Economic and Environmental Feasibility of Energy Extraction from brine of a Geothermal Wellhead Plant

Thesis of 60 ECTS credits submitted to the Department of Engineering at Reykjavík University in partial fulfilment of the requirements for the degree of
Master of Science (M.Sc.) in Sustainable Energy

June 2023

by
Damaris Wacera Njoroge

Supervisors:

Einar Jón Ásbjörnsson
Assistant Professor, Reykjavík University, Iceland

Hlynur Stefánsson
Professor, Reykjavík University, Iceland

Examiner:
Dr. Þórður Víkingur Friðgeirsson
Assistant Professor, Reykjavík University, Iceland

Economic And Environmental Feasibility of Energy Extraction from Brine of a Geothermal Wellhead Plant

Damaris Wacera Njoroge

June 2023

Abstract

The need for sustainability in energy development has resulted in the push to develop sound systems supporting the population's needs while maintaining minimal environmental impacts. This paper describes the utilisation of separated brine for further electricity production, catering to environmental and economic factors. The paper investigates the environmental impact potential through the development of life cycle assessment for geothermal development: drilling, construction and operation phases for two alternatives; double flash and flash-binary plants. The economic analysis involves the computation of the two alternative plants' exergy efficiency and profitability analysis. The environmental analysis uses Life Cycle Assessment modelling to establish the environmental impact potential associated with exergy destruction. Exergy efficiency in both options increases by 75% and 87% for the double flash and the flash-binary plant, respectively. The double flash system has an ROI of 0.32 and an EROI of 0.99. The flash binary has an ROI of 0.28 and an EROI of 0.84. The energy payback ratio is 8 years for the double flash and 9.6 years for the flash binary. The study assigns the factors associated with the alternatives, specifically the components that can be enhanced to improve cost and environmental impacts.

Titll verkefnis

Damaris Wacera Njoroge

júní 2023

Útdráttur

Þörfin fyrir sjálfbærni í orkuþróun hefur leitt til þess að hljóðkerfi eru þróuð sem geta stutt við þarfir íbúanna en viðhaldið umhverfisáhrifum í lágmarki. Í þessari grein er lýst notkun aðskildra saltvatns til frekari raforkuframleiðslu, sem veitir umhverfis- og efnahagslega þætti. Í ritgerðinni er kannað umhverfisáhrifamöguleikann með þróun lífsferilsmats fyrir jarðhitaþróun: boranir, smíði og rekstrarstig fyrir tvo valkosti; tvöfalt flass og flass tvöfaldur plöntur. Efnahagsgreiningin felur í sér útreikning á skilvirkni exergy og arðsemisgreiningu fyrir tvær aðrar plöntur. Í umhverfisgreiningunni er notast við líkan á lífsferilsmat til að ákvarða umhverfisáhrifamöguleika sem tengjast eyðingu exergy. Exergy skilvirkni í báðum valkostunum eykst um 75% og 87% fyrir tvöfalda flassið og flassið tvöfaldan plöntuna, hver um sig. Tvöfalt flasskerfið er með arðsemi 0,32 og EROI 0,99. Flash tvöfaldur er með arðsemi 0,28 og EROI 0,84. Orkubótahlutfallið er 8 ár fyrir tvöfalda flassið og 9,6 ár fyrir flassið tvöfalt. Rannsóknin úthlutar þeim þáttum sem tengjast valunum og sérstaklega þeim íhlutum sem hægt er að auka til að bæta kostnað og umhverfisáhrif.

Economic and Environmental Feasibility of Energy Extraction from Brine of a Geothermal Wellhead Plant

Damaris Wacera Njoroge

Thesis of 60 ECTS credits submitted to the Department of Engineering at
Reykjavík University in partial fulfilment of
the requirements for the degree of
Master of Science (M.Sc.) in Sustainable Energy

June 2023

Student:

Damaris Wacera Njoroge

Supervisors:

Einar Jón Ásbjörnsson, Supervisor
Assistant Professor, Reykjavík University, Iceland

Hlynur Stefánsson
Professor, Reykjavík University, Iceland

Examiner:

Dr. Þórður Víkingur Friðgeirsson
Assistant Professor, Reykjavík University, Iceland

7th June 2023

date

Damaris Wacera Njoroge
Master of Science

I dedicate this to GRO-GTP.

Acknowledgements

Sincere gratitude to GRO-GTP and KENGEN for the opportunity to pursue the MSc venture. The assistance from my supervisors, Einar Jón Ásbjörnsson and Hlynur Stefánsson, I highly appreciate. The support from my family, thank you for the nightly phone calls and prayers and the Almighty. Grow in grace.

Preface

This dissertation is the original work by the author, Damaris Wacera Njoroge.

Contents

List of Figures

List of Tables

List of Abbreviations

MSc	Masters of Science
LCA	Life Cycle Assessment
LCIA	Life Cycle Inventory Assessment
LCOE	Levelized Cost of Electricity
ROI	Return on Investment
EROI	Energy return on investment
EPBP	Energy payback period
CRF	Capital Recovery factor
ORC	Organic Rankine Cycle

List of Symbols

Symbol	Description	Value/Units
$\dot{E}$	Exergy flow rate	MW
$\dot{m}$	Mass flow rate	Kg/s
ex	Specific exergy rate	Kj/kg
$\dot{Q}$	Heat flow rate	MW
W	Power	kW
h	Specific enthalpy	Kj/kg
$\dot{C}$	Cost rate	USD/year
c	Specific cost	USD/Gj
Z	Investment cost	USD
$\dot{Z}$	Component-related cost rate	USD/h
φ	Maintenance factor	-
r_k	Relative cost factor	-
f_k	Exergy-economic factor	-
r_b	Relative environmental factor	-
f_b	Exergy-environmental factor	-

Chapter 1

Introduction

Energy plays a critical role in development; it directly impacts human productivity and economic development. Energy resource that is secure, readily available at a reasonable cost, and sustainable in the long term without causing adverse effects on society is paramount for sustainable development [1]. The energy sector is involved in reducing environmental impacts through technological innovation, with increased thermal efficiency, reduced fuel consumption, and abatement of greenhouse gases[2]. Renewable energy provides opportunities for energy security, social and economic development, energy access, climate change mitigation, and reduction of environmental and health impacts[3].

Geothermal, a renewable energy source, depicts varied environmental impacts in development, primarily due to the different reservoir characteristics in various fields. In addition, the drilling process and energy conversion produce waste, evident in all the operations, drilling, power production and post-recovery [4]. The various emissions and environmental impacts attributed to geothermal development include direct environmental impacts, land use, geological hazards, waste heat, solid waste, water use and consumption, impact on biodiversity, and noise and soil impact [5].

This study investigates the feasibility of introducing a bottoming flash plant and binary cycle on a single flash 5 MW modular geothermal plant. The separated brine from the single flash is utilised for further energy extraction, leading to thermal and economic efficiency and reducing environmental impacts. The study identifies environmental impacts, investment, and thermodynamics.

The study addresses sustainability by investigating the feasibility of a low-pressure turbine and a binary cycle on an operational geothermal modular plant. In addition, the study identifies the relationship between environmental impacts, costs, and thermodynamics.

The research questions of the study are:

i. How are the three variables, exergy, environment, and economics, vary for the two alternatives, the double flash plant and the flash-binary plant?
ii. Are the costs associated with further utilisation of separated brine worth the changes in exergy efficiency?
iii. How does environmental impact causing potential vary when using separated brine for energy extraction?
iv. How do the profitability and energy ratios vary with the two alternatives?

The study begins with analysing the energy system of the study area, followed by a literature review on energy systems relating to exergy, economics and the environment to find the relationship between the three factors.

The methodology used in this work has three aspects to it. The first aspect is the exergy analysis for the proposed - double flash and the flash-binary plants. The second aspect is economic analysis, which brings capital cost and profitability analysis.

Thirdly, the environmental analysis involves conducting a Life Cycle Assessment of the proposed plants to identify the environmental impacts associated with the drilling, construction and operation of the two alternatives and the single flash, with the relative specific environmental impact and energy ratios calculated. Finally, the final chapter has the conclusion of the study.

Chapter 2

Energy Industry in Kenya

Geothermal activity in Kenya is associated with the Eastern African Rift system, with the capacity of generating 2,500 to 6,500 Mw [6]. Exploration in the Olkaria field started in 1956, and deeper drilling and further exploration of the area have gradually progressed. Geothermal utilisation in the country is mainly for electricity production, with various direct-use demonstrations being investigated specifically for agricultural output. Where there is the use of heat in greenhouse farming and carbon dioxide to reduce the use of pesticides, other small-scale utilisation projects include crop drying, industrial use and bathing.

Geothermal development has addressed the increased energy demand in the country. The Olkaria field has several plants: Olkaria I (45 MW), commissioned between 1981 and 1985; Olkaria II (105 MW), commissioned between 2003 and 2010, Olkaria IV and Olkaria I Unit 4 and 5, each 140 MW commissioned in 2014 and 2015, respectively. In addition, Olkaria V (172 MW) and Olkaria I Unit 6 (86MW) were commissioned in 2022. The wellhead plants are 15 units with an installed capacity of 81.1 MW, and Ormat operates Olkaria III (about 150 MW) [7].

The extensive development has seen various studies being undertaken to ensure the sustainability of the resource area; these have included numerical modelling and optimisation for different technological advancements. For example, a study [8] previously conducted on optimising the wellhead plants to ensure optimum output involved single flash condensing, the back pressure, the Organic Rankine cycle with wet cooling and the Organic Rankine cycle with dry cooling [9]. Studies on how best to ensure sustainability have resulted in hybrid cooling options and topping up plants being studied. These studies aim at providing optimal resource utilisation and environmental sustenance.

The wellhead technology ensures that energy demand is met in a shorter period and economically. The endorsement of the wellhead units comes from the shorter payback period, the drilling and well testing could take approximately 5- 6 months, and construction of the wellhead plant takes six months, disregarding the manufacturing of the units. Compared to higher-capacity plants, only one well is required for the plant. Centralised power stations have a broad or intricate steam field compared to modular plants, leading to higher thermal losses and more material requirements. The Olkaria field's wellhead plants are in a unique ecosystem where wildlife and geothermal coexist. The amount of land required for the plant is minimal without an elaborate steam field.

These plants are optimised and designed for the specific wells based on the parameters to maximise output. The wellhead operation is manageable since the outage of one plant does not result in transmission distribution to a greater extent than larger plants. Also, the admittance of a single wellhead does not require changes in the power grid. The unit can adapt to the working conditions of frequent start and stop, which brings convenience to the operation and scheduling of the entire power grid. These plants have portability and are easily moved to other wells in case of the well decline. The plants are skid mounted, which eases the disassembly and assembly of the plant[10],[11].

2.1 Plant Description

2.1.1 Single flash plant

Single-flash geothermal plants are used in liquid-dominated fields and have the highest installed capacity worldwide [12]. The flashing process involves transforming high-pressurised geothermal fluid to a mixture of liquid and vapour by lowering pressure to below the saturation pressure of the geo-fluid. This process can occur as the fluid moves through the permeable rock formation as the fluid gets to the wellhead, resulting from pressure losses from gravity and friction loss or at the separator inlet from the throttling process [13]. The flashing process takes place as the fluid enters the separator. The separation is because of the different densities of the fluid and steam. Power generation utilises the separated steam while separated brine is disposed of through reinjection as hot or cold brine.

Modular or wellhead geothermal plants utilise the concept of single flash. This study analyses a low-pressure turbine for the double flash and flash binary for further energy extraction from the separated brine in the single flash plant. The geothermal fluid temperature in the Olkaria field is above 200 degrees and is re-injected at reasonably high temperatures, which can be utilised further for power generation or direct uses. The utilisation of the separated brine may result in higher output without immense changes in cost, primarily emanating from the drilling process and the abatement of environmental impacts.

The modular plants have approximately an installed capacity of 81.1 MW. The units are C50 (5 MW) and C64 (two turbines of 3.2 MW each). The wellhead (modular) plant illustrated in Figure 1 and used in the case study is a single flash plant [51]. The plant directly taps from the well eliminating an extensive steam gathering system. The basis of the wellhead concept is the ease of mobilisation, demobilisation and faster return on investment against the conventional plants that take several years to develop.

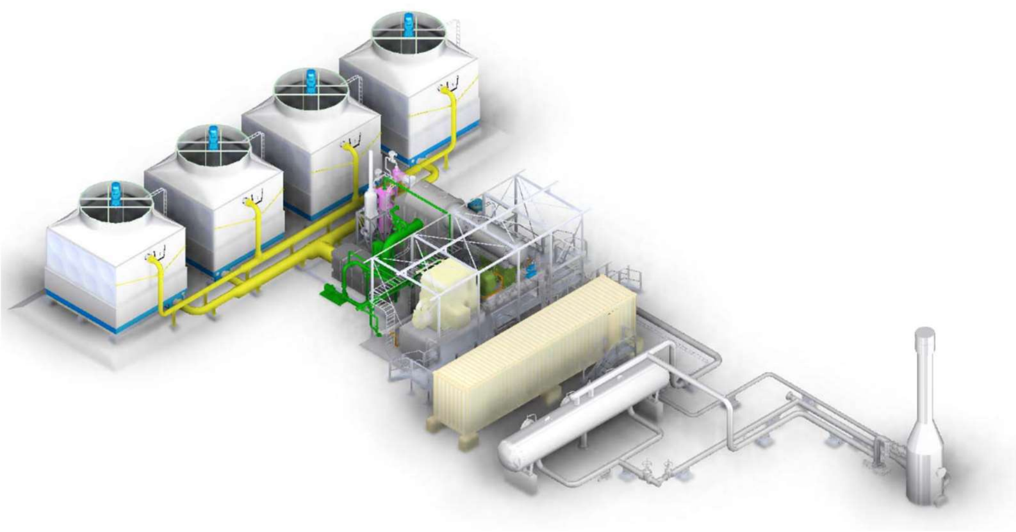

Figure 1 Main components of c50 wellhead plant -Green Energy Group

The components of the wellhead units are similar to the conventional single flash plant. The unit components in Figure 2 are:

i. The hot end, which is the production well, steam separator, steam gathering system and silencer,
ii. The second subsystem has the turbine and generator
iii. The third subsystem is the cold end which has the condensing system, gas extraction system and cooling towers.
iv. The fourth system has an electrical and control system.

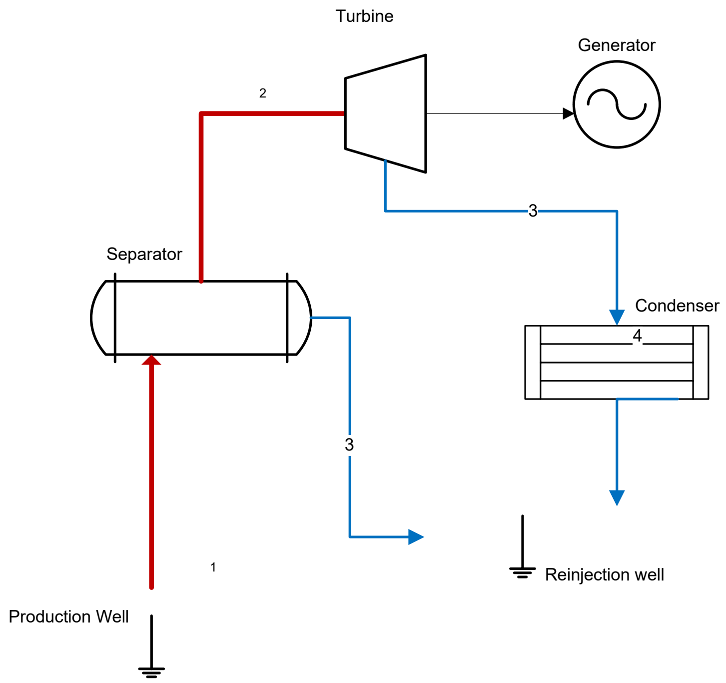

Figure 2 Geothermal modular plant layout

In Figure 2, the two-phase fluid (1) leaves the production well. Next, the fluid goes to the separator, where it is separated, and steam (2) goes to the turbine for power generation. When steam leaves, it moves to the condenser (3), cooled at (6), and the cooling fluid leaves at (7). Finally, the condensed fluid (4) and brine from the separator (5) are re-injected into a reinjection well.

