A Technology Readiness Assessment of Green Hydrogen Production using an Ultra Deep Geothermal Power Plant in the Netherlands

Master Thesis

written by

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Preface

The document that you have before you, is the representation of my thesis in order to obtain my Master in Science from the Delft University of Technology. With a smile on my face and a feeling of pride, I am currently writing these words which will finalize my time as a student. With confidence, I can say that I look back on a time full of experiences and challenges that have truly formed me for the better. Inside and outside of academics.

On a personal note, I would like to thank the people dearest to me. My parents, sister, little brother and the rest of my family. My friends from back home and all the friends that I have made along the way in Delft. Cheesy but true; I could not have done it without you.

Academically, I would like to thank all of my professors and Aad and Rob for guiding me during this thesis. Also, thank you Wisse for the weekly calls. Mostly filled with laughter and good conversations with a touch of serious thesis guidance when necessary. They were the light of my week.

Thank you to all of the people involved in my thesis, irrespective of a big or small contribution, with a special thank you going out to the interviewees; Jan, Lennart, Timme and Anne.

Then finally, I hope that everyone reading this thesis can do so with great interest and enthusiasm. I wish you a pleasant read and that you may learn extensively from my contribution to science.

Enjoy and all the best,
Mats Klijn

Executive Summary

The carbon energy economy is gradually transforming into a sustainable energy economy, of which green hydrogen is regarded as one of the key players within it. However, although green hydrogen is spoken about extensively, significant production volumes and applications are yet to be introduced globally. The same holds for the Netherlands. Therefore, this thesis studied one theoretical production method for green hydrogen and assessed the potential market for it. In order to determine whether or not this technology would seem relevant at the moment of writing and in the near future.

This thesis was done in collaboration with the French multinational Engie, who are a strong contender within the Dutch geothermal energy market and are also interested in renewable energy sources such as green hydrogen. The combination of their geothermal energy expertise and strive for exploring new renewable energy sources brings us to the title of this thesis;

A Technology Readiness Assessment of Green Hydrogen Production using an Ultra Deep Geothermal Power Plant in the Netherlands.

Knowledge Gap & Main Research Question

Developments of renewable energies such as solar and wind have been growing significantly in recent years. However, geothermal energy has been relatively lagging, although geothermal heat beneath the surface arguably has the largest renewable energy potential. From preliminary research, it seemed that in the Netherlands, geothermal energy and green hydrogen production were not developing at the same rate as solar and wind farms either. Therefore, the identified knowledge gap is to gain an understanding of why this is the case.

This research aims to assess the technological maturity of various parameters related to geothermal power plants and green hydrogen production for the geographical scope of the Netherlands. Furthermore, this research aims to provide an assessment of the future developments of this technology, potential applications and to identify barriers or accelerators of growth.
As a result of the identified knowledge gap and the interests of Engie in both geothermal energy and green hydrogen production, the main research question of this research was determined to be;

How should Engie develop their geothermal energy systems by implementing hydrogen production systems in order to expand their positions in both the geothermal- and hydrogen markets?

Research Approach & Research Methods

In order to approach the main research question effectively, two sets of three sub-research questions were determined to be researched. The first set of three is focused on the technology aspect

of this thesis, whereas the second set of three is focused on the impact, applications and challenges of the technology.

To start, a literature review was performed in order to gather all relevant information. A distinction was made between the two main topics of this thesis; hydrogen and geothermal energy. For each of the two main topics, the technology and the market aspects were reviewed in order to gain a solid knowledge base on all that was deemed relevant. This base allowed to partly answer the sub-research questions related to the technology and market aspects of each topic. Furthermore, this prepared the researcher for the interviews and assessment to be conducted in a later stage.

