh/kg and the electricity cost in $/kWh are critical parameters that significantly impact the levelized cost of hydrogen (LCOH).(Hazrat et al., 2022a) A combined analysis of the two factors will provide valuable insights into the influence of these parameters on the LCOH. They will intertwine to shape the economic viability of hydrogen production and determine the levelized cost of hydrogen. However, these two factors are susceptible to fluctuations such as energy prices and technology advancements.

Figure 5-11: Effect of electricity cost vs Higher Heating Value on Levelized cost of hydrogen

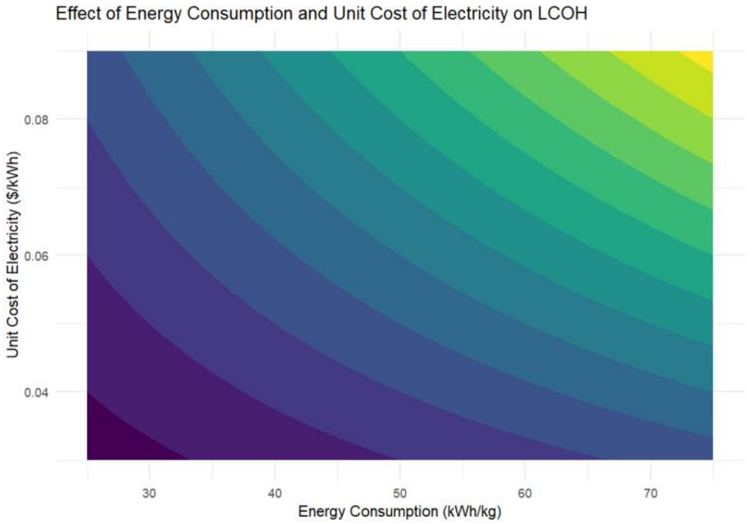
$/Kg		Electrolyser Efficiency				
		30	40	50	60	70
Electricity cost	0.01	1.2426	1.3422	1.4418	1.5414	1.6410
	0.03	1.8403	2.1391	2.4380	2.7368	3.0357
	0.05	2.4380	2.9361	3.4341	3.9322	4.4303
	0.06	2.7368	3.3345	3.9322	4.5299	5.1276
	0.08	3.3345	4.1315	4.9284	5.7253	6.5222
	0.10	3.9322	4.9284	5.9246	6.9207	7.9169

Figure 5-11 illustrates a comprehensive analysis that combines the impacts of both electricity unit cost ($/kWh) and Higher Heating Value (kWh/kg) on the Levelized Cost of Hydrogen (LCOH). The analysis reveals that when the cost of electricity is set at a low level of $0.01 per kWh and the HHV is at 30 kWh/kg, the LCOH registers at a remarkably competitive rate of $1.24 per kg of hydrogen. The analysis also reveals that with an assumed electricity cost of $0.06 per kWh and an HHV set at 40 kWh/kg, the LCOH reaches a stable point equivalent to the previously calculated figure of $3.3345 per kg of hydrogen.

When the parameters are pushed to their upper limits, with an electricity cost of $0.10 per kWh and an HHV of 70 kWh/kg, the levelized cost of hydrogen rises sharply to $7.9 per kg. This analysis is a crucial finding. as it underscores the potential for cost-efficient hydrogen production when both the energy consumption (represented by HHV) and the electricity costs are effectively managed and optimised.

To further analyse these two factors and the impacts of these two key parameters, 1000 simulations were conducted, the results of which are visualised in Figure 5-4. This contour graph effectively illustrates the interplay between electricity cost ($/kWh) and lower heating value (kWh/kg) and their collective impact on the levelized cost of hydrogen. The LCOH gravitates within the same contour at an electricity unit cost of $0.06/kWh and energy consumption of 40 kWh/kg. However, as both the cost per unit of electricity and the unit of energy consumption escalates, a corresponding rise in the LCOH becomes apparent. This reinforces the crucial importance of optimising both these factors – electricity cost and lower heating value – to assure the economic viability of hydrogen production.

Figure 5-12: Effect of energy consumption and unit cost of electricity on Levelized cost of Hydrogen



Source: http://rstudio.com/

5.2.4. Sensitivity to capital cost and electricity cost

Both parameters are fundamental elements in the economic structure of hydrogen production, and their individual and combined effects shape the feasibility of green hydrogen projects. An analysis will deeply explore the relationship between the capital cost and unit electricity cost, and their implications on the LCOH. By employing a sensitivity analysis, we will visualise and understand how alterations in these parameters directly affect the economics of hydrogen production.