2.1.2 Double flash plant

The proposed plant in Figure 3 and Figure 4 show the utilisation of the separated brine in lower pressure turbine for a double flash plant and heat exchanger for the proposed flash binary plant.

The double flash plant is the dual flashing process of geothermal fluid. Figure 3 shows an arrangement where geothermal fluid is flashed twice at different pressure. The structure is of a bottoming plant where waste brine from the first unit is utilised in the other units at lower pressure [13]. The number of flashing processes may depend on the initial temperature of the fluid.

The process of double flash, in Figure 3 and Figure 4 [13], represents dual flashing of separated brine at different pressure. The geothermal fluid from the well has a high temperature, denoted as 1 in Figure 4. The fluid goes through the flashing process with temperature reduction. The super-heated steam and compressed liquid are separated in the separator, and the steam is pushed to the turbine at point 4. The steam expands in the turbine at constant pressure. The compressed liquid undergoes the second flashing process at lower pressure 6-7, resulting in steam utilised in the lower pressure turbine at point 8. The steam from the high-pressure and low-pressure turbine collects at the condenser as a mixture of liquid vapour before disposal.

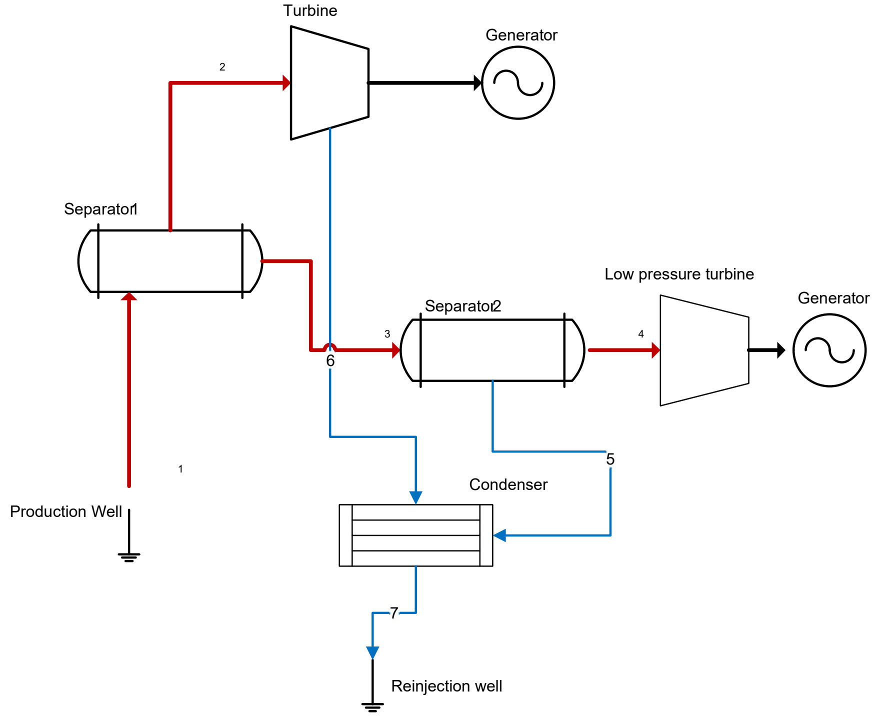

Figure 3 Proposed double flash plant

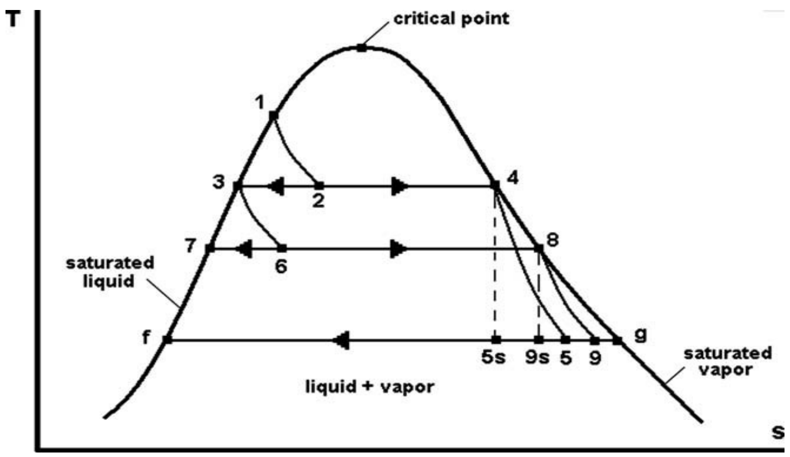

Figure 4 Temperature entropy diagram for the double flash plant

2.1.3 Flash binary plant

The flash-binary plant Figure 5 integrates the process of the flash plant and a binary plant. The binary plant is attached to an existing flash plant. The geothermal fluid enters the wellhead and goes through the flashing process at point 2 before entering the separator. The super-heated steam and compressed liquid separate at the separator based on their different densities. The super-heated steam is utilised in the turbine, like in the single flash; the process is at constant pressure at points 4-5. The separated liquid, organic fluid, is redirected to a heat exchanger, which heats a secondary fluid. The secondary fluid works in a closed cycle. The geothermal fluid heats it to the critical point, evaporating the organic fluid and turning the turbine at constant pressure. The working fluid is selected based on thermodynamic properties, critical temperature and pressure, safety and environmental impacts [13]. The cooling process occurs in the condenser, 6-7, before reinjection.

Binary plants, as bottoming plants, utilise waste heat from the separator or otherwise before entering the condenser. The bottoming cycles increase the efficiency of the plants and the overall output of the plant [13].

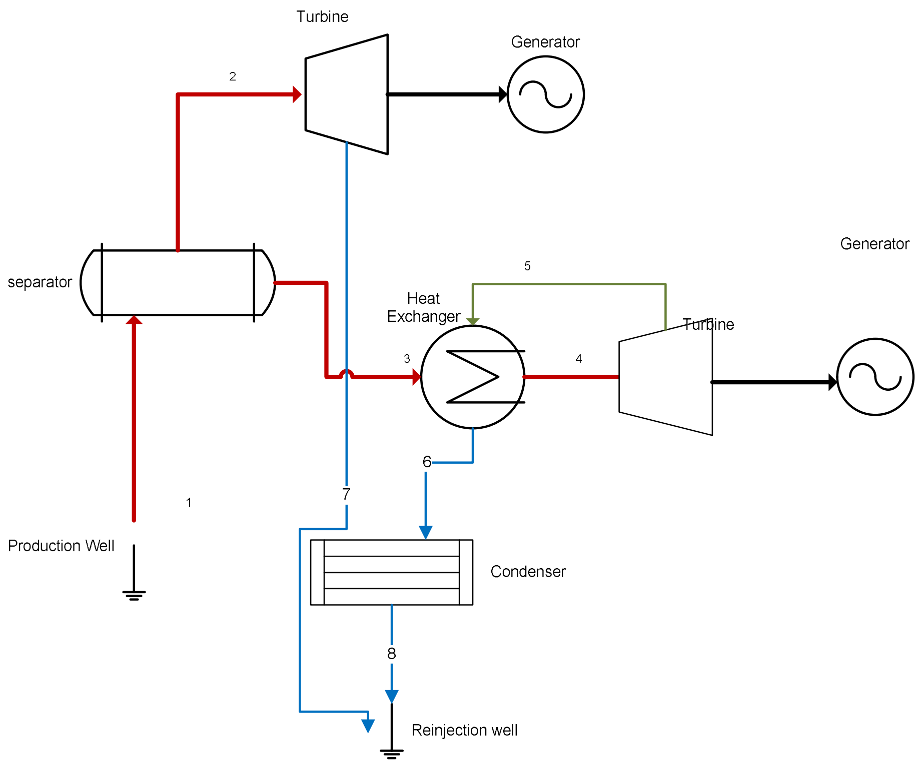

Figure 5 Proposed flash-binary plant

Chapter 3

Exergy, Economy and Environment

Exergy, economic and environmental concepts are associated with energy systems optimisation. Various terms are used in the study of the three and their interaction in energy systems. Exergy-economic and exergy-environmental analysis demonstrate the implication of the exergy, economics and environment relationship. The exergetic values of an energy conversion system are systematically assigned monetary values and assigned weighted environmental effect ratings. The exergy-economic analysis focuses on overall costs associated with exergy, while the exergy-environmental focuses on the environmental impacts.

There is an interrelation between investment costs, environmental impacts and exergy destruction. High investment costs do not directly mean lower environmental impacts because the materials and energy utilised to develop higher-efficiency machines increase while there is an increase in exergy destruction and environmental impacts[14]. The two analysis methods can be used in design processes to ensure optimal designs for energy systems. Thermodynamic inefficiencies lead to high fuel consumption, increasing environmental impacts and costs. Otherwise, minimising the inefficiencies increases the materials and energy requirements for redesigned components with higher efficiency. Exergy analysis demonstrates the potential that is not used. This is due to internal irreversibility associated with the second law of thermodynamics. Exergy methods evaluate and improve efficiency, improving sustainability[1] .

Exergo- economic and thermo-economic involves identifying and evaluating cost formation and flow of these costs in an energy conversion system [16]. It combines a financial system assessment with exergy and energy analysis, respectively. The concept aims to identify areas of system optimisation regarding cost and improved thermodynamic efficiency. However, changes to ensure thermodynamic efficiency often increase costs [16]. It entails calculating costs relating to the system and depends on the accounting principle, which involves estimating total capital investment and calculating total revenue requirements (operational, maintenance and disposal costs) land the levied product costs [2].

The exergy-environmental analysis focuses on the environmental impacts associated with the operation of a system. Firstly, the study involves exergy analysis. The second step is determining the environmental impacts through the application of LCA. Thirdly, exergy-environmental variables are calculated, and evaluation is carried out [2]. Then allows areas of improvement to be identified for environmental performance. Finally, materials and exergy streams' specific environmental impact rates are calculated. The exergy-environmental variables developed indicate the potential for reducing the environmental impact associated with a system [2].

An exergy-economic study conducted by Bina et al. on a single and double flash system involved economic and thermodynamic analysis of a geothermal energy system in Sabalan, Iran. The research involved energy and exergy economic analysis. The double flash system had higher energy and exergy efficiencies for individual components and higher electrical output. The single flash had lower total costs and production cost rates than the double flash system. The environmental benefits were studied based on the reduction of fossil fuel savings and pollutants because of the utilisation of geothermal, which has more significant benefits than fossil fuel-based plants. The single flash plant has a lower price, while the decrease in fossil fuel requirement and pollutants is higher in the double flash plant[17].

A study on exergetic analysis and optimisation of geothermal double flash systems coupled with reheating [18] was analysed. The geothermal fluid enters the cyclone separators, and steam is sent to the high-pressure turbine; the separated brine moves to the reheater before being pushed to the low-pressure turbine. The analysis included the performance with interstage moisture removal, silica precipitation and enthalpy effects on the system. In addition, they compared this to a basic double flash system. Exergy analysis showed the areas of major exergy losses, the addition of the reheater to the system contributed to exergy loss, and the payback for the expansion was a relatively short period [19].

DORA 1 and DORA2 power binary cycles in the Aydin Geothermal field were studied [20]. The study entailed energy, exergy and exergy-economic analysis. The net power generated changed with air temperature changes. Energy and exergy analysis was conducted for all components in the cycles. The study [21] involved basic ORC, dual-pressure ORC, dual-fluid ORC and the Kalina cycle for power generation from the geothermal fluid. The components were analysed for maximum electrical power output and minimum cost output. The study concluded that the dual pressure ORC had the highest electrical output of the systems analysed, while the Kalina cycle resulted in the minimum unit cost of power [21].

A trigeneration system [22] composed of a micro gas turbine prime mover with a topping (based on the Brayton cycle), an ORC (Bottoming cycle) and a single-effect absorption chiller was studied. The purpose is the provision of cooling, domestic hot water production, and electricity generation. The research aimed to perform thermodynamic modelling and exergy and environmental analysis. The study identified the relationship between exergy efficiency, exergy destruction, and the sustainability index. The trigeneration system had higher exergy efficiency than combined heat and power systems, gas turbine cycles, and less carbon dioxide emissions. The combustion chamber and the heat exchanger had the highest exergy destruction due to temperature differences in heat transfer and combustion processes. The efficiency of the system and sustainability index were affected by the compressor pressure ratio and the turbine inlet temperature. [22].

An exergy-environmental analysis of a binary geothermal plant in Turkey was conducted [23]. The research involved evaluating the equipment (construction, operation/maintenance, and disposal) of exergy destruction and pollution. The study also analysed the effects of ambient and brine input temperatures concerning environmental impact factors on the system. Exergy analysis, life cycle assessment and exergy-environmental analysis correlating environmental impacts with exergy streams are conducted. The study demonstrated that 38.1% (21.03Mw) of exergy was utilised for energy production. The highest environmental impacts were associated with exergy destruction and NCG, majorly CO2 emissions. The total environmental impact was 2284.7 Pts/h. The plant had an environmental impact of electricity of 0.108 Pts/kWh for power generation of 21Mw [23].

Research on the cost of environmental externalities using the case of Reykjanes, Iceland and Vendenheim, France [24] was conducted. Environmental lifecycle costing ensured the entire lifecycle was catered for while including environmental externalities. The categories included investment, operation and maintenance, end of life or disposal and externalities. The deep-drilling geothermal project involved the drilling of one well in

Reykanes and the other project involved two wells drilled in Vendenhein France. The life cycle impact factors were converted into economic costs for externalities using the ReCiPe approach. The study involved the conversion of environmental impacts to economic cost value. The environmental externalities incorporated into the operation phase were greenhouse gases and other pollutants. The externalities cost derived from various sources were both costs, such as municipality costs and probabilistic costs calculated from multiple studies. Costs linked to externalities in the case study account for 2% of the total environmental life cycle cost [24]. The ELCC of the Reykjanes project was estimated between 14.47–15.78 million euros compared to Vendenheim project, which was between 91.90-113.97 million euros, with investment and well drilling projected to constitute 83% of these amounts.

Exergy and exergy-environmental analysis of Castelnuovo pilot project in Italy was carried out [25]. The 5 MWe ORC plant design consisted of two production wells and one reinjection well. The research aimed at demonstrating complete reinjection of the resource (brine and NCGs). It was estimated that the NCG mass content was about 8%, of which 7.8% was CO2 and 0.2% was H2S. The highest exergy destruction was at the heat exchanger. From the LCA, the total environmental impact associated with electricity production was 3.20 Pts/MWh. The highest impact was related to drilling, contributing approximately 87.6% of the total impact. 2.81Pts/MWh attributed to the utilisation of diesel in drilling. In the power plant, the main heat exchanger had the highest total environmental impact in the operation phase, with 15% of the total impact associated with environmental cost in construction and 85% associated with exergy destruction.

Another similar study [26] was based on developing geothermal resources at Torre Alfina (IT) Site in Italy, a binary cycle with five production wells and four reinjection wells. The two systems analysed were the use of isobutane (subcritical) and R1234yf (supercritical) fluids in the ORC. Exergy and energy analysis was conducted then the LCA and exergy-environmental analysis was carried out. From the study, using the supercritical cycle results in the more effective use of the geothermal brine. The cycle heat requirement was reduced, lowering the geothermal resource's impact. Higher exergy efficiency was also evident, coupled with lower exergy destruction. The research showed a slight difference while using subcritical and supercritical fluids. The heat exchanger, condenser, and reinjection pump were noted with possible improvements. The aspect of reinjection of the NCGs gases showed an improvement in environmental impacts as compared to wind and solar projects. The drilling of the wells had the most significant environmental impact compared to the power plant.

In four geothermal power cycles, the simple ORC, single flash, double flash, and flash-binary [27] plant configurations were analysed based on energy, exergy, and exergy-economic performance. Multi-objective optimisation of the configurations was carried out, and sensitivity analysis was performed on the effect of production well temperature variations on the energy, exergy, and economic parameters. From the study, it was concluded that the flash-binary cycle had the highest thermal and exergy efficiency. On the other hand, the ORC recorded the highest generated power cost and payback period[27].