Following the literature review, a methodology was required to be sought out in order to effectively research and answer the the various research questions. In consultation with my TU Delft and Engie supervisors, expert interviews and a Technology Readiness Assessment (TRA) seemed logical. These methods were also how Engie partly assesses their new business opportunities. For the interviews, the researcher chose to conduct semi-structured interviews as this is a qualitative data collection method which allows for in-depth research on specific phenomenon. The semi-structured form seemed most relevant as it allows for the answer the question the researcher deems relevant beforehand, but it also gives room to touch upon topics during the interview that the interviewee deems to be relevant as well. Therefore allowing for new insights and expert information.

Four interviews were conducted with experts in various domains. The experts that were selected to interview covered various topics related to geothermal business, geosurface exploration, subsurface permeability and hydrogen production research and development. All interviews touched upon each individuals expertise but also spoke about other aspects such as market and political influences in their personal work. The data collected from the interviews built upon the knowledge base required for the assessment to be done.

Following the created knowledge base in the literature review and the information gathered during the expert interviews on the various relevant topics and aspects of this thesis, is the assessment. The conducted assessment is the TRA framework which is a combination of the Technology Readiness Level (TRL) and Technology Assessment (TA) frameworks.

As a result of combining the TRL and the TA into the TRA, the TRA allowed for a broader assessment than solely a technological one. The added TA allows hydrogen production using geothermal plants to also be assessed on its potential market impact and applications. The goal of the TRA is to combine all information retrieved during the thesis, from literature and interview data, in order to confidently answer all sub-research questions and of course, finally, the main research question.

Assessment & Results

The TRL focused on four technological aspects of the hydrogen and geothermal technologies; geosurface exploration, drilling, geothermal plant and hydrogen production. The assessment was done using the technology readiness level framework. In short, the main barrier of the proposed technology set-up is the geosurface exploration technology level which was set at the experimental research level, level 3. The geosurface exploration capabilities are the clear showstopper technology wise. It is still incredibly difficult to understand, find and visualize what the geosurface looks like at depths of 4.000 meters. Essentially, only guesstimates can made which can only be validated by drilling to the proposed depths. Drilling entails significant risks, uncertainties and costs, making it an unattractive business for most. Furthermore, most current exploration is focused on depths irrelevant to the depths required for the proposed geothermal plant. The other 3 aspects; drilling, geothermal plant and hydrogen production levels were rated at technology readiness levels of 9, 9 and 6 respectively.

The TA focused on four aspects as well. Three were related to potential commodity outputs of the proposed plant (hydrogen, electricity and heat) and the fourth aspect was related to the political influences and impacts that could be relevant. The hydrogen output was assessed to be mostly relevant in decarbonising the (heavy) industry as this sector currently already uses extensive amounts of grey hydrogen every year. Furthermore, the heavy mobility sector was considered to be interesting as well. Seasonal storage of geoheat over the summer periods was considered to be economically unfeasible. The electricity output was deemed as an irrelevant output for an ultra deep geothermal plant. It seems illogical to produce electricity at 8% efficiency when there is a market for the initial output of the plant; heat. Also, other renewable energy sources seem much more efficient and interesting for electricity production. Thirdly, heat output. Heat is currently often produced using natural gas or by transforming electricity to heat. For much of the same reasons why electricity output seems illogical, heat output seems logical as this is the exact commodity which is retrieved from the earth. Therefore not needing to transform electricity to heat as would be for wind or solar electricity, seems like a suitable market. Markets for ultra deep geothermal heat of over 100°C were determined to be refining of diesels and naptha, production of plastics or sterilisation of milk, amongst other markets. Furthermore, residual heat can be used in markets already existent; the built environment and horticulture.

Conclusion

In short, the main research question was answered as; Engie should not develop their geothermal systems to implement hydrogen production systems. The reasons were threefold; round trip efficiency for hydrogen production from an ultra-deep geothermal plant were under 6%, the aforementioned geosurface exploration capabilities are far below the required capabilities and focus on explorers is on depths far from the required depths for ultra deep plants, economic competitiveness of hydrogen production from geothermal plants is deemed too low.