Figure 5-13: Effect of Capex and electricity cost on Levelized Cost of Hydrogen

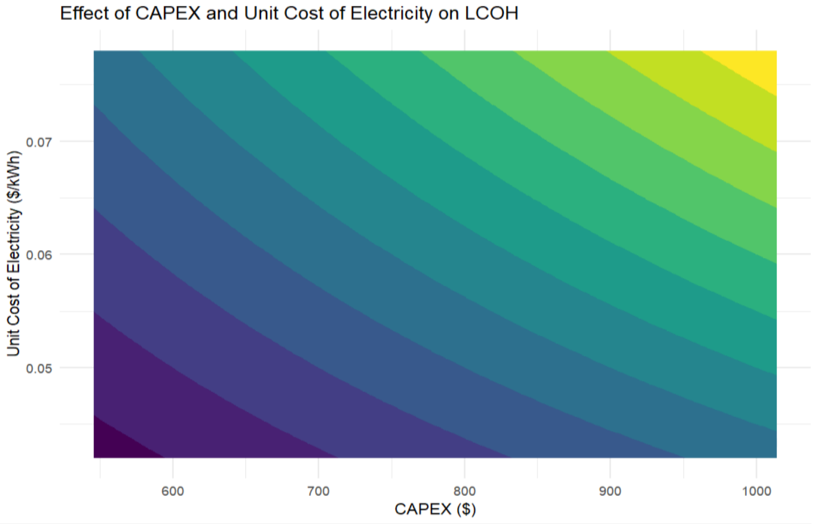
$/Kg	CAPEX 400	600	780	900	1000
Electricity cost 0.01	1.078806	1.217434	1.342198	1.425375	1.494689
0.03	1.875737	2.014365	2.139129	2.222306	2.291619
0.05	2.672668	2.811295	2.93606	3.019236	3.08855
0.06	3.071133	3.209761	3.334525	3.417702	3.487015
0.08	3.868064	4.006691	4.131456	4.214633	4.283946
0.10	4.664995	4.803622	4.928387	5.011563	5.080877

Figure 5-5 presents an analysis between capital cost and electricity cost a unit electricity cost of $0.1/kWh and capital costs standing at $400/kW. At this juncture, the LCOH equates to $1.07/kg. This relatively low LCOH at this point reflects the synergy of moderate capital costs and electricity prices, creating an environment conducive to affordable hydrogen production.

After introducing the values assumed in this study, which include an electricity cost of $0.06/kWh and capital costs of $780/kW, the LCOH increases to $3.3345/kg. This rise in LCOH presents an increment in capital costs, signifying its influence on hydrogen production economics.

Lastly, an electricity cost of $0.1/kWh and a significantly higher capital cost of $100/kW. The resultant LCOH soars to $5.08/kg, underscoring how higher electricity and capital costs can potentially pose a challenge to the economic viability of hydrogen production. These findings depict the relationship between capital cost and electricity cost and their effect on the LCOH. Therefore, for green hydrogen to be economically competitive capital and electricity have to be competitive.

Figure 5-14: Effect of Capex and unit cost on Levelized Cost of Hydrogen



Source: http://rstudio.com/

To gain a deeper understanding of the relationship between the unit cost of electricity and the capital expenditure (capex) in shaping the levelized cost of hydrogen (LCOH), a simulation was conducted. The resulting data is displayed in Figure 5-14 as a contour graph. The contour graph effectively visualizes the relationship between these two factors. The intersection points at a unit electricity cost of $0.06/kWh and a capex of $780,000 fall within the same contour, demonstrating how these values collectively influence the LCOH.

5.2.5. Electrolyser scaling

Scaling, as part of sensitivity analysis, is an essential tool that helps understand how changes in the size or volume of a system, or some of its parameters, affect the system's performance or cost (Kim et al., 2017). In the context of hydrogen production, scaling can be applied to several variables, including the size of the electrolyser, the volume of water used, and the electricity capacity, among others.

In this thesis, the electrolyser's size will be adjusted to capacities of 10 Megawatts (MW) and 50 MW to examine the impact on the system cost and the levelized cost of hydrogen. The concept of economies of scale suggests that an increase in production can lead to a reduction in the unit cost of hydrogen production. This is largely due to the fact that as production expands, the fixed costs are spread over a larger number of output units, resulting in a lower cost per unit.

Table 5-7: Scaling factor

Alkaline Water Electrolyser					
	INPUTS	**UNITS**			
	SCALE		Small	Medium	High
	PLANT SIZE	**MW**	**1**	**10**	50
Economic factor	Discounting rate	%	9%	9%	9%
Geothermal Inputs	Tariff /unit cost	$/kWh	0.06	0.06	0.06
	Capacity factor	%	90%	90%	90%
Capital cost	Project life	Year	20	20	20
	Electrolyser	$	780,000	6,240,000	26,694,230
	Electrolyser scaling factor	%	0.8	0.8	0.8
	Stack replacement cost	USD	179,152	1,433,215	6,131,182
Operating Cost	OPEX[3]	$	356,013	3,560,133	17,800,664
	Water cost	$/KL	64,336	643,364	3,216,818
	Energy cost	kwh/$	3,449,235	34,492,347	171,563,609
TOTAL COST		**%**	4,828,736	46,369,058	225,406,503
H2 Produced		Kg	1,442,716	14,427,162	72,135,809
	LCOH	$/kgH2	3.347	3.214	2.997
	LCOE	kwh/$	0.1004	0.096	0.090

Table 4-1 demonstrates an average availability of excess geothermal energy amounting to approximately 500 GWh annually. Given this data, a 50 MW plant could potentially be sustained entirely by this surplus power. Consequently, this study has examined the implications of scaling up the electrolyser size to 10 MW and 50 MW, with a specific focus on its effect on the Levelized Cost of Hydrogen (LCOH). Table 5-7 scaling from the base case of a 1 MW electrolyser (with a calculated LCOH of $3.347/kg) to a 10 MW electrolyser showed a slight decrease in the LCOH to $3.214/kg. Even more

[3] OPEX and insurance costs were combined for sensitivity analysis.

striking was the effect of scaling up to a 50 MW electrolyser, which led to a further reduction in the LCOH to $2.99/kg. This analysis thus suggests that economies of scale do indeed come into play when increasing the electrolyser size.