A study was conducted on a geothermal combined heating and power system [28]. The geothermal fluid was utilised to heat the ORC working fluid for power generation. The geothermal brine was then used to heat water for a radiant floor heating system. Multi-objective optimisation was conducted to obtain the maximum power output, minimum Levelized cost per exergy unit and minimum levelized environmental impact per exergy unit. The cooling water had the highest Levelized exergy cost, and the heat exchanger in the system had the highest environmental impact-reducing potential. The optimal system is based on an 11 °C super-heat degree and 833 kPa ORC turbine inlet pressure, with the net power output recorded as 1.19 MW. The Levelized cost per exergy unit was 4.80 $/GJ and the environmental impact per exergy unit 16.0 mpts/GJ were recorded.

Two ORC units were compared: Conventional ORC and ORC with Internal Heat Exchanger [17]. The study investigated the optimisation of the systems to achieve the maximisation of thermodynamic efficiency and minimisation of production cost rate and environmental benefits. Comparative analysis for the two cycles was studied to achieve optimal results. Cost changes and thermodynamic efficiencies were observed with changes in operating conditions, such as changes in turbine inlet and outlet pressure or condenser temperature. The study presented a case where a higher output was achieved in the conventional ORC with lower condenser temperatures and a bigger heat exchanger, which resulted in higher costs. The Internal Heat Exchanger ORC had the highest energy and exergy efficiencies, and the geothermal fluid exiting the heat exchanger had higher temperatures. The system's environmental benefits were calculated based on annual fossil fuel requirements for production and avoided greenhouse gas emissions. The exergy destruction was the highest at reinjection for both cycles, with higher exergy efficiency in the internal heat exchanger ORC cycle. The cycle had higher environmental benefits and thermo-economic results [17].

A trigeneration energy system that consisted of a gas cycle, steam cycle, ORC, and absorption carbon capture monoethanolamine (MEA) system assessed the system; Energy, exergy, economic, exergo-economic, exergo-environmental (5E) analysis [29]. The analysis investigated the efficiency of the system as well as waste heat recovery and the effect of the carbon capture system on the analysis. The carbon capture system decreased this efficiency due to the utilisation of power for the system. In terms of economic indicators, the CCS increased the payback period resulting from the decrease in production as part of the energy produced in the steam cycle is utilised in the CCS. The steam turbine had the highest cost rate associated with exergy destruction at about 1.165 $/s. Other components with high exergo-economic factors were the steam cycle evaporator, combustion chamber, carbon capture system and gas turbine. Exergo-environmental analysis shows that about 627,000 metric tons of CO2 emissions are avoided [29].

A study [30] on exergo-economic and exergo-environmental analysis on energy systems and coupling it with emergy concept, exergoeconoenvironmental involved a gas turbine-based cogeneration system with the plant's main components being the air compressor, an air preheater, a combustion chamber, a gas turbine, and a heat recovery steam generator. The research proposed a framework to assess a system's thermodynamics, economics and environmental viability. The framework was based on the eco-costs/value ratio concept attributed to sustainability. The Eco costs represent the prevention costs of the environmental burden of a product and the value represents the actual costs to the market. A low exergoeconoenvironmental factor indicates that the eco-cost/value ratio synonyms with exergy destruction eco-costs/value ratio is higher than that of a specific component's design and construction phase. The eco-costs/value ratio based on exergy destruction is compared to the component-related eco-costs /value ratio. An exergoeconoenvironmental factor with a lower value means that the component's exergy destruction eco-costs/value ratio is more significant than its design and construction eco-costs/value ratio.

Chapter 4

Exergy and Economic Analysis

This chapter describes the analysis of exergy and economic analysis for the proposed plants, the double flash plant and flash-binary plant. The chapter has the study framework, energy and exergy analysis, and profitability assessment.

4.1 A framework of the study

The study involves conducting an economic and environmental assessment while utilising principles of specific exergy costing analysis and life cycle assessment. The below diagram shown in Figure 6 [31] outlines the process of the study follows.

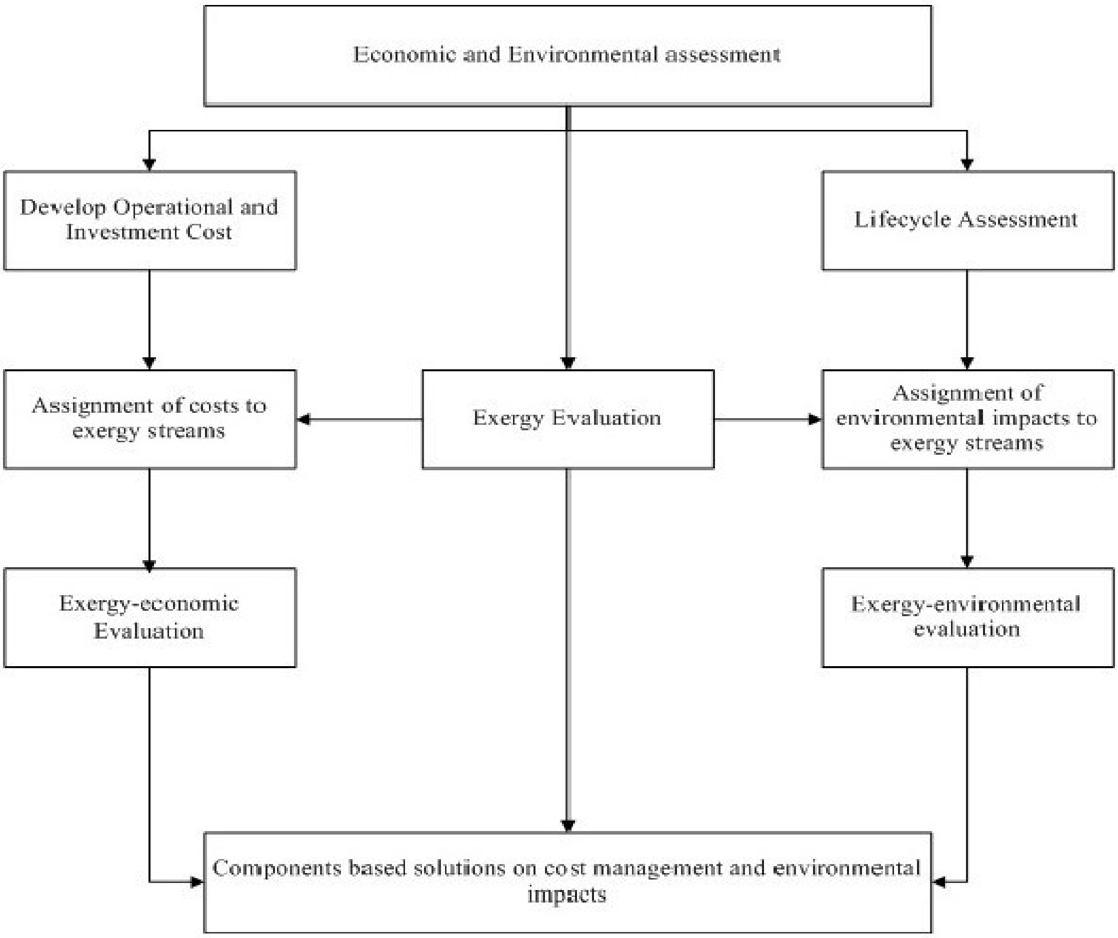

Figure 6 Framework for economic and environmental assessment

4.2 Energy and Exergy analysis

Exergy is the maximum useful work obtained from a substance in specified thermodynamic surroundings, this implies that the investigated system experiences no losses or friction and that the fluid has no potential for more work [21]. Exergy measures the potential to cause change because of not being in a stable environment relative to the reference environment. The analysis is beneficial in identifying the area of exergy efficiency improvement [1].

The exergy and economic analysis are based on the Specific Exergy Costing (SPECO) principles. It involves determining the exergy streams of the system, defining fuel and product and developing cost equations [32].

Energy and exergy analysis is based on various equipment or components of the system. The energy rate balance equations are the following:

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{4.1}$$

$$\sum (\dot{m}h)_i + \dot{Q} = \sum (\dot{m}h)_e + \dot{W} \tag{4.2}$$

Where i and e represent the inlet and outlet, and $\dot{m}$, h, Q and $\dot{W}$ are mass flow rate (Kg/s), enthalpy (kJ/kg), heat transfer and work, respectively. The energy balance equations for the cycles are given in Table 1.

The exergy flow rate is calculated with equation 2.3.

$$\dot{E}x = \dot{m}(ex) \tag{4.3}$$

The specific exergy rate:

$$ex = (h - h_0) - T_0(s - s_0) \tag{4.4}$$

The exergy balance for the kth component is.

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \tag{4.5}$$

Where $\dot{E}_{P,k}$the exergy of the product of the kth component is, $\dot{E}_{F,k}$ is the exergy of fuel.

The exergy destruction rate is equal to the:

$$E_{D,K} = T_0 S_{gen,k} = T_0 m_k S_{gen,k}$$

4.6

Exergy is destroyed because of irreversibility in the system. The exergy destruction above is calculated from the entropy balance. If $E_{D,K}$ is equal to zero, the process is ideal.

For the overall system, the exergy balance is calculated as follows:

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \sum_{k=1}^{n} \dot{E}_{D,k} + \dot{E}_{L,tot}$$

4.7

Exergetic efficiency of the kth component

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}}$$

4.8

Exergy destruction ratio.

$$y_k = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$$

4.9

While exergetic efficiency of the overall system

$$\varepsilon_{tot} = \frac{\dot{E}_{P,tot}}{\dot{E}_{F,tot}} = 1 - \sum_{k=1}^{n} y_k - \frac{\dot{E}_{L,tot}}{\dot{E}_{F,tot}}$$

4.10

The mass and energy rate balance equations for the proposed double flash and flash-binary plants shown in Figure 3 and Figure 5, respectively, are given in Table 1.

Table 1 Mass and energy balance equations of. the proposed plants

Component	**Energy rate balance equation**
Double Flash system	
Separator	$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_4 h_4$
Turbine 1	$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{W}_{T1}$
Expansion valve 2	$h_4 = h_5$
Separator 2	$\dot{m}_5 h_5 = \dot{m}_6 h_6 + \dot{m}_9 h_9$
Turbine 2	$\dot{m}_6 h_6 = \dot{m}_7 h_7 + \dot{W}_{T2}$

Condenser	$\dot{Q}_{Cond} = (\dot{m}_3 h_3 + \dot{m}_7 h_7) - \dot{m}_8 h_8 = \dot{m}_{cw}(h_{11} - h_{10})$
Flash Binary system	
Expansion Valve 1	$h_1 = h_2$
Separator 1	$\dot{m}_1 h_1 = \dot{m}_2 h_2 + \dot{m}_4 h_4$
Turbine 1	$\dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{W}_{T1}$
Condenser 1	$\dot{Q}_{Cond} = (\dot{m}_3 h_3 + \dot{m}_5 h_5) - \dot{m}_9 h_9 = \dot{m}_{cw}(h_{11} - h_{10})$
Heat Exchanger	$\dot{Q}_{Hex} = \dot{m}_{wf}(h_6 - h_8) = \dot{m}_{gf}(h_4 - h_5)$
Turbine 2	$\dot{m}_6 h_6 = \dot{m}_7 h_7 + \dot{W}_{T2}$
Condenser 2	$\dot{Q}_{Cond} = \dot{m}_{wf}(h_7 - h_8) = \dot{m}_{cw}(h_{13} - h_{12})$

The exergy destruction rates Table 2:

Table 2 Exergy Destruction Equations for the double flash and flash-binary plants

Components	**Exergy destruction**
Double Flash system	
Separator1	$\dot{E}xD_{sep} = \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_4$
Turbine 1	$E\dot{x}D_T = \dot{E}x_2 - \dot{E}x_3 - \dot{W}_T$
Expansion valve 2	$ExD_{Ev} = \dot{E}x_4 - \dot{E}x_5$
Separator 2	$\dot{E}xD_{sep2} = \dot{E}x_5 - \dot{E}x_6 - \dot{E}x_9$
Turbine 2	$\dot{E}xD_{T2} = \dot{E}x_6 - \dot{E}x_7 - \dot{W}_{T2}$
Condenser	$\dot{E}xD_{cond} = \dot{E}x_3 + \dot{E}x_7 + \dot{E}x_{10} - \dot{E}x_8 - \dot{E}x_{11}$
Flash-Binary system	
Separator 1	$\dot{E}xD_{sep} = \dot{E}x_1 - \dot{E}x_2 - \dot{E}x_4$
Turbine 1	$E\dot{x}D_T = \dot{E}x_2 - \dot{E}x_3 - \dot{W}_T$
Condenser 1	$\dot{E}xD_{cond} = \dot{E}x_3 + \dot{E}x_7 + \dot{E}x_{10} - \dot{E}x_8 - \dot{E}x_{11}$
Heat Exchanger	$\dot{E}xD_{Hex} = \dot{E}x_3 + \dot{E}x_7 + \dot{E}x_{10} - \dot{E}x_8 - \dot{E}x_{11}$
Turbine 2	$\dot{E}xD_{T2} = \dot{E}x_6 - \dot{E}x_7 - \dot{W}_{T2}$
Condenser 2	$\dot{E}xD_{cond} = \dot{E}x_7 + \dot{E}x_{12} - \dot{E}x_8 - \dot{E}x_{13}$

The parameters for the 5 Mwe plant are listed in Table 3. These are based on the well parameters and manufacturer specification (GEG). The reference conditions are specified as follows; the temperature is 25◦ C, and at sea level, that is, pressure at 1 atm.

Table 3 Well and plant parameters

Parameter	**Value**	**Units**
Separator pressure	13	bar
Turbine Inlet pressure	13	bar
Two-phase flow	77	tph
Steam flow rate	44	tph
Brine flow	33	tph
Plant Rating	5.5	Mw

4.3 Economic analysis

The economic analysis in this chapter relates to the cost of a product which affects the design and operations of a plant. It involves calculating the location, magnitude and cost of thermodynamic inefficiencies. As noted earlier, exergy analysis evaluates the useful energy that is converted into work. The cost represents the monetary value associated with the use of energy. The purpose is to identify the optimal design and operation to minimise cost subject to energy and environmental conditions [33].

The exergy costing principle asserts that exergy is the rational basis for assigning cost values to thermal systems [32]. It involves the determination of cost balances for each component separately, based on exergy transfer and power (W). The sum of exiting exergy streams equals the sum of exergy entering streams plus the components' capital cost, operation and maintenance costs. The below equations depict the relationships.

$$\dot{C}_i = c_i \dot{E}_i = c_i \dot{m}_i e_i \qquad 4.11$$

Where c_i denotes the average cost per unit of exergy, $\dot{C}_i$ is the cost stream associated with the corresponding exergy stream and is denoted by the mass-related specific exergy.

$$\sum_e c_e \dot{E}_e + c_{w,k}\dot{W}_k = c_q \dot{E}_{q,k} + \sum c_i \dot{E}_{ik} + \dot{Z}_k \qquad 4.12.$$

The operating and maintenance factor can be calculated as follows:

$$\dot{Z}_k = \frac{\dot{Z}_k CRF\varphi}{N3600} \qquad 4.13$$

Zk, φ and N denote the investment cost of the kth component ($) respectively, the maintenance cost factor of 1.06, [21] and the annual plant working hours (capacity factor 0.85), which are 7446 h. CRF is defined [21] as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad 4.14$$

Capital Recovery factor (CRF) is derived from the interest rate *i,* which is 9% and n, the plant's lifetime, which is ten years.