Research Recommendations

Although the main topic of this thesis and research question was focused on hydrogen production, the researcher would like to point out that ultra deep geothermal plants should not be deemed unfeasible overall. Once geosurface exploration technologies are developed further and high risks can be taken away, then such a plant may be possible. Also, the focus market for such a plant should then be on heat as this is a market where there is a large market for net zero heat and competing alternative technologies would be few.

Furthermore, research should continue and potentially be accelerated for geosurface fluid and rock exploration methods as geothermal heat below the surface in there in abundance. The challenge currently is to locate it. Support and research should be kept going for institutions such as REFLECT and SCAN in order to achieve this.

This thesis did not focus on extensive regulatory and financial aspects of UDGE. These should be researched in a later stage in order to assess if UDGE is economically feasible. One such plant, the Trias Westland, has once tried to go to 4.000 meter depths but was then considered as unfeasible. Future technological developments risk mitigation factors might be able to lower costs and increase feasibility in the future. The same holds for (sustainable energy) regulatory aspects, which could form incentives for UDGE developments and benefit risk mitigation's.

Research Limitations

First, most experts that were interviewed were experts in a technological domain. The researcher acknowledges that interviewing market experts or employees in certain identified industries would have been beneficial to interview as well. The same holds for contacting government officials working on sustainable energy domains and operators of existing Binary Cycle Power Plant (BCPP) across the globe. Furthermore, speaking to more than one expert per domain would have been beneficial for validation of information.

TRL related limitations were identified to be the level of depth chosen per parameter of the technology. This research assessed technologies on a relatively broad domain. TA limitations are the difficulty and speculative nature of estimating future impacts and applications. Finally, the TRA fails to address aforementioned topics such as regulatory and financial topics.

Contents

Acronyms

AEM Anion Exchange Membrane. 31

AGS Advanced Geothermal System. 22, 46

BCPP Binary Cycle Power Plant. v, x, xii, 17–22, 24–26, 29, 33, 34, 36, 47, 48, 52, 53, 61–63, 67, 68

BEV Battery Electric Vehicle. 51, 52

CAPEX Capital Expenditures. 22, 28, 30, 34, 38, 45, 47, 49

EBN Energie Beheer Nederland. 39, 40

EGS Enhanced Geothermal System. 22

EU ETS European Union Emission Trading Scheme. 37

EZK Ministerie voor Economisch Zaken en Klimaat. 40, 56

FCEV Fuel Cell Electric Vehicle. 51

GE Geothermal Energy. 16, 22–24, 26–28, 32, 62

GES Geothermal Energy Systems. 16, 17, 23, 24, 26, 27

GOUD Geothermie Oost-Utrecht Duurzaam. 39, 69

GWT Geothermal Well Temperatures. x, 17–19, 21, 24, 27, 45–47, 49, 53, 62

HPS Hydrogen Production Systems. 24

IEA International Energy Agency. 2

IRENA International Renewable Energy Agency. 3, 49, 52

OPEX Operational Expenditures. 34, 47, 49

ORC Organic Rankine Cycle. x, 18–20

PEM Polymer Electrolyte Membrane. 30, 31, 37, 49

RES Renewable Energy Source. xii, 1–3, 26, 27, 61, 64

ROI Return on Invesment. 34

SMR Steam Methane Reforming. 37

SOE Solid Oxide Electrolyte. 30, 49

TA Technology Assessment. iii–v, vii, 13, 15, 44, 50, 63, 64

TRA Technology Readiness Assessment. iii, v–vii, 4, 6, 9, 10, 13, 15, 44, 61, 63–65

TRL Technology Readiness Level. iii, v, vii, x, 8, 13–15, 44, 46, 48–50, 61, 63–65

UDGE Ultra Deep Geothermal Energy. iv, v, 13, 30, 33–36, 39–42, 44, 45, 48, 52–56, 60–65, 69, 70

WEA World Energy Assessment. 26

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Chapter 1

Thesis Introduction

In prospect of the climate goals set to be achieved in 2050 by the Paris Agreement, multinational firms, and industry in general, are expected to innovate and adjust their business models in order to contribute in achieving said climate goals. The main method of achieving the Paris Agreement climate goals is the decarbonisation of the energy sector. One development gaining widespread attention within in this sector in recent years is the potential introduction of a hydrogen economy.