The capacity scaling for capital expenditure was assumed to follow a power law with an exponent of 0.8, reflecting the decrease in specific cost (cost per unit of capacity) associated with larger systems. This assumption aligns with general economic principles and numerous empirical studies that confirm a cost reduction trend with an increase in system size. Scaling as part of sensitivity analysis is a critical tool for assessing the implications of changes in size or volume on a system's performance and cost. In the case of hydrogen production, it helps identify the optimal sizes or volumes for various parameters to achieve the most cost-effective and efficient hydrogen production.

5.2.6. Storage cost

This study applies Compressed Air Energy Storage (CAES) for hydrogen storage. The CAES is a proven and effective method of storing energy and can be particularly suited for hydrogen due to its high energy density and the relatively low cost of compression and storage infrastructure compared to other forms of energy storage (Rasul et al., 2022). In considering the cost of hydrogen storage, the study adopts the cost assumptions applied by (Elberry et al., 2021b) specifically a capital cost of $1500/kg for the storage infrastructure and an operational cost that amounts to 2% of the capital cost(Spataru et al., 2015). An important aspect of energy storage systems is their round-trip efficiency(Abdin et al., 2022), which refers to the energy retained after a complete cycle of charging and discharging. The study assumes a round-trip efficiency of 90% for the hydrogen storage system. This means that for every unit of energy stored, 0.9 units can be effectively retrieved while the remaining 10% is lost, primarily due to conversion losses during the charging and discharging processes.

In this research, a hydrogen storage facility capable of storing a three-day supply of hydrogen is proposed, with a daily output of 500kg of hydrogen, from the 1MW plant. This design consideration is made to ensure the reliability and stability of hydrogen supply in scenarios of variable renewable energy generation, as well as potential operational or maintenance-related downtimes of the electrolyser unit. the incorporation of storage costs into the levelized cost of hydrogen (LCOH) adopts a similar approach to the original concept of LCOH.

$$LCOH = \frac{capital\ (Electrolyser + Storage)\ NpvOpex(storage + electrolyser)}{NpvH2(Hydrogen)}$$

Table 5-8: Storage cost analysis

Storage cost	Input	Unit	Unit cost	Total cost$
System inputs	Project life	year	20	20
	storage capacity	kg		1500
	Energy stored/day	kg	339.092364	500
	storage time	days	3	
	Capital cost	$	1,500	2,25,000.00
	Energy loss	%		10%
Operating cost	OPEX	%	2%	825,688.07
	Energy Consumption	5.00		50,229.36
Storage cost				3,125,917.53
Electrolyser cost				4,810,774.71
Total cost				7,936,693.24
H2 Produced		kg		2,142,047.86
	LCOH	$/kGH2		5.01
	LCOE	kwh/$		0.150183306

The integration of storage costs into the total expenses of hydrogen production significantly impacts the levelized cost of hydrogen (LCOH). Following the implementation of a three-day storage facility with the specified storage costs ($850/kg capital cost, and a 2% operational cost), the estimated LCOH increases to $5.01 per kg

5.2.7. Application of the curtailed geothermal power of Hydrogen production

The study proposes a system where excess energy generated by geothermal power plants during off-peak and mid-peak hours is utilised and charged at a rate of 0.1$/kWh of the regular tariff. By leveraging the surplus energy during periods of lower electricity demand, the system aims to optimize the utilization of renewable energy resources and promote the production of hydrogen as a clean energy carrier. This approach helps to maximize the efficiency and cost-effectiveness of the overall energy system by effectively utilizing excess renewable energy that would otherwise go to waste.

The discounted rate for the excess energy incentivizes the generation of hydrogen during specific periods when the electricity demand is lower. By using this excess energy to produce hydrogen, which can be stored and later converted back to electricity or used as a clean fuel, the system contributes to grid stability, energy storage and reduction of fossil fuels.