The cost associated with exergy destruction is:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \qquad 4.15$$

The CEPCI (Chemical Engineering Plant Cost Index) is applied to consider annual inflation. This index is updated to the year 2021 [34]:

$$PEC_k = Z_k \times \left(\frac{CEPCI_{2021}}{CEPCI_{2017}}\right) \quad 4.16$$

Computation of the capital costs for the components of the plants are in Table 4:

Table 4 Capital costs for the components

Component	Cost correlation	Reference
Separator	$Z_{sep} = 280.3 \times (\dot{m})^{0.67}$	[35]
Turbine	$Z_T = 6000 \times (\dot{W}_T^{0.7})$	[35],[29]
Condenser	$Z_{Cond} = 1773\dot{m}$	[21]
Heat exchanger	$Z_{HX}=130\ (A_{HX}/0.093)^{0.78}$	[36]
Expansion valve	$Z_{EV} = 114.5 \times \dot{m}$	[35]

The unit cost of exergy for the geothermal resource is assumed to be 1.3$/GJ [21]. The cost rate balance equations are determined by applying economic analysis as a function of fuel and the sum of operating and maintenance costs.
The cost equations for the systems are as Table 5 :

Table 5 Cost equations

	Cost flow rate equations
Double flash system	
Separator1	$\dot{C}_1 + \dot{Z}_{sep1} = \dot{C}_2 + \dot{C}_4$
Turbine 1	$\dot{C}_3 + \dot{C}_{W,Tur} = \dot{C}_2 + \dot{Z}_{Tur}$
Expansion valve 2	$\dot{C}_5 = \dot{C}_4 + \dot{Z}_{Ev}$
Separator 2	$\dot{C}_6 + \dot{C}_9 = \dot{C}_5 + \dot{Z}_{Sep2}$
Turbine 2	$\dot{C}_7 + \dot{C}_{W,Tur2} = \dot{C}_6 + \dot{Z}_{Tur2}$
Condenser	$\dot{C}_8 + \dot{C}_{11} = \dot{C}_7 + \dot{C}_{10} + \dot{Z}_{Con}$
Flash-binary system	
Separator1	$\dot{C}_1 + \dot{Z}_{sep1} = \dot{C}_2 + \dot{C}_4$
Turbine 1	$\dot{C}_3 + \dot{C}_{W,Tur} = \dot{C}_2 + \dot{Z}_{Tur}$
Condenser 1	$\dot{C}_9 + \dot{C}_{11} = \dot{C}_3 + \dot{C}_7 + \dot{C}_{10} + \dot{Z}_{Con}$
Heat exchanger	$\dot{C}_4 + \dot{C}_8 = \dot{C}_6 + \dot{C}_5 + \dot{Z}_{Hex}$
Turbine 2	$\dot{C}_7 + \dot{C}_{W,Tur2} = \dot{C}_6 + \dot{Z}_{Tur2}$
Condenser 2	$\dot{C}_7 + \dot{C}_{12} = \dot{C}_8 + \dot{C}_{13} + \dot{Z}_{Con2}$

4.3.1 Indices

The exergy destruction rate of a component in the system represents inefficiency and helps identify elements ideal for cost minimisation while maximising efficiency in the overall system [33].

The relative cost difference expresses the increase in the average cost per energy unit between fuel and the product of the component [37]. Figure 7 [33] shows that the capital investment per unit of exergy increases with a decrease in the exergy destruction. The shaded area shows the range by which the investment cost and exergy destruction rate can vary. The component to be considered should be such that there is lower exergy destruction at lower investment costs. The selection of a component is based on two aspects, components that exhibit an increase in the investment cost or constant investment cost with increased exergy destruction are not ideal for optimisation. The selection should be based on a considerable reduction of exergy destruction at a reasonable investment cost [33].

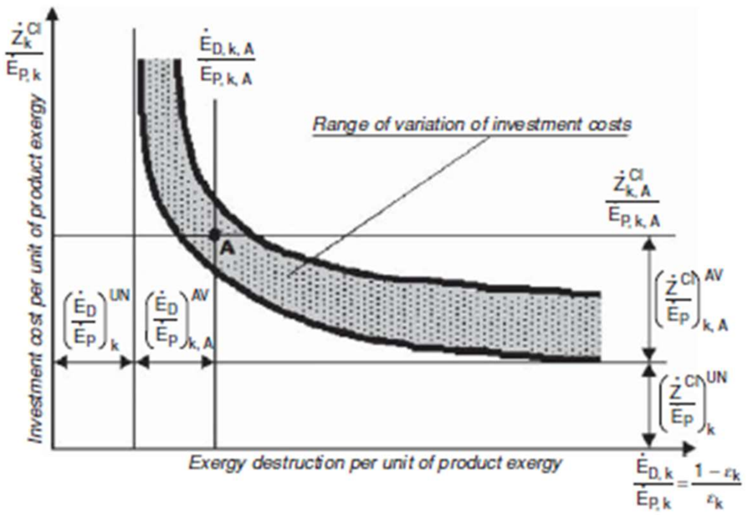

Figure 7 Relationship between investment cost and exergy destruction

The relative cost difference and exergy-economic factor are expressed as follows [35]:
Relative cost difference

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \quad 4.17$$

Exergoeconomic factor:

$$f_k = \frac{\dot{Z}_K}{\dot{Z}_k + \dot{C}_{D,k} + \dot{C}_{L,k}} \quad 4.18$$

The exergy-economic factor (f_k) indicates the investment viability in each component. It compares capital costs and exergy destruction cost rates for equipment [38]. A low f_k

value implies that the costs associated with irreversibility are significant compared to the capital cost of the equipment.

A high value of the exergy-economic factor shows that the investment costs for a component are high. In contrast, a low value suggests that cost savings in the entire system can be achieved by improving the efficiency of a component, that is, reducing exergy destruction even if the capital investment for this component increases [39].

4.3.2 Profitability analysis

Return on investment-(ROI) is the net profit to total cost of investment ratio.

$$ROI = \frac{(1 - t_{corp})(S_{annual} - C_{TPC}}{C_{TCI}}$$

4.19

Where:
S_{annual}-annual sales revenue
C_{TPC}-total production cost
C_{TCI} -total capital investment
t_{corp} -corporate tax

The corporate tax is 30%, and a feed-in tariff of 0.088 $/kWh. The availability factor of the plant is 0.85.

The investment and operational cost for the proposed plants during the lifetime are in Table 6 [35]

Table 6: Investment and operational costs

Cost components	Equations
Cost of wages and benefits, C_{WB}	C_{WB}= 0:035C_{TDC}
Cost of salaries and benefits, C_{SB}	C_{SB}=0:25C_{WB}
Cost of materials and services, C_{MS}	C_{MS}=C_{WB}
Cost of maintenance overhead, C_{MO}	C_{MO}=0.05C_{WB}
Direct manufacturing costs, C_{DMC}	C_{DMC} = C_{WB}+C_{SB}+C_{MS}+C_{MO}
Cost of property taxes and liability insurance, C_{PI}	C_{PI}=0.02C_{TDC}
Fixed manufacturing costs, C_{FIX}	C_{FIX}= C_{PI}
Total annual cost of manufacture, C_{COM}	C_{COM}=C_{DMC}+C_{FIX}
General expenses, C_{GE}	$C_{GE}=0$
Total production cost, C_{TPC}	$C_{TPC}=C_{COM}+C_{GE}$

The payback period is calculated as the number of years to get a positive investment return.

$$PBP = \frac{C_{TDC}}{Cahflow} = \frac{C_{TDC}}{(1-t)(S_{annual} - C_{TPC} + C_D} \tag{4.20}$$

The depreciation $C_{D,}$ in this case, is assumed to be zero.

Levelized cost of electricity.

The LCOE indicates the power generation costs for a plant over its lifetime. It is an estimate of the cost of electricity generated [39]. LCOE helps in making comparisons over various modes of generation. The calculation for this is [39].

$$LCOE = \frac{C_{TCI + \sum_{t=1}^{n} \frac{C_{TPC}}{(1+i)^n}}}{\sum_{t-1}^{n} \frac{M_{el}}{(1+i)^n}} \tag{4.21}$$

M_{el} is the electricity output for the lifetime, and the annual interest rate is 9%.

Chapter 5

Environmental Analysis

5.1 Life Cycle Assessment

The environmental analysis involves identifying the environmental impacts associated with a product or service. The Life cycle assessment (LCA) approach follows the process of a product or a service from conception to the end of life [40]. LCA evaluates the environmental impacts related to products or services[23]. LCA is a tool that quantifies environmental impacts and guides the consumption and production of various resources [41].

LCA results are calculated by mapping all emissions and resources and developing potential impacts associated with the resource use or emissions generated [41]. LCA can be utilised for making the comparison of systems and products through the quantification and evaluation of environmental performance. Data requirements for such quantification include by-products, energy consumption, and materials used for the processes [42]. The life cycle stages include raw materials acquisition, design, production, transportation, use, end-of-life treatment, and disposal. LCA involves the analysis of the life stages of a product. These are[43]:

- Cradle to grave: this considers the assessment of the impacts of a product or service from raw materials extraction, transportation, and use to disposal.
- Cradle to the gate: this involves assessing resource extraction to develop the product; the use phase and disposal are omitted.
- Cradle–to–site: the assessment considers the product development and transportation to the use location.
- Cradle to cradle: this is a closed loop, where the concept involves resource extraction, development, use, and end-of-life management regarding reuse or recycling.

The life cycle assessment framework shown in Figure 8 involves the following stages [40],[45]

i. *Goal and scope* - include the study's reason, the system's boundary, the functional unit and the impact assessment methods in the study design.
ii. *Inventory analysis* -this involves data collection for the study purpose. The inventory includes the inputs for the process.
iii. *Impact assessment* - Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
iv. *Interpretation*– This evaluates the inventory and impact of different products and

services.

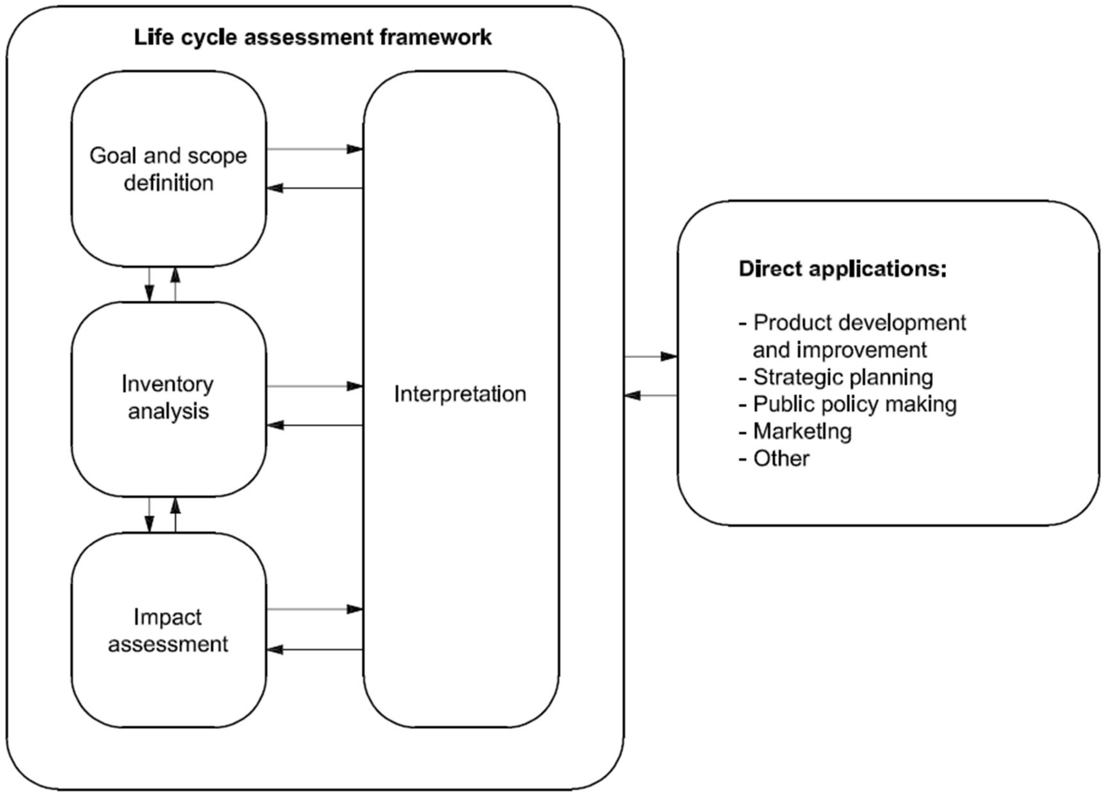

Figure 8 Phases of LCA [45]

5.1.1 Goal and scope

The intention of this LCA is to analyse and forecast the environmental impact of geothermal technology and the impact associated with energy extraction from separated brine for higher electric production. The LCA identifies the components with the highest contribution to the environmental effects concerning exergy destruction.

The system boundary of the study defined in Figure 9 is on the geothermal development process, which are exploration, drilling, construction and operations. The life cycle addresses the drilling, construction and operations, which have various activities, each outlined in Figure 9. The process does not include the disposal phase and transportation.

The drilling phase includes the materials utilised in mud drilling, cementing casing and fuel required for the rig. The construction phase has all the components pertinent to the power plant. These are the separator, turbine and generator, condenser, heat exchanger and cooling towers. The operations phase includes the geothermal fluid, air and freshwater emissions recorded during the plant's lifetime and the power output.

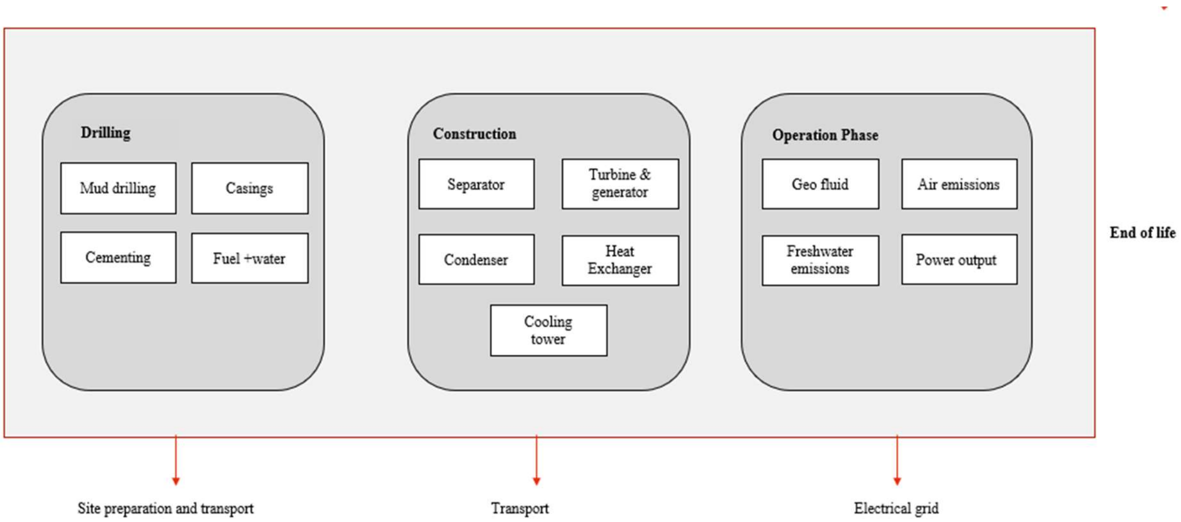

Figure 9 System boundary

The functional unit for the study is MJ. The purpose of the LCA is the feasibility study to investigate the changes in environmental impacts associated with the geothermal system and the related exergy destruction. The objectives of the LCA are as below:

i. Evaluate the environmental impact potential of brine separation for the proposed alternatives, double flash and flash-binary plant.
ii. Compare exergy destruction and environmental impacts of the alternatives and components.
iii. Evaluate energy ratios for the alternatives.

5.1.2 Life Cycle Inventory

The life cycle inventory development starts with defining the product or service development processes. The smallest element in the input-output data is a unit process. A unit process has input flows: materials, energy and resources. The output flows are products, waste and emissions [41]. Elementary flows relate to the use of resources and subsequent release to the air, water or land [40]. The life cycle inventory links the unit processes required for a product or service development [41]. The life cycle inventory is divided into the phases of the projects Figure 9. The source of data determines the accuracy level; these are high (h), moderate (m), and low (l).

Drilling

The wellhead plant utilised for this project is wellhead KWG-09, which started operations on May 2015. The wellhead plant is connected to well OW-915C. This directional well was drilled in the Olkaria field, domes area. The depth was 3010mRKB in 39 days. The inventory of the drilling materials utilised in Table 7 is based on data collected for the well; the primary materials used are captured.

Table 7 Inventory of drilling materials.

Material	Unit	Amount	Accuracy
Drilling bentonite	kg	12340	h
Starch	kg	710	h
Caustic soda	kg	1880	h
Drilling detergent	kg	82000	h
Neat cement	kg	76430	h
Mica flakes	kg	920	h
Fluid loss	kg	110	h
Casing	kg	174376.3	h
Diesel	kg	183000	h
Drilling water-fresh water	kg	65800	h

Construction

The construction phase includes the main power plant components defined in Figure 9, which include the foundation support and pipelines.