For one, hydrogen molecules are the most abundant molecules available, accounting for around 75% of all mass known to man. Henceforth, the main attraction of a hydrogen economy lies in its theoretically abundant availability. However, it is not readily available and, as-of-today, needs to be produced using methods that require a heavy dependency on energy. Nevertheless, a fully emission-free production process is theoretically possible.

Furthermore, hydrogen is argued to be applicable for numerous applications such as being used as an energy storage medium for energy production systems that, at times, produce energy surpluses, to being the driving fuel source for heavy-duty vehicles such as trucks or airplanes. However, although the technology is being adopted in various projects over the globe, the technology is still a niche relative to current sizeable energy industries. Nevertheless, this situation should not hamper or constrain further research, but research should be fuelled by hydrogen's theoretical potential.

Today, virtually all hydrogen is produced using fossil fuel and hence, carbon-emitting production methods. In the Netherlands, industry produces around 800,000 tonnes of hydrogen annually for use in its own production processes [43]. Mostly by converting natural gas (primarily CH_4) into hydrogen (H_2) and carbon dioxide (CO_2) at high temperatures [75]. Therefore, the hydrogen economy as it stands does not contribute to the decarbonisation of the energy economy. There are however, developments in which hydrogen is produced using Renewable Energy Source (RES) such as in solar and wind farms. Production of hydrogen using green methods essentially tackles two problems at once; a major reduction of CO_2 emissions and the use of CH_4 [75].

This focus of this thesis lies on the production of hydrogen from a more unknown RES within the Netherlands, geothermal power. Currently, geothermal plants in the Netherlands mainly focus on geothermal heat for the horticulture and residential sector in comparison to electricity generation (which is required for hydrogen production). In short, the main difference between plants focusing on heat and plants focusing on electricity generation has to do with the depth and temperature of the well that a geothermal plant retrieves its heat from. The deeper the well, the higher the temperature and therefore the application possibilities of the geothermal plant. A more elaborate scope for this thesis is provided in section 1.3.

This thesis is written in collaboration with the Dutch branch of the French energy firm, Engie. From this moment onwards, when the name *Engie* is mentioned, the researcher refers solely to the Dutch brand of this firm.

1.1 Problem Statement

Engie wants to be a leader within the sustainable energy transition. For this, they regard hydrogen as one of the potential technological advances that can further them in this quest. Currently, hydrogen is mostly produced using natural gas, resulting in carbon emissions, and hence contradicting the sustainable energy goals.

Nevertheless, it is possible to produce hydrogen in a green manner using RES. Therefore, the challenge to be addressed during this thesis is to understand the possibilities of green hydrogen production using knowledge of energy domains that fit well within Engie's current energy portfolio. One of these energy domains that Engie is strong in is the geothermal energy domain. Therefore, in this thesis, the production of hydrogen through geothermal power plants in the Netherlands will be researched. Hence, this research strives to enable Engie to understand and pursue potential new business models within this domain that seem promising, profitable and achievable.

1.2 Relevance of Research: Knowledge Gap

In prospect of the climate goals set by the Paris Agreement, to be achieved in the year 2050, energy markets are challenged to develop innovative carbon-reduced or carbon-free energy production. While for years, the largest electricity generating Renewable Energy Source (RES) has been hydro power globally, its year-on-year absolute capacity increase has been declining for the past five years [41]. In comparison, developments of renewable energies such as wind and solar power have been growing exponentially in recent years.