Table 5-9: proposed tariff -levelized cost of hydrogen

ALKALINE WATER ELECTROLYSIS				
	INPUT	**UNITS**	**$**	
Economic factors	Discounting rate	%	9	9
Geothermal factors	Tariff	$/kWh	0.06	0.06
	Capacity factor	%	90%	90%
	Plant Size	**MW**	**1**	50
Capital cost	Project life	Year	20	20
	Electrolyser Capex	$	780,000	26,694,230
	Capex scaling factor		0.9	0.9
Operating Cost (NPV)	OPEX	$	356,013	17,800,664
	Water cost	$	64,336	3,216,818
	Stack replacement cost	USD	39,482	1,351,207
	Energy cost	$/kWh	341,333	17,871,209
TOTAL COST		$	1,581,164	66,934,128.43
H2 Produced		Kg	901,698	45,084,881
	LCOH	$/kgH2	1.754	1.485
	LCOE	$/kWh	0.0526	0.0445

The Levelized cost of hydrogen significantly reduces from 3.3$/kgH2 to 1.754$/kgH2 at 1 MW. 2.9$/kgH2 to 1.485$/kgH2 at 50 MW due to economies of scale. The reduction in the levelized cost of hydrogen makes it a more economically viable option for power production. By utilizing the excess energy generated during off-peak and mid-peak hours, the system avoids purchasing additional electricity at regular tariff rates. The discounted energy cost, charged at $0.01/kWh, contributes to lower overall production costs for hydrogen. Lastly, instead of letting surplus energy go to waste, it is harnessed to produce hydrogen, resulting in improved cost efficiency.

5.2.8. Application of the proposed tariff and storage costs

The study conducts an analysis using the proposed tariff and storage cost to determine the levelized cost of hydrogen at 50 MW for 3 days. By considering the discounted energy tariff of $0.01/kWh during off-peak and mid-peak hours, and factoring in the associated storage costs, the levelized cost of hydrogen is calculated.

Table 5-10:Levelised cost of hydrogen and storage costs

storage cost	INPUT	UNITS	unit cost	Total cost$
System inputs	Project life	year	20	20
	storage capacity	kg		21,500
	Energy stored per day	kg	21,193.27	21,500
	storage time	days	3	
	Capital cost	$	1,500	66,222,224
	Energy loss	%		10%
Operating cost	OPEX	%	2%	24,301,733
	Energy Consumption	5.00		359,977.06
Storage cost				90,883,936.10
Electrolyser cost				66,934,128
Total cost				157,818,065
H2 Produced		kg		49,593,368.98
	LCOH	$/kGH2		3.1822
	LCOE	kwh/$		0.0955628

The levelized cost of hydrogen, considering the associated cost of storage, is determined to be $3.18/kWh when utilizing the geothermal generation cost of $0.01/kWh. This cost is significantly lower compared to the levelized cost of hydrogen at the normal tariff rate of $0.06/kWh, which amounts to $5/kWh.

By implementing the proposed system and utilizing excess geothermal energy at a discounted rate during off-peak and mid-peak hours, the cost of hydrogen production is substantially reduced. This cost reduction is primarily attributed to the lower energy input required for hydrogen production when utilizing discounted geothermal energy.

5.3. Chapter summary

5.3.1. Key findings

The findings of this thesis highlight key aspects in the determination of the Levelized Cost of Hydrogen (LCOH). Primarily, it's observed that electricity costs and capital expenditure play significant roles in the economic viability of hydrogen production. The Levelized cost of hydrogen at $3.3/kg which is within the international pricing for green hydrogen (IRENA, 2020).

Sensitivity analysis of the levelized cost of Hydrogen with an electricity cost set at $0.1/kWh and capital cost at $400/kW, the LCOH settles at a relatively low figure of $1.123/kg. This demonstrates that a balance of moderate capital costs and electricity prices can foster an environment conducive to cost-effective hydrogen production. A further increase in both electricity cost to $0.1/kWh and capital cost to $1200/kW results in a marked rise in LCOH to $4.4/kg. This highlights the potential for escalated electricity and capital costs to affect the affordability of hydrogen production.

Scaling the size of the electrolyser from 1 MW to 10 MW and 50 MW, has a notable effect on LCOH as well, decreasing it to $3.2/kg and $2.9/kg respectively. This indicates potential economies of scale, making hydrogen production more cost-effective as the size of the electrolyser is increased.

The introduction of storage facilities also impacts the LCOH, causing it to surge to $5.0 /kg. A 3-day storage facility capable of handling a daily output of 1,500kg, equivalent to the daily output of a 1 MW electrolyser, was considered. Further sensitivity analysis indicates that at the lowest assumed electricity cost of $0.1/kWh for 50 MW, the LCOH significantly reduces to $3.18/kg.

5.3.2. Policy implications

The policy implications of this thesis are as follows:

First, the key findings emphasize the crucial role of electricity costs and capital expenditure in hydrogen production economics. Hence, strategies to reduce electricity costs, such as leveraging renewable energy resources and optimizing operational efficiencies, could significantly contribute towards enhancing the economic viability of hydrogen production and storage.

Second, the electrolysis process requires a substantial amount of water to produce hydrogen. The amount of water used by a 1 MW electrolyzer is dependent on the operating hours, but typically, around 9 to 10 litres of water are required to produce 1 kg of hydrogen. This means that for an electrolyser operating continuously at full capacity, approximately 20,000 to 22,000 litres of water would be required per day. If the water is taken from rivers or lakes, this could affect the water levels in these bodies and potentially harm local aquatic ecosystems. It is also important to consider the quality of the water being used. Electrolysis requires relatively pure water, and if the water needs to be treated or purified before use, this could add to the environmental impact and the cost of the process. It is important to conduct an environmental assessment to determine the local water availability.