The separator installed on the wellhead plant is a horizontal separator with the gravity technique. The two-phase fluid enters the vessel, and gravity separates the steam. The steam goes to the turbine while the brine leaves the separator. The pressure at the wellhead pressure is 13 bar. The separator has an insulation of 60 mm rock wool, a total insulation thickness of 120 mm and is clad with 1,2 mm thick aluminium.

The steam gathering system in the wellhead unit has similar characteristics to a conventional single flash plant, with the only exception being the length of the steam field as the plant is at the well site. The steam field has carbon steel pipes for the two-phase fluid, while steel pipes are for fresh water. The carbon steel pipes are coated with rock wool and aluminium cladding to prevent heat losses.

The turbine is C50, which has a capacity of 5000kW. The turbine's total weight, including the gearbox on skid mounting, is 24,000 kg. Steam from the turbine enters the condenser. At the condenser, steam is mixed with cooling water, which condenses the steam, creating a back-pressure vacuum. The plant has a direct-type condenser with condensing pressure of 0.1 bar and mechanical draft cooling towers.

The second turbine for the double flash and flash binary utilises the parameters of 3200kW turbine, the weight of the turbine, inclusive of the gearbox, is 16 metric tonnes, with the insulation material being fibre glass wool and an aluminium sheet of 1.5 mm.

Table 8 and Table 9 give the quantities for the two systems and the materials utilised in manufacturing the components: the separator, turbine, condenser, heat exchanger and cooling towers. The data was retrieved from manufacturers manuals which includes the weight of the component except for the heat exchanger, which is derived from secondary literature.

Table 8 Inventory of system components double flash plant

Component	Material	Quantity	Accuracy
Separator 1	Steel low alloyed (kg)	13506	h
	Aluminium cladding (kg)	233	m
	Rock wool spiral (m)	8	l
Separator 2	Steel low alloyed (kg)	13506	h
	Aluminium cladding (kg)	233	m
	Rock wool spiral (m)	8	m
Turbine 1	Steel low alloyed (kg)	24000	h
	Aluminium cladding (kg)	207	m
	Cladding fibre glass (kg)	4	m
Turbine 2	Steel low alloyed (kg)	16000	h
	Aluminium cladding (kg)	145	m
	Cladding fibreglass (kg)	3	m
Condenser	Steel low alloyed (kg)	13150	h
Cooling Tower	Steel low alloyed (kg)	7108	h
Foundation/supports	Cement	697.64416	m
	Steel low alloyed (kg)	127914.7826	l
Pipeline	Carbon steel (kg)	236971.5	m
	Stainless steel (kg)	820216	m

Table 9 Inventory of system components flash binary plant

Component	Material	Quantity	Accuracy
Separator 1	Steel low alloyed (kg)	13506	h
	Aluminium cladding (kg)	233	m
	Rock wool spiral (m)	8	l
Turbine 1	Steel low alloyed (kg)	24000	h
	Aluminium cladding (kg)	13150	m
	Cladding fibreglass (kg)	4	l
Heat Exchanger	Steel low alloyed (kg)	840	l
Turbine 2	Steel low alloyed (kg)	16000	h
	Aluminium cladding (kg)	145	m
	Cladding fibreglass (kg)	3	l
Condenser	Steel low alloyed (kg)	13150	h
Cooling Tower	Steel low alloyed (kg)	7108	h
	Cladding glass fibre	16588	m
Foundation/supports	Cement	639.36416	m
	Steel low alloyed (kg)	135044.3478	l
Pipeline	Carbon steel (kg)	236971.5	m
	Stainless steel (kg)	820216	m

Operation

The operations phase involves the utilisation of steam and brine.The constituents calculated in Table 10 are based on the well characteristics and ten years of plant life. The non-condensable gas constituents are based on the design parameters of the turbine. The separated brine is piped into a pond and re-injected into a well.

Table 10 Inventory of operation constituents

Resources	Input/Output	Quantity	Unit
Brine	input	289,080,000.00	kg
Steam	input	385,440,000.00	kg
Cooling tower water	input	9,864,460,800.00	
Emissions to air			
CO_2	output	106,174,301.04	kg
H_2S	output	1,397,990.88	kg
CH_4	output	202,334.98	kg
H_2	output	305,167.56	kg
N_2	output	15,018,319.90	kg
Final waste flows			
Brine (re-injected)	output	282,142,080.00	kg
Steam-evaporated condensate	output	12,204,432.00	kg
Condensate	output	370,793,280.00	kg

5.1.3 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) involves associating the LCI results with impact categories [44]. In addition, the process results in the aggregation of inventory data for interpretation [43]. The LCIA process outlined in Figure 10 [40] is an iterative process with three mandatory steps.

i. Selection- this involves the selection of impact categories, indicators and characterisation model and LCIA methods.
ii. Classification- Inventory results are mapped to relevant impact categories based on the LCIA method [44]. This process is based on the study's goal and scope and justifies the selection of the various models and methods that exist.
iii. Characterisation- this is assigning impact categories to elementary flows from the inventory [41]. The characterisation process translates the LCIA results by allocating scores for each impact category based on the flows [41]. The characterisation process involves assigning a specified environmental impact to a specified environmental stressor. Characterisation aims to ensure that the impact categories are converted to units that can be used for comparison. The midpoint characterisation is concerned with immediate impacts that can be linked to original emissions [44]; these are directly observable concerns [41]. The endpoint impact indicators are concerned with downstream effects. These are concerned with the entire ecosystem. They include human health, ecosystem quality and natural resources and ecosystem services.

For example, greenhouse gas emissions calculations reference carbon dioxide that $kgCO_2$ e/kg 1 kg of methane has 28 kg of carbon dioxide global warming potential in a 100-year timeframe according to IPCC [44].

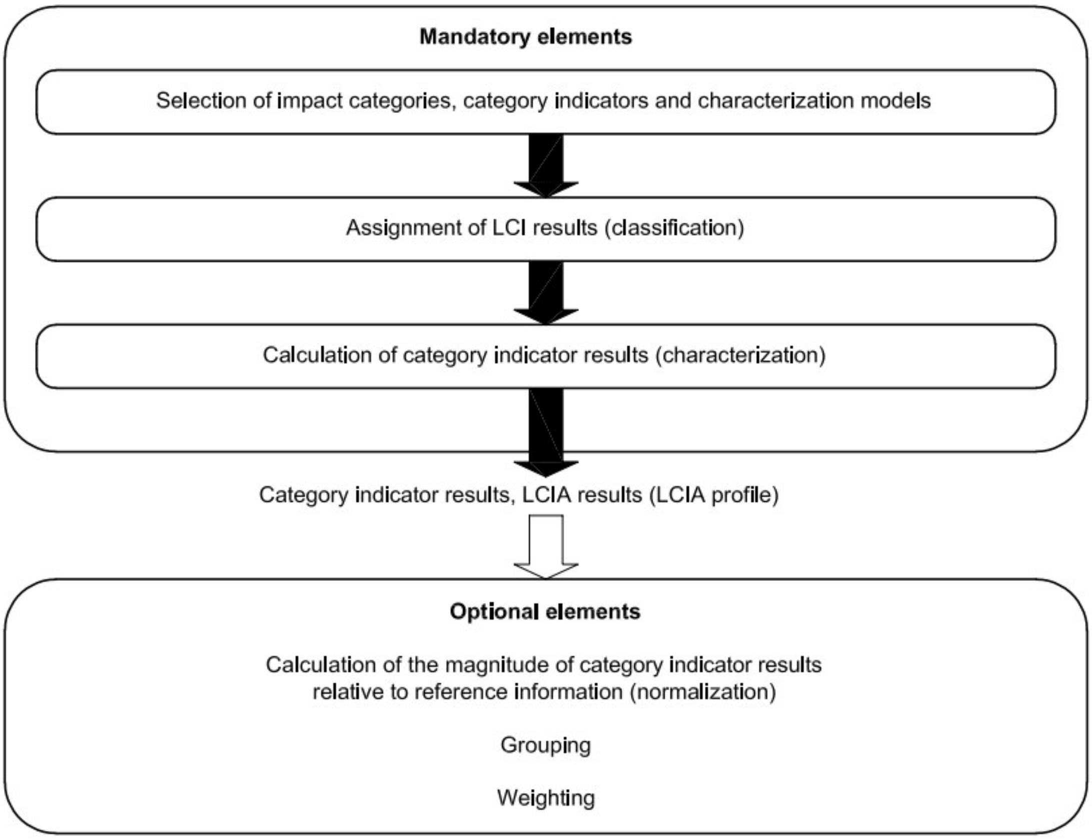

Figure 10 LCIA Process [45]

The optional processes defined in Figure 10 are normalisation, grouping and weighting. Normalisation involves the validation of results based on a specified perspective. Grouping is the ranking of the characterised or normalised LCIA results.

Weighting- involves giving weighing factors to the impacts and setting scoring for the impact categories. Weighting in LCIA may be subjective depending on the study itself, those involved, or even the purposes of the study[41]. The involvement of stakeholders can determine weighting. It is a means of supporting the interpretation of environmental impacts. It assigns scores to different impact categories based on perceived importance or severity[41]. However, a weighting factor has been determined through the applying cultural theories. Three perspectives and objectives defined represent values and a set of choices, such as the horizon and technology change expectations [44]. These perspectives are utilised for endpoint analysis.

- Individualist: This reflects short-term objectives; it reflects an optimistic view of technology and based on a short time horizon (20-year instead of 100-year GWP).
- Hierarchist: is based on policy principles on timing and technology, based on medium time horizons. (100-year GWP).
- Egalitarian: represents long-term interests based on precautionary principle thinking, which accounts for temporal horizons. (500-year GWP).

The environmental impacts categorisation based on ReCiPe 2016 [46],[45] are shown in Figure 11. ReCiPe 2016 is a life cycle impact assessment method developed with characterisation factors based on midpoint and endpoint levels. The midpoint level is defined with various parameters per midpoint. For example, kg is the reference for emissions and resource scarcity, while land use utilises the area. The endpoint level characterisation is on the areas of protection: human health, ecosystem quality and resource scarcity. The endpoint is cognisant of the environmental relevance of the flows with more uncertainty, while the midpoint is certain of environmental flows [46], [45].

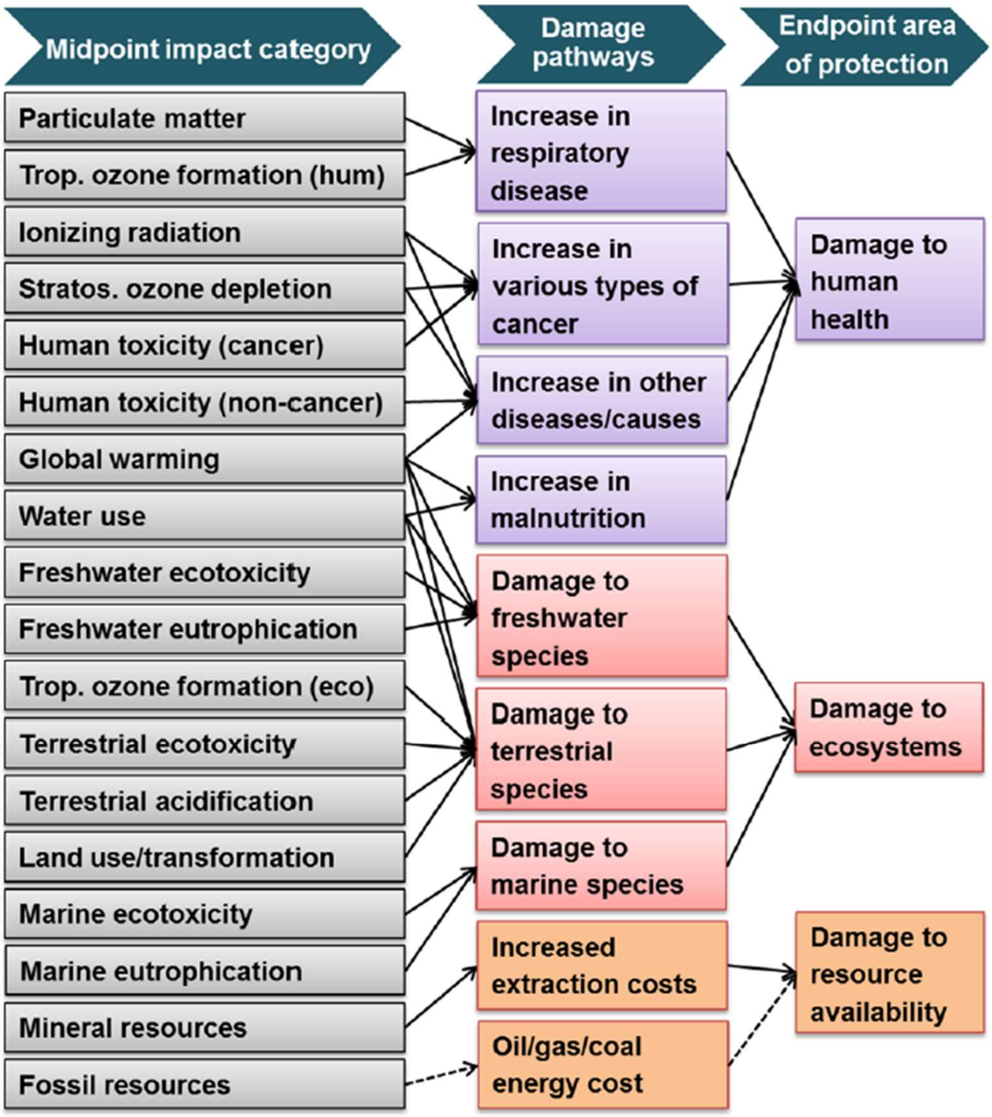

Figure 11 Environmental impact categories based on ReCiPe 2016 [46], [45]

5.2 Exergy Environmental Analysis

The environmental impacts calculated through the LCA are analysed to assess the impacts over the project's lifetime. It involves connecting environmental impacts to exergy streams[23]

The component related environmental impact is:

$$\dot{Y} = \dot{Y}^{CO} + \dot{Y}^{OM} + \dot{Y}^{DI}$$

5.1

$\dot{Y}^{CO}$ environmental impacts relating to construction $\dot{Y}^{OM}$ is the impact relating to operations and $\dot{Y}^{DI}$ impact relating to disposal.

The environmental impacts are related to the flow that is fuel and product calculations. The environmental impact balance is given as.

$$\dot{B}_P = \dot{B}_F + \dot{Y}$$

5.2

$$\dot{B}_P = b_P . \dot{E}_P$$

5.3

The product equations

$$\dot{B}_F = b_F . \dot{E}_F$$

5.4

$\dot{B}$ is the environmental impact rate, and b is the environmental impact per exergy unit. The Levelized environmental cost of the system is:

$$b_{product} = \frac{\dot{Y}_{total}}{W_{net} + E_{heat}}$$

5.5

The relative difference signifies environmental impact-reducing potential. A component with a high relative difference suggests the potential to reduce the impacts compared to components with a lower relative difference. The exergy-economic factor gives a component-related environmental impact compared with the total environmental impact. A factor higher than 0.7 signifies that the component-related environmental impact of a component is more important than the effect of the exergy destruction. A factor is lower than 0.3; indicates the environmental impact is dominated by exergy destruction [28].

The relative difference is.

$$r_b = \frac{b_p - b_f}{b_f}$$

5.6

The exergy-environmental factor

$$f_b = \frac{\dot{Y}}{\dot{Y} + \dot{B}_D} = \frac{\dot{Y}}{\dot{B}_{total}}$$

5.7

$\dot{B}_D$ is the environmental impact rate related to exergy destruction.

$$\dot{B}_D = b_f . \dot{E}_D \quad (5.8)$$

5.2.1 Energy return ratios

The energy payback ratio is the ratio of the total energy produced during the lifespan of a system compared to the energy required to build, maintain and fuel the system[47]. It is a measure of energy efficiency, analysing the energy investment lifecycle to determine relevance in exploitation. The ratios have complexities associated with their calculation because of boundary requirements and are also subjective, based on the life cycle boundary out [48].

Energy Return on Investment

The energy return on investment ratio is the energy output compared to the energy input[49]. The energy output is energy delivered to society, what is available for use, while energy input is the energy required to produce energy. Which includes direct and indirect inputs; these are inputs in the production of materials, operation and investment[49].

$$\boldsymbol{EROI} = \frac{\boldsymbol{Quantity\ of\ energy\ supplied}}{\boldsymbol{Quantity\ of\ energy\ used\ in\ supply\ process}} \quad (5.9)$$

The EROI proposed [49]

$$EROI = \frac{\sum \beta}{ED_{in} + \sum \gamma_k I_k} \quad (5.10)$$

β - total energy minus losses at the wellhead.
ED_{in} - energy required for building, operating and maintaining the power plant,
γ_k and I_k - coefficient inputs and energy per unit of a given coefficient.