Lagging firmly behind the three aforementioned renewable energies with respect to electricity generation, is geothermal energy, as can be seen in data provided by the International Energy Agency (IEA) in figure 1.1.

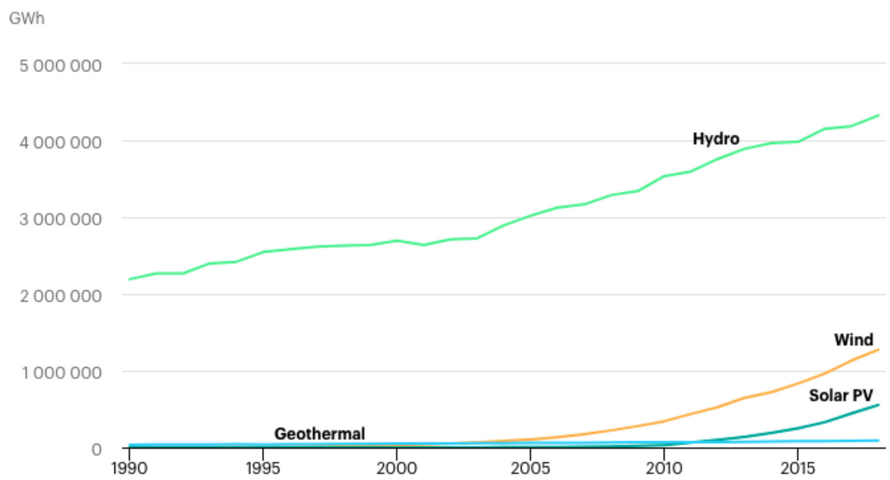

Figure 1.1: Global Renewable Electricity Generation by Source (non-combustible) in the period 1990-2018 [42]

However, it is interesting to mention that although geothermal energy is lagging other RES's, it is arguably the RES with the largest potentially available resource (see table 1.1 for an overview) according to a research conducted by Li et al. (2015) [52]. Hence, from a technological view on the topic of this thesis, it is interesting to conduct research into further advances in geothermal renewable electricity production and therefore also, the potential production of hydrogen since the potential of this energy source is vast but currently relatively untapped.

Energy Type	Energy Potential (GW)	Installed Power (GW)	Increased Power Last 5 Years (GW)	Installed Capacity (%)
Hydro	1600	1000	125	17.4
Solar	49900	139	116	2.4
Wind	20300	318	159	5.5
Geothermal	158500	12.0	1.10	0.21

Table 1.1: Comparison of global RES [52]

Furthermore, the International Renewable Energy Agency (IRENA) published a technology brief in 2017, indicating the current technology status, highlights, potentials and barriers concerning geothermal power. In this publication, among other topics, they indicate various developments within the geothermal domain which are expected to increase the efficiencies of geothermal plants [20]. However, among the proposed efficiency increasing activities, I was unable to identify energy storage possibilities such as hydrogen production which could ensure a higher plant capacity factor at times when the demand of heat or electricity is lower.

From the preliminary literature review and discussions done within Engie prior to the acceptance of this thesis topic, it was evident that there is a knowledge gap to be filled as to why the production of electricity, and hence also the production of hydrogen, using geothermal plants is not applied extensively in the Netherlands as of the moment of writing. As electricity generation through geothermal plants is happening in other countries such as Iceland and the United State of America.

Therefore, for now, the main knowledge gap to be addressed during this thesis is to conduct a research into why the introduction of green hydrogen production using green electricity generated from geothermal plants is not developing in the Netherlands currently. Following the main outcome of this initial research, the researcher would subsequently want to address a recommendation for the firm, Engie, on this topic as this thesis is written in collaboration with said firm regarding the aforementioned.