Lastly, the proposal to charge 0.01$/kwh of the geothermal tariff, for this excess geothermal power can have a major positive impact on the overall economics of hydrogen production. This approach leverages an underutilized resource to minimize costs, ultimately contributing to a more favourable LCOH. However, Power purchase Agreements, which are fixed legally binding documents for the geothermal power plants might pose a challenge to this proposal.

Chapter VI

Conclusion and Policy Implications

6.1. Conclusion

Kenya has substantial geothermal resources and is uniquely positioned to pioneer this technology in Africa. Harnessing its geothermal prowess, the nation can transform what was once considered a challenge - excess geothermal energy during off-peak times - into a significant asset for sustainable hydrogen production. The cost of hydrogen production can be significantly reduced by applying a reduced tariff to this excess energy, sufficient to cover operational expenses.

This study analysis clearly shows that the cost of electricity plays a critical role in the overall economics of hydrogen production. The techno-economic evaluation of geothermal hydrogen production highlighted the critical role of capital and operational costs, specifically electricity costs, in determining the Levelized Cost of Hydrogen (LCOH). With an assumed electricity cost of $0.06 per kWh, the LCOH was $3.3 per kg of hydrogen. Higher electricity and capital costs directly increase the LCOH, affecting the economic feasibility of hydrogen production. It emphasizes the need to minimize electricity costs for more economically viable hydrogen production. Strategies might include optimizing operational efficiencies and leveraging affordable and consistent power sources like geothermal energy.

The economies of scale indicate that scaling up the electrolyzer size can potentially decrease the levelized cost of hydrogen, making hydrogen production more cost-effective. An increase from 1 MW to 50 MW electrolyzer setup resulted in a marked reduction from $3.3/kg to $2.9/kg in the Levelized Cost of hydrogen. Furthermore, the initial capital cost is another significant factor affecting the LCOH. As evidenced in the study, higher capital costs lead to an increase in the LCOH. Therefore, controlling these costs through efficient design and deployment is crucial.

The introduction of storage facilities increases the LCOH due to the additional costs associated with these systems. However, these costs may be necessary for ensuring a consistent supply of hydrogen, highlighting the balance that must be struck between cost and operational needs.

The study introduces an innovative approach that leverages Kenya's excess geothermal power to significantly impact the Levelized Cost of Hydrogen (LCOH). The proposal recommends an alternative tariff structure that prices the currently vented excess geothermal energy at $0.01 per kWh, which significantly lowers the Levelized Cost of Hydrogen and the storage cost from $5.01/Kg its falls to a much more economical $2.3 per Kg.

The economic viability of hydrogen production is a complex issue that is affected by multiple factors, including electricity costs, capital expenditures, system scale, and storage facilities. By managing these variables carefully, it's possible to enhance the economic feasibility of hydrogen production and pave the way for more widespread use of this clean energy source. The use of excess geothermal energy, in particular, represents an exciting opportunity to further improve the economics of hydrogen production while also promoting sustainability.

6.2. Policy recommendations

Kenya, abundant in geothermal resources, is strategically positioned to pioneer the transition to a renewable, hydrogen-based energy system. The rapid advancement of hydrogen technologies, particularly geothermal hydrogen, opens many opportunities for the country to realize its energy security, decarbonization, and economic growth ambitions. However, the evolution and adoption of geothermal hydrogen as a mainstream energy source require robust and concerted policy support. This study aims to outline policy recommendations based on its analysis.

First, the development and application of regulations, coupled with rigorous standards, are necessary for the safe, efficient realization of geothermal hydrogen. Concurrently, investing in the research and development of technological advancements in geothermal hydrogen production is vital for enhancing efficiency and reducing costs.

Secondly, engaging in collaborations with international bodies and partners could facilitate the exchange of knowledge and expertise in the realm of geothermal hydrogen production. Complementing this with awareness-raising and educational campaigns could effectively underscore the benefits of geothermal hydrogen generation, spurring its adoption nationwide.

Thirdly, the establishment and execution of comprehensive policies and strategies are needed to seamlessly incorporate geothermal hydrogen into the national energy composition, with the end goal of achieving energy stability and sustainability. This shift would be further bolstered by infrastructure development, including the construction of hydrogen fuelling stations to nourish the growth of the geothermal hydrogen sector in Kenya.

Fourthly, implement tax incentives and financial support for businesses and organizations investing in geothermal hydrogen generation. Implementing fiscal incentives and providing financial aid for enterprises and institutions that invest in geothermal hydrogen production is a pivotal move. Such economic measures can effectively incentivize investment, promote industry growth, and accelerate the integration of this sustainable energy source into our power systems. By reducing the financial risk associated with initial investments, these strategies can stimulate the transition toward green energy and ensure a more sustainable future.

Fifth, apart from energy production, geothermal hydrogen can be utilized in various sectors within Kenya, notably in manufacturing, transportation, and agriculture. These sectors represent significant Power-to-X (P2X) opportunities that can be exploited for substantial economic, environmental, and social benefits. The adoption of a geothermal-hydrogen system in Kenya offers vast P2X opportunities that extend beyond energy production. With appropriate policies, the country can capitalize on these opportunities, fostering a more sustainable, resilient, and inclusive economy.