Energy Payback Ratio

The energy payback time is the amount of time it takes to produce the same amount of power utilised in the construction and production of subsequent equipment for the plant, including energy used in the maintenance and operation of the plant over its lifetime [50].

$$EPR = \frac{E_{n,L}}{\left(E_{mat,L} + E_{Con,L} + E_{op,L} + E_{dec,L}\right)} \quad 5.11$$

E_n, - the net electrical energy produced.
E_{mat} - total energy invested in materials used
E_{con} - total energy invested in construction for a plant.
E_{op} - total energy invested in operating the plant.
E_{dec} - total energy invested in decommissioning a plant after it has operated
L - lifetime of the plant

Chapter 6

Results

This chapter gives the results; first, the exergy analysis is conducted based on the parameters of an existing modular unit, as discussed in the previous chapter. Second, the results of the Specific exergy costing and profitability analysis. Finally, the Life Cycle Assessment results and the energy ratios.

6.1 Exergy analysis

The calculation results on the double flash, and flash-binary plant parameters are in Table 11. The results on the single flash represent the initial conditions of the system. The parameters are per the manufacturers' specifications of the different components, solved in Excel using the cool prop extension.

Table 11 Exergy analysis results

Parameter	**Single flash**	**Double flash**		**Flash-Binary**	
		Cycle 1	Cycle 2	Cycle 1	Cycle 2
Steam quality at separation	0.57	0.57	0.96	0.57	
Mass flow at separation (kg/s)	12.2	12.2	8.84	12.2	13.2 ORC fluid
Total net power produced (kW)	4870	6172		7324	
Energy efficiency	0.65	0.83		0.98	
Exergy efficiency	0.18	0.75		0.87	

The double flash and flash-binary plants result in higher net outputs 6172 kW and 7324 kW, respectively. Both plants have higher energy and exergy efficiency than the single flash plant. The overall exergy efficiency in the flash-binary plant is 87%, while the double flash has 75%. The flash-binary plant's energy efficiency is 98%, while the double flash has 83%.

The exergy destruction ratio presented in Figure 12 shows that the highest exergy destruction is in separator 1, followed by the condenser at 0.59 and 0.26. Turbine 2 has 0.14 while turbine 1 is 0.

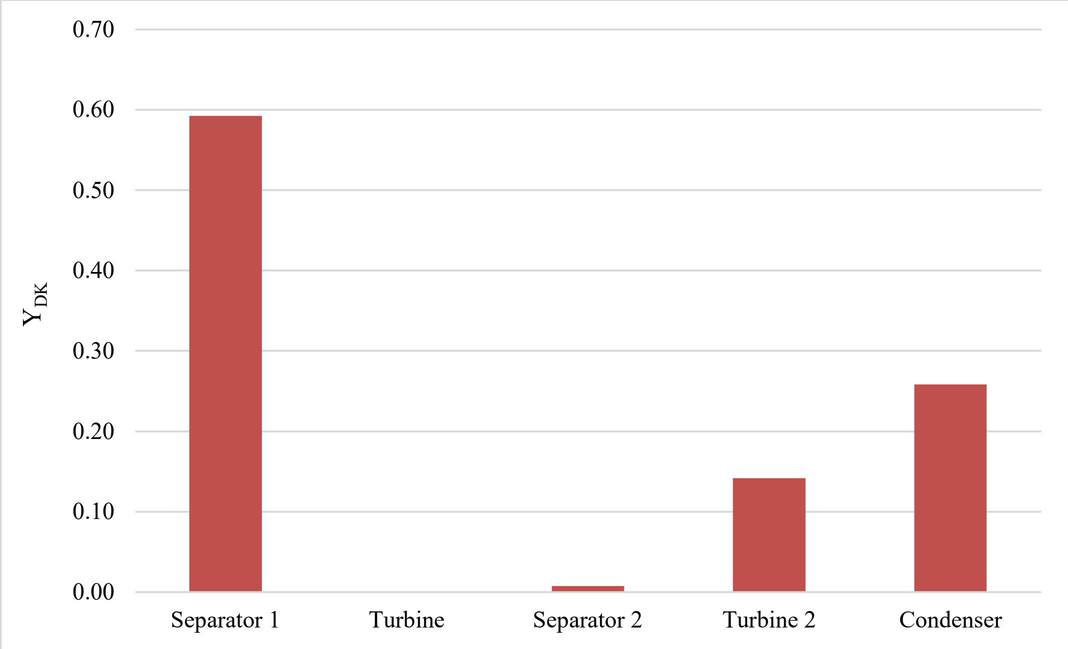

Figure 12 Exergy destruction ratio for double flash plant

In the flash-binary plant Figure 13, the separator has the highest exergy destruction ratio of 0.36. The exergy destruction ratio in the condenser is 0.03, turbine 2 has 0.02, and the heat exchanger is 0.04.

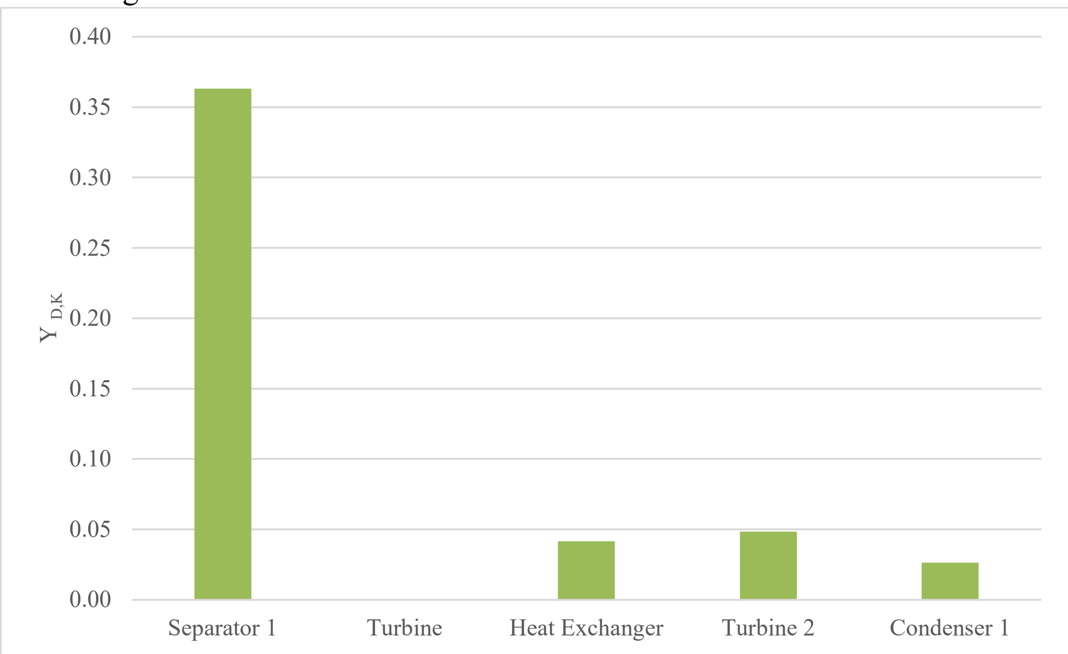

Figure 13 Exergy destruction ratio for flash-binary plant

6.2 Economic analysis

The economic analysis is based on the earlier discussed process in 4.3. Each component's fuel and product cost rates are defined, and the capital costs of the relevant components are developed.

From Table 12, the relative cost factor is highest in turbine 2 followed by turbine 1; this implies that the two components have the most significant potential for improvement, and this will reduce the average cost per exergy unit. Relative cost difference (r_k) increases the average cost per exergy unit. The most significant value of the exergy economic factor in the double flash system Table 12 is the turbine and separator 2, which implies that the cost of these components could be minimised.

Table 12 Cost rates for the double flash plant

Component	c_{fk} (USD/GJ)	c_{pk} (USD/GJ)	r_k	f_k
Separator 1	1.30	2.9957	1.304	0.89
Turbine	3.00	288.16	95.189	1.00
Separator 2	3.00	2.9957	0.00	1.00
Turbine 2	3.00	3248.9	1083.492	0.88
Condenser	3.00	2.9957	0.00	0.73

In the flash-binary plant, in Table 13 the condenser has the highest relative cost followed by the separator, and in terms of the exergy economic factor, the separator has the highest ratio.

Table 13 Cost rates for flash-binary plant

Component	c_f (USD/GJ)	c_{pk} (USD/GJ)	r_k	f_k
Separator	47.780	507.46	9.6206	0.89
Turbine 1	286.689	1171.4	3.0858	1.00
Heat Exchanger	0	0	0	1.00
Turbine 2	635.866	-727.64	-2.144	0.96
Condenser	1118.074	17069	151.67	0.27

6.3 Profitability Analysis

Calculations on profitability are based on the analysis of total capital investment. In Table 14, the flash binary exhibits a lower return on investment and a longer payback period than the double flash, attributed to higher costs associated with the investment in the flash binary system. The Levelized cost of electricity in both cases compares relatively fair to the expected LCOE for geothermal projects.

Table 14 Profitability parameters

	Double flash	Flash binary
Return on Investment	0.32	0.28
Payback Period	2.2 years	2.6 years
Levelized cost of electricity	0.052 $/kWh	0.045 $/kWh

6.4 Life Cycle Assessment

The LCA was conducted on GaBi software with the Eco Invent database. The midpoint environmental impacts are analysed in Figure 14. The double flash plant exhibits higher rates across all impact categories except for climate change and freshwater consumption than the flash-binary plant. The single flash plant has the highest ratios for all impact categories except climate change and freshwater consumption.

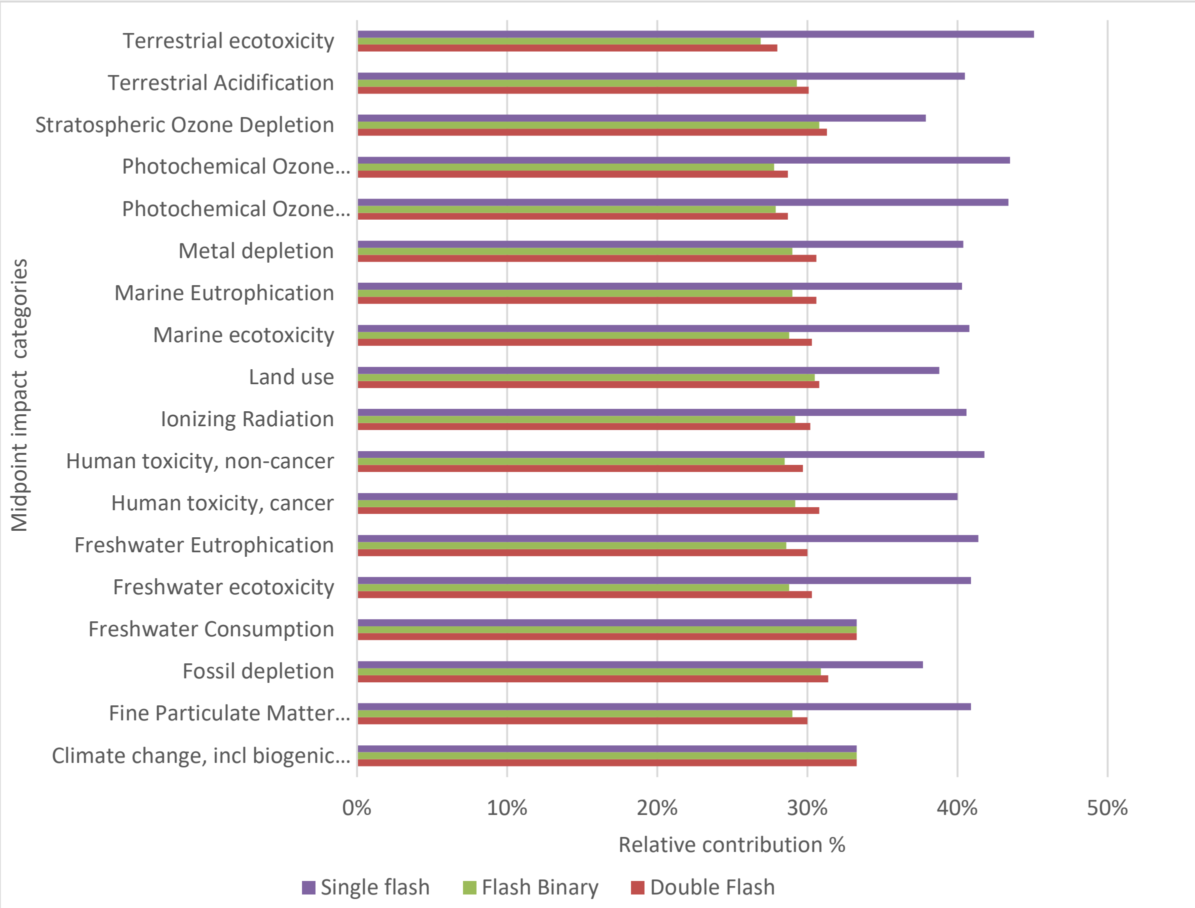

Figure 14 Environmental impact per plant

6.4.1 Environmental Impact per Phase

The single flash plant, Figure 15 exhibits the highest contribution in the drilling phase and spikes of high impact in the operations phase for climate change, freshwater consumption, and land use.

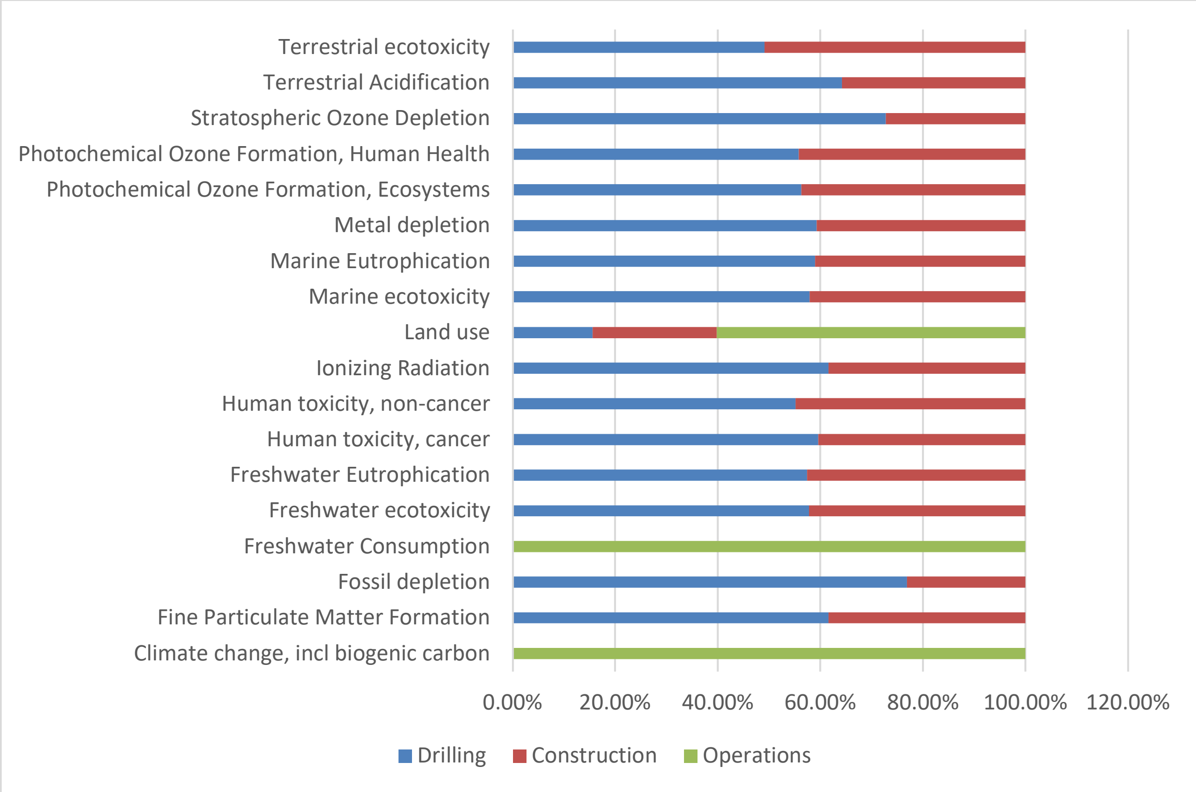

Figure 15 Phase contribution to impact categories in the single flash plant

For the double flash plant, Figure 16, the drilling phase exhibits the highest contribution in most environmental impact categories except for land use, freshwater consumption, and climate change; the operations phase has the highest contribution for these impact categories.