6.3. Limitations and Further research

This study explores a new cutting-edge technology of geothermal-hydrogen power generation, particularly its implementation within the favourable context of Kenya. While geothermal energy has been harnessed extensively in the country, the concept of combining it with green hydrogen production is novel, offering an innovative path towards sustainable and carbon-neutral energy generation.

However, venturing into this pioneering domain presents unique challenges and limitations that will shape this thesis. Geothermal-hydrogen power generation is scanty. There are inadequate practical examples, leading to a lack of operational data to be analyzed. To draw definitive conclusions is a challenge. Furthermore, the lack of standardized data necessitates reliance on projections or simulations, which may not always mirror future operational realities accurately.

The economic assumptions, such as capital expenditure of the geothermal-hydrogen power generation, remain unclear due to its novelty, and a variety of factors, such as geological, technological, and market, may affect them. This ambiguity might impede the accurate evaluation of the thesis.

The regulatory framework supporting geothermal-hydrogen power generation is still under development in Kenya, just as in many other countries. It influences the feasibility and the potential scalability of geothermal-hydrogen power generation in Kenya. This could also pose challenges when discussing the study's policy implications or academic recommendations.

There are abundant opportunities for further studies due to the novelty of the green hydrogen field, especially in Kenya. Upon development of the hydrogen framework in the country, a ray of studies areas in the field could be considered. Further studies might examine how to develop a policy framework in Kenya and how it can support the expansion of the hydrogen economy. This could involve a comparative analysis of hydrogen policies in other countries and recommendations for enhancing Kenya's regulatory framework.

Research could be undertaken to investigate the infrastructure needed to support a thriving hydrogen economy in Kenya. This could include studies on the design and operation of hydrogen production facilities, storage systems, and refuelling infrastructure for hydrogen fuel cell vehicles.

A study on Kenya's wind and solar hydrogen generation has been conducted (Müller et al., 2023b). However, the country is endowed with expansive renewable resources. Hydropower is a rich resource in Kenya, with several large-scale installations already in operation. Future research could assess the viability of utilizing existing hydroelectric infrastructure for this purpose and explore the potential for developing new, small-scale hydropower installations specifically for hydrogen production. Technical aspects to consider would include the efficiency of water electrolysis using hydropower and the associated engineering challenges. Finally, economic analysis, including cost-benefit and return on investment studies, would help understand the financial viability of such ventures.

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Appendix

Appendix 1

	HOURS	00.30	01.00	01.30	02.00	02.30	03.00	03.30	04.00	04.30	05.00	05.30	06.00	06.30	07.00	07.30	08.00	08.30	09.00
MONDAY 19/07/2022	GEOTHERMAL EFFECTIVE CAPACITY	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871
	GEOTHERMAL GEN	571	541	508	508	505	507	506	503	535	575	690	776	788	766	758	789	792	790
	EXCESS POWER	299.67	329.98	362.99	363.16	365.94	364.13	364.67	368.36	336.18	295.58	181.17	94.71	83.37	105.17	112.56	81.95	78.70	81.11
TUESDAY 20/07/2022	HOURS	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	GEOTHERMAL EFFECTIVE CAPACITY	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871
	GEOTHERMAL GEN	661	644	636	609	599	615.696	614.272	584.848	578.734	615.118	669.718	715.736	742.724	779.518	792.196	796.304	795.29	795.08
	EXCESS POWER	209.70	227.15	234.84	262.07	272.17	255.30	256.73	286.15	292.27	255.88	201.28	155.26	128.28	91.48	78.80	74.70	75.71	75.92
WEDNESDAY 21/07/2023	HOURS	00.30	01.00	01.30	02.00	02.30	03.00	03.30	04.00	04.30	05.00	05.30	06.00	06.30	07.00	07.30	08.00	08.30	09.00
	GEOTHERMAL EFFECTIVE CAPACITY	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871
	GEOTHERMAL GEN	585.764	561.168	530.726	530.474	533.526	532.384	533.314	532.424	534.056	634.388	690.228	767.682	792.17	791.446	749.23	750.406	781.332	794.112
	EXCESS POWER	285.24	309.83	340.27	340.53	337.47	338.62	337.69	338.58	336.94	236.61	180.77	103.32	78.83	79.55	121.77	120.59	89.67	76.89
THURDAY 21/07/2024	HOURS	00.30	01.00	01.30	02.00	02.30	03.00	03.30	04.00	04.30	05.00	05.30	06.00	06.30	07.00	07.30	08.00	08.30	09.00
	GEOTHERMAL EFFECTIVE CAPACITY	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871
	GEOTHERMAL GEN	585.764	561.168	530.726	530.474	533.526	532.384	533.314	532.424	534.056	634.388	690.228	767.682	792.17	791.446	749.23	750.406	781.332	794.112
	EXCESS POWER	285.24	309.83	340.27	340.53	337.47	338.62	337.69	338.58	336.94	236.61	180.77	103.32	78.83	79.55	121.77	120.59	89.67	76.89
FRIDAY 22/07/2025	HOURS	00.30	01.00	01.30	02.00	02.30	03.00	03.30	04.00	04.30	05.00	05.30	06.00	06.30	07.00	07.30	08.00	08.30	09.00
	GEOTHERMAL EFFECTIVE CAPACITY	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871
	GEOTHERMAL GEN	612.286	571.398	533.08	534.384	558.018	552.632	541.874	543.802	560.518	607.252	660.77	770.46	794.616	798.126	783.722	766.802	751.898	750.85
	EXCESS POWER	258.71	299.60	337.92	336.62	312.98	318.37	329.13	327.20	310.48	263.75	210.23	100.54	76.38	72.87	87.28	104.20	119.10	120.15
SATURDAY 23/07/2026	HOURS	00.30	01.00	01.30	02.00	02.30	03.00	03.30	04.00	04.30	05.00	05.30	06.00	06.30	07.00	07.30	08.00	08.30	09.00
	GEOTHERMAL EFFECTIVE CAPACITY	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871
	GEOTHERMAL GEN	604.542	569.77	557.83	557.188	543.09	537.84	536.632	538.546	547.684	592.072	641.97	685.188	678.096	668.368	705.42	749.674	753.716	752.51
	EXCESS POWER	266.46	301.23	313.17	313.81	327.91	333.16	334.37	332.45	323.32	278.93	229.03	185.81	192.90	202.63	165.58	121.33	117.28	118.49
SUNDAY 24/07/2026	HOURS	00.30	01.00	01.30	02.00	02.30	03.00	03.30	04.00	04.30	05.00	05.30	06.00	06.30	07.00	07.30	08.00	08.30	09.00
	GEOTHERMAL EFFECTIVE CAPACITY	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871	871
	GEOTHERMAL GEN	600.684	552.194	539.25	539.412	537.298	521.376	518.608	545.346	556.864	546.836	583.756	574.266	606.442	625.216	645.886	669.8	705.78	754.408
	EXCESS POWER	270.32	318.81	331.75	331.59	333.70	349.62	352.39	325.65	314.14	324.16	287.24	296.73	264.56	245.78	225.11	201.20	165.22	116.59

Appendix 2

Country	Methodology	COST	Author/Year
Kenya	PESTLE analysis		(Report et al., n.d.)
Turkey	PEM electrolysis	2.366 $/kg H2	(Yilmaz, 2017)
Iran	Techno-economic optimization	$2.366/kg to $3.14/kg H2	(Mahmoud et al., 2021)
Turkey	Thermo-economic modelling	0.979 $/kg to 2.615 $/kg H2	(Yilmaz et al., 2012c)
Iran	Thermodynamic and cost analysis	4.257$/kg	(Kianfard et al., 2018)
Korea	Techno-economic analysis and Monte Carlo simulation	7.16 $/kgH2	(Jang et al., 2022)
Iran	Thermodynamic modelling and optimization	2.84 $/kg and 0.03 $/kWh	(Rezaei et al., 2020)
China	Flash, cycle, Kalina Cycle	1.33$/kg	(Cao et al., 2018)
Italy	Economic feasibility	10$/kg	(Fragiacomo & Genovese, 2020b)
Iran	Regenerative ORC	4.921 $/GJ	(Ghaebi et al., 2018)
Australia	Levelized Cost of Hydrogen (LCOH)	2 $/kg H2	(Hazrat et al., 2022b)
Djibouti	Economic feasibility	$3.31-4.78/kg H2	(Awaleh et al., 2022b)
Germany, Spain	Economic feasibility	3.2 €/kg	(Kuckshinrichs et al., 2017b)
China	Economic feasibility	2–3$/kg.	(Lee, 2016b)
Australia	Economic feasibility	$3.2-$7.7/kg	(Abdin et al., 2022)
France	Economic feasibility and monte carlo simulation	2.5-3.2$/kg	(Gerard et al., 2022)
Denmark	Techno-economic analysis	3.2 -1.9$/kg	(Nami et al., 2022)

Abstract (Korean)

세계의 에너지 공급은 화석 연료에서 지속가능한, 재생가능한 에너지원으로 전환하고 있다. 이러한 전환은 화석 연료의 소비에 따른 기후변화의 가속화를 완화하기 위한 전 세계적인 요망에 따라 추진되고 있다. 이러한 에너지 전환에서 녹색 수소(green hydrogen)의 역할이 최근 들어 크게 주목받고 있다. 중소득 국가로 성장일로에 있는 케냐에서는 전력수요 첨두부하 시간이나 바람과 태양 같은 간헐성(intermittent) 재생가능 에너지의 공급이 부족한 때에는 화석 연료에 전적으로 의존하고 있다. 이러한 전통적인 화석 연료의 과다소비는 높은 비용과 함께 환경에도 나쁜 영향을 미친다.

케냐의 지열 발전소는 기저수요 시간대에도 발전하여 남는 지열스팀을 외부로 방출하고 있다. 이 과정은 에너지 낭비적이며 환경에 해롭습니다. 대형 배터리 에너지저장 시스템(BESS)은 상당한 자본 지출(CAPEX)이 소요되어 큰 도전이 되고 있습니다. 반면 과잉 지열 에너지와 수전해 수소생산 시스템을 결합하면 지속가능하고 비용효과적 해결책이 나오게 된다. 이렇듯 수소는 첨두부하 시간대 전력수요/공급 제를 해결하고 지속적고 안정적인 전력 공급이 가능하게 된다. 또한 버려지는 전력을 수전해 과정에 사용하면 발전비용을 더욱 줄일 수 있어, 지열-수소 하이브리드 발전이 케냐에게 비용 효과적인 옵션이 될 수 있다.