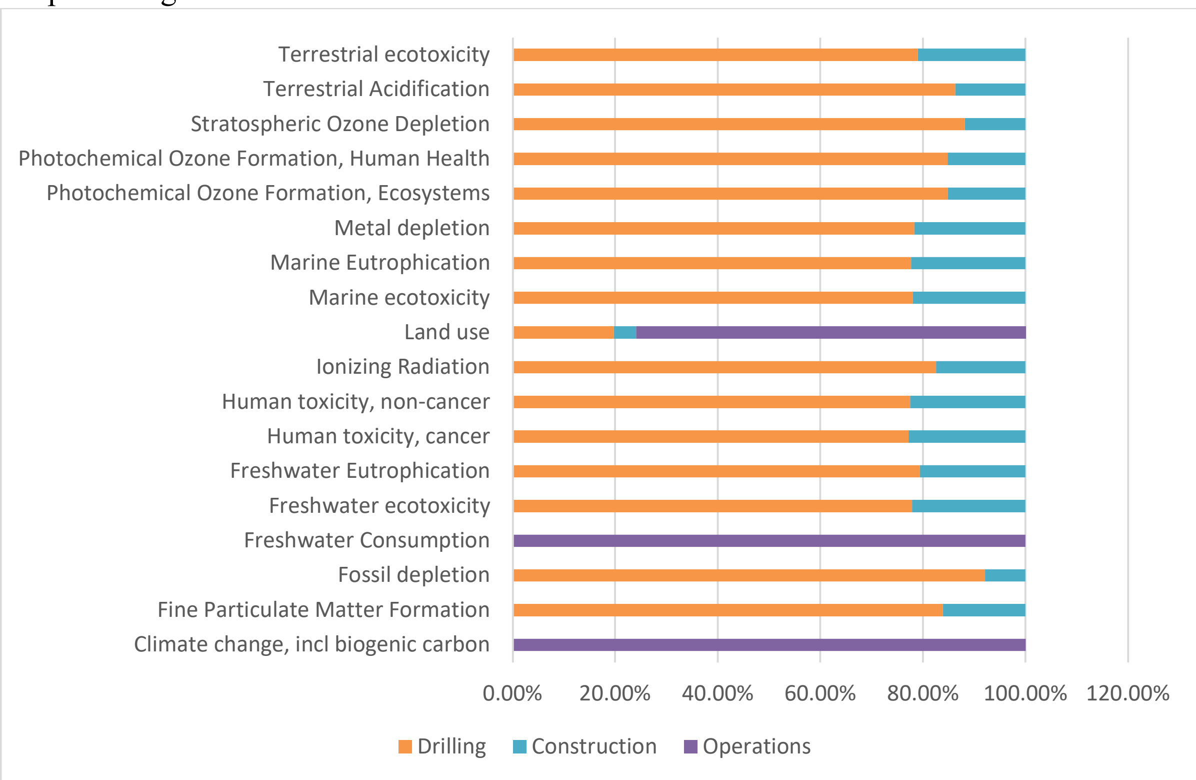

Figure 16 Phase contribution to impact categories in the double flash plant

The flash-binary plant, Figure 17 has the drilling phase being the highest contributor of the impact categories except for land use, freshwater consumption and climate change. The operations phase exhibits the highest contributions across the three categories.

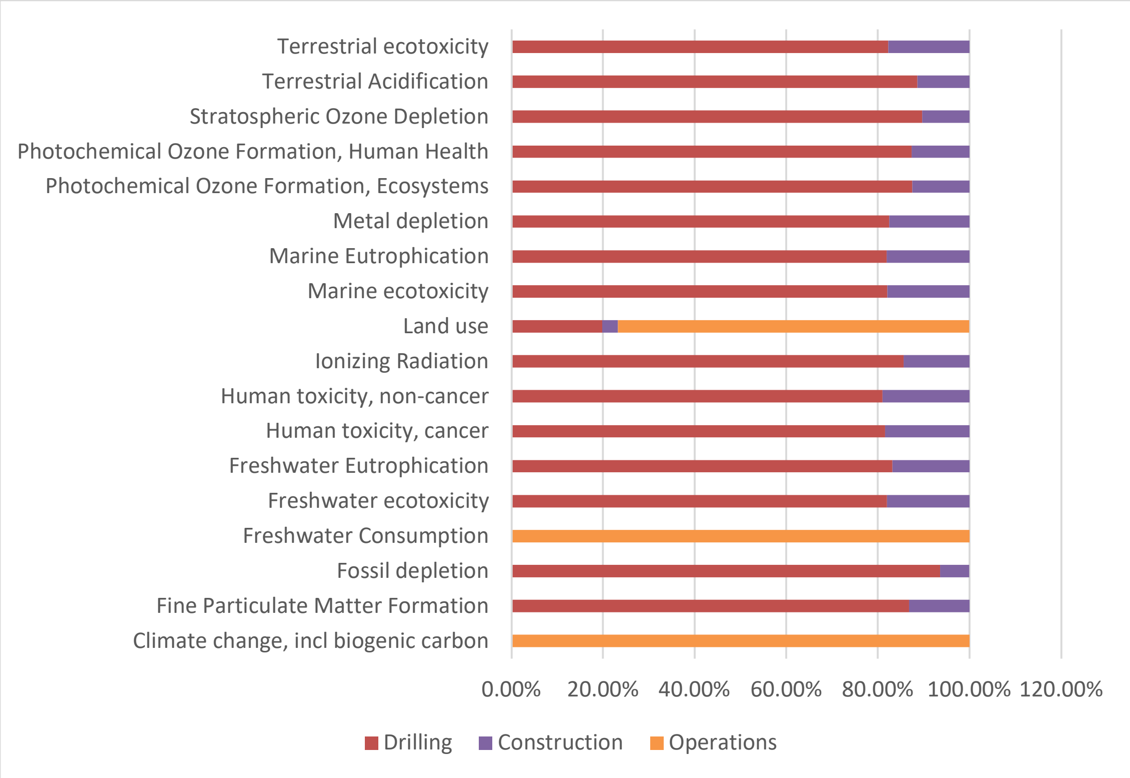

Figure 17 Phase contribution to impact categories in the flash-binary plant

6.4.2 Environmental impact category contribution per component

The calculations carried out on the contribution of each component are Table 15. Turbine 1 contributes the most to environmental impact causing potential in all the plant configurations. Separator 2 in the double flash plant exhibits 22% while the condenser exhibits 21% and turbine 1 at approximately 40% contribution in Figure 18.

Table 15 Environmental impact components contributions

Plant	Condenser	Cooling Tower	Separator 1	Separator 2	Turbine 1	Turbine 2	Heat Exchanger
Double Flash	21.72%	12.80%	0.92%	22.29%	39.63%	2.64%	
Flash Binary	27.55%	15.89%	1.16%		50.28%	3.35%	1.76%
Single Flash	29.06%	16.66%	1.23%		53.05%		

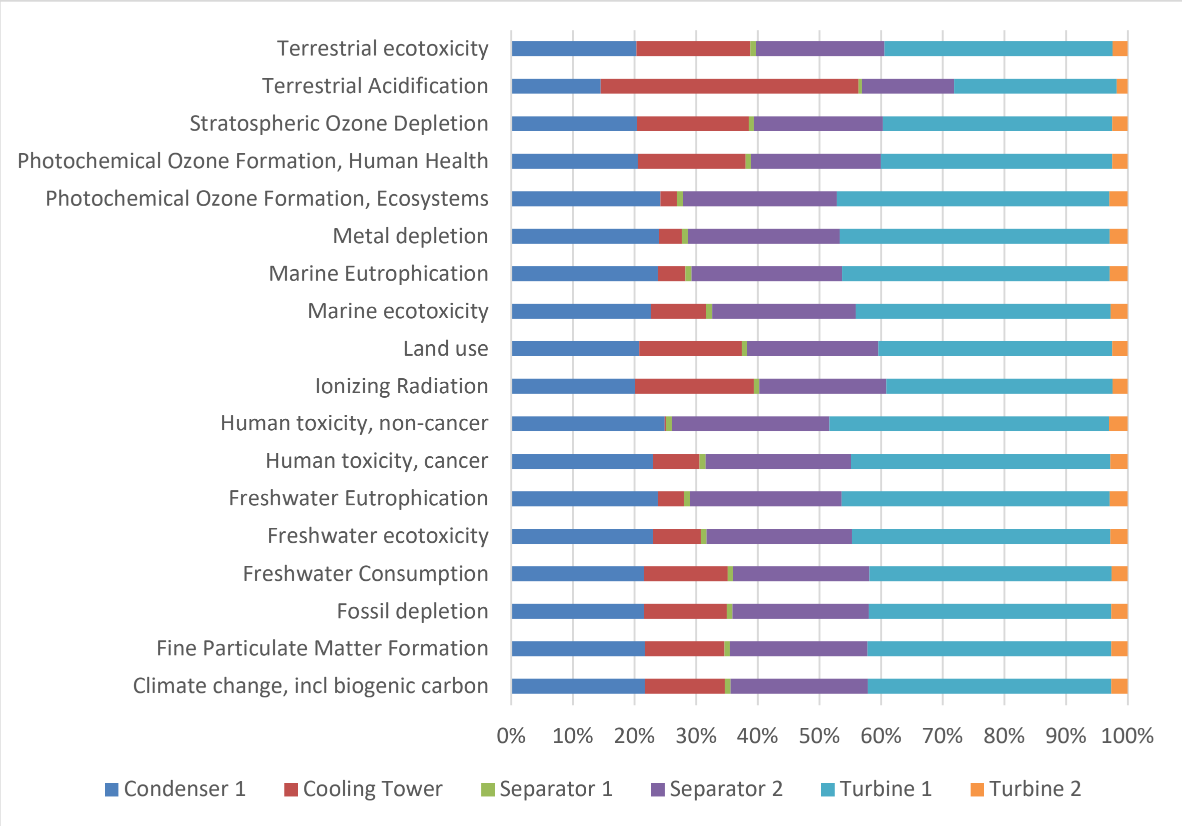

Figure 18 Double flash plant component environmental impact contribution

The flash-binary plant, Figure 19 , has the highest contribution from turbine 1 at 50%, followed by the condenser at 28%. Turbine 2 and the heat exchanger have lower contributions at 3% and 2%, respectively.

In the single flash, the turbine has the highest environmental impacts contribution at 53% condenser at 29%, the cooling tower at 17%, and the separator at 1%

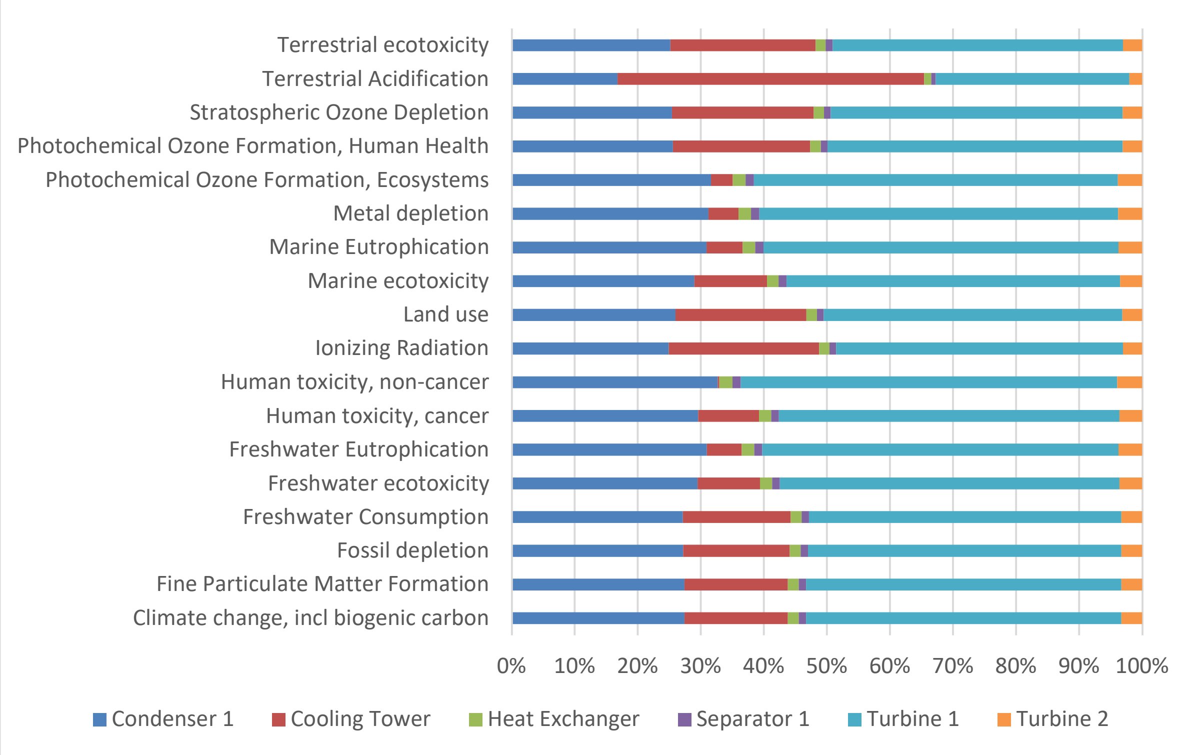

Figure 19 Flash-binary plant component environmental impact contribution

Table 16 evaluates the environmental impacts based on the exergy stream, fuel and product to identify the environmental impacts ratio associated with these streams. The climate change impact category was selected and analysed to determine the relative difference and the exergy-environmental factor. Notably, different results could be achieved if all impact categories were analysed; this could give a specific impact/component relative impact difference.

Table 16 Relative difference of specific environmental impact per component

Double flash plant			Flash binary plant		
Component	Relative difference of specific environmental impact (r_b)	Exergy-environmental factor (f_b)	Component	Relative difference of specific environmental impact (r_b)	Exergy-environmental factor (f_b)
Cooling tower	14.246	-0.002	Cooling Tower	28.618	0.000
Condenser	-0.996	0.000	Condenser 1	-0.997	0.000
Separator 1	-0.566	0.000	Separator 1	-0.566	0.000
Turbine 1	0.000	1.000	Turbine 1	-0.511	1.000
Separator 2	-0.028	0.005	Heat Exchanger	1.588	0.000
Turbine 2	-0.194	0.000	Turbine 2	-2.748	0.000

The relative difference in the double flash plant signifies that the cooling tower has the most significant potential for reducing environmental impacts. In the flash-binary plant, the cooling tower also has the highest potential for impact reduction. The exergy-environmental factor for turbine 1 is the highest in both double flash and flash-binary plants; this shows that the impact is associated with exergy destruction.

6.4.3 Energy ratio results

The energy payback ratio for the two systems is calculated based on the net electrical output for ten years and energy from the three phases: drilling, construction and operations. The energy utilisation is derived from analysis of the LCIA in the three phases. From Table 17, the double flash plant has an EROI of 0.99, while the flash binary has 0.84. Results show a payback of 8 years for the double flash and 9.6 years for the flash-binary plant.

Table 17 Energy ratios

Ratio	Double flash	Flash binary
Energy payback time	8.09	9.6
Energy Return on Investment	0.99	0.84

6.5 Summary of the results

From the analysis, the investment in the two alternatives is beneficial with higher energy production in both plants. However, the flash-binary plant exhibits a higher exergy efficiency than the double flash, with 87% compared to 75%. Energy efficiency is also higher in the flash-binary plant. The separator has the highest exergy destruction ratios, followed by the condenser.

In a double flash, the improvement of turbine 2, which exhibits the highest relative cost difference, would positively affect the energy system in cost and efficiency. For the flash binary, the condenser has the highest relative cost difference and would require the least effort in changes for higher efficiency and low cost.

Environmental impact analysis shows that the drilling phase exhibits the highest environmental impact contribution. The single flash system has the highest environmental burden of the three plants. The components in the alternatives show that the cooling towers have the highest environmental impact potential contribution for the climate change impact category. Turbine 1 environmental impact potential is associated with exergy destruction in both the alternatives.

Profitability ratios for the analysis show a payback period of 2.6 years in the flash-binary cycle and 2.2 years in the double flash and ROI of 0.28 and 0.32, respectively. The LCOE for both plants is 0.045 $/kWh for the double flash plant and 0.052$/kWh in the flash-binary plant.

The energy ratio exhibits a similar trend as the profitability ratio, with the flash-binary's energy payback return being higher than the double flash plant's 9.6 and 8.09 years, respectively. The energy return on investment for the flash-binary system is 0.84, while that of the double flash plant is 0.99.

6.6 Discussion

Based on the analysis and results, the research questions' solutions are as follows.

i. How are the three variables, exergy, environment, and economics, vary for the two alternatives, the double flash plant and the flash-binary plant?

The exergy analysis shows that exergy efficiency increases with the double flash and flash-binary plants. The flash-binary plant exhibits higher exergy efficiency compared to the double flash plant. The double flash plant shows a slightly higher rate across the environmental impact categories than the flash-binary plant. The flash-binary plant exhibits a higher investment cost than the double flash plant.

ii. Are the costs associated with further utilisation of separated brine worth the changes in exergy efficiency?

The net output in the flash-binary increases to 7.3 Mw from the single flash at 4.8 Mw, and the double flash plant has a net output of. 6.2Mw Turbine 2 in the double flash plant and the condenser in the flash-binary plant have the potential for improvement in exergy efficiency and cost.

iii. How does environmental impact causing potential vary when using separated brine for energy extraction?

The environmental impact categories associated with drilling across the two alternatives and the initial plant show that the drilling process significantly contributes to environmental impacts. The double flash plant exhibits higher impact rates than the flash-binary plant. The double flash and flash-binary plants have a lower environmental impact rate than the existing single flash plant. The double flash, however, exhibits higher rates than the flash binary except for the impact categories, climate change and freshwater consumption, which are equal for both plants. The cooling towers in both plants have the highest environmental impact potential contribution to climate change.

iv. How do the profitability and energy ratios vary with the two alternatives?

The energy return on investment for the double flash is higher than that of the flash-binary plant. The return on investment is higher in the double flash at 32% and flash binary at 28%. The energy output compared to energy utilised is higher in the double flash at 0.99 compared to the flash-binary plant at 84%. The energy payback period is also shorter for the double flash plant at 8 years compared to approximately 9.6 years for the flash-binary plant.

Chapter 7

Conclusion

The study evaluates the feasibility of energy extraction from separated brine from the existing single flash plant with two alternatives: a double flash and a flash-binary plant. Exergy analysis of the options achieves this. Further, an economic analysis involves establishing investment and component costs. The lifecycle assessment shows the environmental impact related to the components and overall plants.

From the results, the double flash plant exhibits lower output at 6172 kW with an exergy efficiency of 75%. The plant has a higher ROI of 32%, a payback of 2.2 years, and a lower investment cost. The environmental impacts associated with the double flash are slightly higher, less than 1%, of the flash-binary plant. The drilling phase has the highest environmental impact potential. Turbine 2 in both plants could be improved regarding cost and exergy destruction, while the cooling tower, in both scenarios, has a high capacity for environmental impact causing potential for the two alternatives. The EROI of the double flash is 0.99, with an energy payback period of 8.1 years. The flash-binary plant has an output of 7324 kW with an exergy efficiency of 87%. The plant has a lower ROI of 28%, a payback of 2.6 years, and a higher investment cost. The EROI of the flash binary is 0.84, with an energy payback period of 9.6 years.

In conclusion, an optimisation study would be beneficial to understand better the suitable operating parameters for the alternatives and the influence on cost and environmental impact. The LCA and energy ratios are limited to the LCA boundary and can be further studied to include the transport and disposal phases. Further analysis can involve developing a multi-criteria decision analysis to analyse the two alternatives and the parameters calculated to pick the most appropriate plant.

Bibliography

[1] I. Dincer and M. A. Rosen, 'Thermodynamic aspects of renewables and sustainable development', *Renewable and Sustainable Energy Reviews*, vol. 9, no. 2, pp. 169–189, Apr. 2005, doi: 10.1016/j.rser.2004.02.002.
[2] L. Meyer, R. Castillo, J. Buchgeister, and G. Tsatsaronis, 'Application of Exergoeconomic and Exergoenvironmental Analysis to an SOFC System with an Allothermal Biomass Gasifier', p. 11.
[3] P. A. Owusu and S. Asumadu-Sarkodie, 'A review of renewable energy sources, sustainability issues and climate change mitigation', *Cogent Engineering*, vol. 3, no. 1, p. 1167990, Dec. 2016, doi: 10.1080/23311916.2016.1167990.
[4] O. Hanbury and V. R. Vasquez, 'Life cycle analysis of geothermal energy for power and transportation: A stochastic approach', *Renewable Energy*, vol. 115, pp. 371–381, Jan. 2018, doi: 10.1016/j.renene.2017.08.053.
[5] P. Bayer, L. Rybach, P. Blum, and R. Brauchler, 'Review on life cycle environmental effects of geothermal power generation', *Renewable and Sustainable Energy Reviews*, vol. 26, pp. 446–463, Oct. 2013, doi: 10.1016/j.rser.2013.05.039.
[6] P. A. Omenda, 'The Geothermal Activity Of The East African Rift', p. 12.
[7] P. Omenda, P. Mangi, C. Ofwona, and M. Mwangi, 'Country Update Report for Kenya 2015-2019'.
[8] 'OlkariaConceptualModelPhaseIRepOct2011-Draft(2)20Oct2011.pdf'.
[9] '5692083-000-MRP-0003 (Optimisation) - *DRAFT REPORT-1 OF 5-23 DEC 2015.Pdf'.*
[10] D. L. Imaidi, 'Analysis Of Maintenance Methods And Developing Strategies For Optimal Maintenance Of Wellhead Power Plants At Olkaria Geothermal Field In Kenya'.
[11] T. Mutero, P. Muchiri, and N. Mariita, 'Wellhead Power Plants Improvement by Introduction of Double Flashing Cycle', *IJSRSET*, pp. 24–32, May 2019, doi: 10.32628/IJSRSET196311.
[12] R. Bertani, 'Geothermal power generation in the world 2010–2014 update report', *Geothermics*, vol. 60, pp. 31–43, Mar. 2016, doi: 10.1016/j.geothermics.2015.11.003.
[13] R. DiPippo, *Geothermal power plants: principles, applications and case studies*, 2. ed., Repr. Oxford Heidelberg: Elsevier, BH, 2009.
[14] 'Dinçer and Rosen - 2007 - Exergy energy, environment, and sustainable devel.pdf'.
[15] I. Dincer and M. A. Rosen, 'Thermodynamic aspects of renewables and sustainable development', *Renewable and Sustainable Energy Reviews*, vol. 9, no. 2, pp. 169–189, Apr. 2005, doi: 10.1016/j.rser.2004.02.002.
[16] L. Meyer, G. Tsatsaronis, J. Buchgeister, and L. Schebek, 'Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems', *Energy*, vol. 34, no. 1, pp. 75–89, Jan. 2009, doi: 10.1016/j.energy.2008.07.018.
[17] S. Mohammadzadeh Bina, S. Jalilinasrabady, and H. Fujii, 'Exergoeconomic analysis and optimisation of single and double flash cycles for Sabalan geothermal power plant', *Geothermics*, vol. 72, pp. 74–82, Mar. 2018, doi: 10.1016/j.geothermics.2017.10.013.
[18] R. DiPippo, 'Geothermal double-flash plant with interstage reheating: An updated and expanded thermal and exergetic analysis and optimisation', *Geothermics*, vol. 48, pp. 121–131, Oct. 2013, doi: 10.1016/j.geothermics.2013.07.006.
[20] D. Yildirim and L. Ozgener, 'Thermodynamics and exergoeconomic analysis of geothermal power plants', *Renewable and Sustainable Energy Reviews*, vol. 16, no. 8, pp. 6438–6454, Oct. 2012, doi: 10.1016/j.rser.2012.07.024.
[21] N. Shokati, F. Ranjbar, and M. Yari, 'Exergoeconomic analysis and optimisation of basic, dual-pressure and dual-fluid ORCs and Kalina geothermal power plants: A comparative study', *Renewable Energy*, vol. 83, pp. 527–542, Nov. 2015, doi: 10.1016/j.renene.2015.04.069.
[22] P. Ahmadi, I. Dincer, and M. A. Rosen, 'Exergo-environmental analysis of an integrated organic Rankine cycle for trigeneration', *Energy Conversion and Management*, vol. 64, pp.

447–453, Dec. 2012, doi: 10.1016/j.enconman.2012.06.001.
[23] 'Başoğul, Y. (2019). Environmental assessment of a binary geothermal sourced power plant .pdf'.
[24] D. Cook, H. Æ. Sigurjónsson, B. Davíðsdóttir, and S. G. Bogason, 'An environmental life cycle cost assessment of the costs of deep enhanced geothermal systems – The case studies of Reykjanes, Iceland and Vendenheim, France', *Geothermics*, vol. 103, p. 102425, Jul. 2022, doi: 10.1016/j.geothermics.2022.102425.
[25] D. Fiaschi, G. Manfrida, B. Mendecka, M. Shamoushaki, and L. Talluri, 'Exergy and Exergo-Environmental analysis of an ORC for a geothermal application', *E3S Web Conf.*, vol. 238, p. 01011, 2021, doi: 10.1051/e3sconf/202123801011.
[26] D. Fiaschi, M. Leveni, G. Manfrida, B. Mendecka, and L. Talluri, 'Geothermal power plants with improved environmental performance: assessment of the potential for an Italian site', *E3S Web Conf.*, vol. 238, p. 01010, 2021, doi: 10.1051/e3sconf/202123801010.
[27] M. Shamoushaki, M. Aliehyaei, and M. A. Rosen, 'Energy, Exergy, Exergoeconomic and Exergoenvironmental Impact Analyses and Optimization of Various Geothermal Power Cycle Configurations', *Entropy*, vol. 23, no. 11, p. 1483, Nov. 2021, doi: 10.3390/e23111483.
[28] W. Huang, J. Wang, Z. Lu, and S. Wang, 'Exergoeconomic and exergoenvironmental analysis of a combined heating and power system driven by geothermal source', *Energy Conversion and Management*, vol. 211, p. 112765, May 2020, doi: 10.1016/j.enconman.2020.112765.
[29] P. Talebizadehsardari *et al.*, 'Energy, exergy, economic, exergoeconomic, and exergoenvironmental (5E) analyses of a triple cycle with carbon capture', *Journal of CO2 Utilization*, vol. 41, p. 101258, Oct. 2020, doi: 10.1016/j.jcou.2020.101258.
[30] M. Aghbashlo and M. A. Rosen, 'Consolidating exergoeconomic and exergoenvironmental analyses using the emergy concept for better understanding energy conversion systems', *Journal of Cleaner Production*, vol. 172, pp. 696–708, Jan. 2018, doi: 10.1016/j.jclepro.2017.10.205.
[31] M. Mehrpooya, H. Ansarinasab, and S. A. Mousavi, 'Life cycle assessment and exergoeconomic analysis of the multi-generation system based on fuel cell for methanol, power, and heat production', *Renewable Energy*, vol. 172, pp. 1314–1332, Jul. 2021, doi: 10.1016/j.renene.2021.03.111.
[32] A. Lazzaretto and G. Tsatsaronis, 'SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems', *Energy*, vol. 31, no. 8–9, pp. 1257–1289, Jul. 2006, doi: 10.1016/j.energy.2005.03.011.
[33] 'Tsatsaronis, G., Bakshi, B. R., Gutowski, T., & Sekulic, D. (2011). Exergoeconomics and exergoenvironmental analysis.pdf'.
[34] S. K. Effatpanah, M. H. Ahmadi, S. H. Delbari, and G. Lorenzini, 'Energy, Exergy, Exergoeconomic and Emergy-Based Exergoeconomic (Emergoeconomic) Analyses of a Biomass Combustion Waste Heat Recovery Organic Rankine Cycle', *Entropy*, vol. 24, no. 2, p. 209, Jan. 2022, doi: 10.3390/e24020209.
[35] M. Shamoushaki, M. Aliehyaei, and M. A. Rosen, 'Energy, Exergy, Exergoeconomic and Exergoenvironmental Impact Analyses and Optimization of Various Geothermal Power Cycle Configurations', *Entropy*, vol. 23, no. 11, p. 1483, Nov. 2021, doi: 10.3390/e23111483.
[36] K. Li, Y.-Z. Ding, C. Ai, H. Sun, Y.-P. Xu, and N. Nedaei, 'Multi-objective optimisation and multi-aspect analysis of an innovative geothermal-based multi-generation energy system for power, cooling, hydrogen, and freshwater production', *Energy*, vol. 245, p. 123198, Apr. 2022, doi: 10.1016/j.energy.2022.123198.
[37] S. B. Ferreira, P. de M. R. Pinto, and S. L. Braga, 'Exergy analysis of BIGGT and EFGT cycles', *IJEX*, vol. 5, no. 5/6, p. 638, 2008, doi: 10.1504/IJEX.2008.020830.
[38] A. da S. Marques, M. Carvalho, Á. A. V. Ochoa, R. J. Souza, and C. A. C. dos Santos, 'Exergoeconomic Assessment of a Compact Electricity-Cooling Cogeneration Unit', *Energies*, vol. 13, no. 20, p. 5417, Oct. 2020, doi: 10.3390/en13205417.
[39] S. Karimi and S. Mansouri, 'A comparative profitability study of geothermal electricity production in developed and developing countries: Exergoeconomic analysis and optimisation of different ORC configurations', *Renewable Energy*, vol. 115, pp. 600–619, Jan. 2018, doi: 10.1016/j.renene.2017.08.098.
[40] International Organization for Standardization. (2006). *Environmental management*

Life cycle assessment Principles and framework (ISO Standard No. 14040:2006).
[41] M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Eds., *Life Cycle Assessment: Theory and Practice*. Cham: Springer International Publishing, 2018. doi: 10.1007/978-3-319-56475-3.
[42] S. Sulistyawati, A. P. Iswara, and R. Boedisantoso, 'Impacts Assessment of Crude Oil Exploration Using Life Cycle Assessment (LCA)', *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 506, no. 1, p. 012025, May 2020, doi: 10.1088/1755-1315/506/1/012025.
[43] European Commission. Joint Research Centre. Institute for Environment and Sustainability., *International Reference Life Cycle Data System (ILCD) Handbook :general guide for life cycle assessment : detailed guidance.* LU: Publications Office, 2010. Accessed: Apr. 10, 2023. [Online]. Available: https://data.europa.eu/doi/10.2788/38479
[44] Matthews, H. S., Hendrickson, C. T., & Matthews, D. (2014). Life cycle assessment: quantitative appro aches for decisions that matter. Open access textbook..
[45] G. G. Sondakh, 'Life Cycle Assessment of the Geothermal Power Plant in the Patuha Geothermal Field, Indonesia', 2022.
[46] M. A. J. Huijbregts *et al.*, '© RIVM 2017 Parts of this publication may be reproduced, provided acknowledgement', 2016.
[47] L. Gagnon, 'Civilisation and energy payback', *Energy Policy*, vol. 36, no. 9, pp. 3317–3322, Sep. 2008, doi: 10.1016/j.enpol.2008.05.012.
[48] T. Buus, 'Energy efficiency and energy prices: A general mathematical framework', *Energy*, vol. 139, pp. 743–754, Nov. 2017, doi: 10.1016/j.energy.2017.07.159.
[49] R. S. Atlason and R. Unnthorsson, 'Hot water production improves the energy return on investment of geothermal power plants', *Energy*, vol. 51, pp. 273–280, Mar. 2013, doi: 10.1016/j.energy.2013.01.003.
[50] S. W. White, 'Net Energy Payback and CO2 Emissions from Three Midwestern Wind Farms: An Update', *Nat Resour Res*, vol. 15, no. 4, pp. 271–281, Mar. 2007, doi: 10.1007/s11053-007-9024-y.
[51] KenGen reports and power plant c50 and c64 manuals