따라서 본 연구의 목표는 케냐의 지열-수소 발전에 대한 기술-경제 분석과 이러한 혁신적인 기술의 개발 및 도입/확산을 위한 정책적 함의를 도출하는 것이다. 이러한 연구목표를 달성함으로써, 케냐의 지속 가능하고 균형 잡히고 미래 지향적인 에너지시스템 구축에 기여할 수 있을 것이다. 또한 본 연구는 케냐의 다양한 발전 원/기술과 설비용량, 일일 및 연간 전력부하패턴, 그리고 지열발전 상황에 대한 정보 및 심층분석 결과를 제공하고 있다. 케냐 발전부문에 대한 종합적인 이해는

지열-수소 발전의 비용효과적 통합시스템을 구축하기 위한 선결 조건이다.

본 논문은 케냐 발전부문에서 알칼리 수전해(Alkali Water Electrolysis: AWE)를 사용한 지열-수소 발전에 대한 종합적인 기술-경제 접근법을 시도하였다. 잠재적인 전력수급 해결책의 여러 측면을 평가하는 가운데, 본 연구는 수소생산의 경제적 타당성의 주요 지표로서 평균수소생산단가 (Levelized Cost of Hydrogen: LCOH)에 분석의 초점을 맞추고 있다. 여러 매개변수를 고려한 종합적인 모델이 개발된 바, 이에는 자본비, 운영비, 전기료, 그리고 수소의 연소열(Higher Heating Value: HHV)이 포함된다. 분석결과로서 계산된 LCOH 은 다양한 조건과 가정 하에 $3.3~$5.01/kgH 의 범위를 나타낸다. 전기료와 자본 비가 LCOH 에 중대한 영향을 미치면서, 수소 생산의 경제성을 결정하는 중요한 변수로 작용한다.

본 연구는 LCOH 에 대한 기술 및 경제 매개변수의 변화의 영향을 알아보기 위해 민감도 분석을 실시하였다. 민감도 분석의 역할은 전해설비 효율, 전기료, 자본비 등의 변수가 지열-수소 발전의 경제성에 어떻게 영향을 미치는지 보여주는 것이다. 더 나아가 재생가능 에너지의 간헐적인 특성을 상쇄하기 위해 압축공기 에너지저장 시설을 통합하는 대안도 검토하였다. 저장시설의 포함은 추가부담 비용과 에너지 손실을 늘리지만, 수소의 일관된 공급을 보장함으로써 시스템의 운용성을 크게 향상시킨다.

본 연구에서 제안하는 새로운 해결책은 현재 방출되고 사용되지 않는 과잉 지열 에너지를 수소생산에 활용하여 운영 비용을 줄이는 동시에 발전시스템의 안정적 운영을 기하는 것이다. 과잉 지열에너지가 운영비용을 저감하는 시스템을 제안함으로써(전기료: $0.01/kWh), LCOH 를 더욱 낮춰, 수소 생산의 경제적 타당성을 높일 것으로 기대된다. 또한 규모의 경제로 인해 LCOH 가 1MW 규모설비의 경우 3.3$/kgH2 에서

1.754$/kgH2 로, 50 MW 경우 2.9$/kgH2 에서 1.485$/kgH2 로 크게 감소했습니다.

본 연구의 중요한 정책함의의 하나로서 케냐의 지열-수소 발전에 대한 표준 및 안전에 대한 정책의 개발 및 적용을 들 수 있다. 지열-수소발전 시스템은 신규 첨단 기술로서 기술 교환과 전문 지식의 공유를 위한 국제협력이 필요하다. 기술개발에 대한 다양한 정책지원과 투자기관에 대한 재정 지원 제공을 통해 지열-수소 발전의 상용화를 촉진시키도록 한다. 발전부문 외에도 수소 제조, 운송, 농업-비료 생산 등의 Power-to-X (P2X) 기술은 사회적, 환경적, 경제적 편익을 창출하게 될 것이다.

결론적으로 본 연구를 통해 케냐에서 지열-수소 발전이 경제적으로 실현 가능하다는 것이 입증되었다. 이는 새로운, 지속가능하고, 비용 효과적인 에너지 전환의 가능성을 보여줍니다. 또한, 정부, 산업, 연구소 등 이해 당사자들에게 혁신적인 에너지 솔루션을 개발하고 적용하는 데 유용한 통찰력을 제공할 것이다. 지열-수소 하이브리드 발전은 케냐의 미래 지속가능한 에너지믹스의 중요한 대안으로 정착할 것으로 기대된다.

키워드: 알칼리수전해(AWE), 지열 발전, 그린수소, 수소 평균생산단가 (LCOH), 압축 공기 에너지 저장 (CAES), P2X 기술

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