1.3 Thesis Framework & System Scope

In order to prevent this thesis being too broad to research, a research scope has been constructed. In essence, this scope creates a border of the system to be researched. This system entails two main topics; the technical subsystem and the market subsystem. Both will be addressed below. Furthermore, although not within the border of the system to be researched in full, the two subsystems can be affected by exogenous influences such as political or social influences. Such minor influences are mentioned throughout this thesis to be important at times, but as stated, are not researched in full. A Visualisation of this thesis' framework system scope is presented in figure 1.2 and further elaborated in text below.

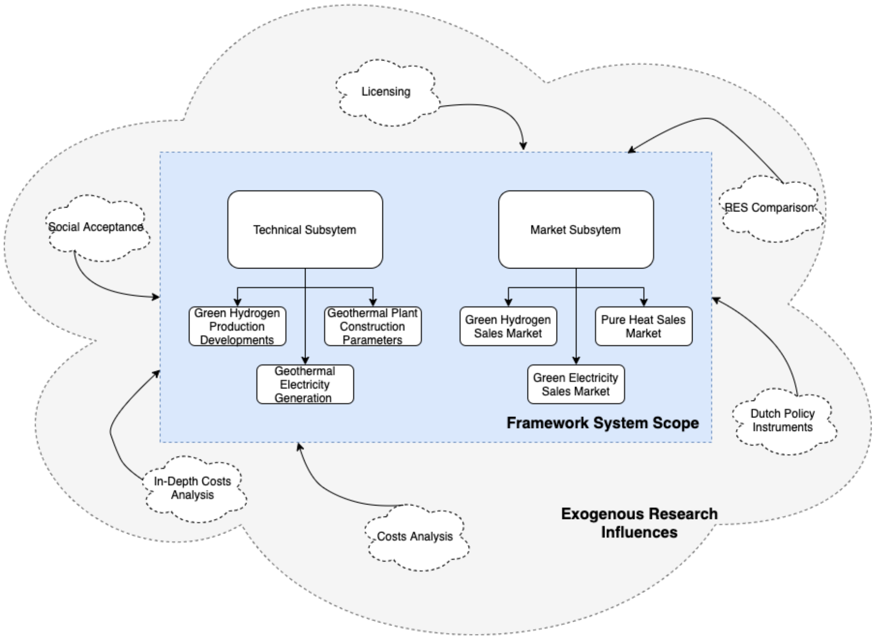

Figure 1.2: Visualisation of the Framework System Scope

Technical Subsystem

The technical subsystem of this research topic involves three aspects; hydrogen production methods, electricity generation through geothermal plants and the main parameters of importance for geothermal plant construction. For each aspect, the technical capabilities are researched and assessed on a *need-to-know* level such as basic working concepts, required inputs or efficiencies. It should be noted that the precise science behind each aspect is not addressed. As an example, if we regard the hydrogen production methods aspect, this research will focus on existing and in development production methods in order to create a need-to-know level of knowledge on what can be expected. This research will however not address the exact science of hydrogen production, such as how electrolysis works on an electron level.

Market Subsystem

The market subsystem addresses potential sales markets for the commodity outputs from the geothermal plant, being; the green hydrogen market, the green electricity market and the pure heat market within the Netherlands. With respect to each commodity, the various applications for each sales market are considered and hence, are encompassed within the overall system.

Exogenous Influences

Exogenous influences are aspects that are not regarded as main research topics for this thesis, such as the technological and market subsystems, but which do influence those topics. Relevant influences are aspects such as social acceptance influences, Dutch governmental policy instruments and organisations, and specific related costs, amongst others. For example, these influences are mentioned in the data collection and Technology Readiness Assessment (TRA) as they are important and can have an effect on for instance, the sales market for green hydrogen. However, this thesis will not dive into the specifics or an analysis of their effect and the changes that should be imposed to ensure improvements as it is beyond the scope. This information is merely found, collected and used without pursuing improvements on these aspects as this is considered as a whole new topic of research.

1.4 Research Objective

The objective of this thesis will be to understand if and how the integration of hydrogen production can be implemented into geothermal energy systems. Furthermore, the objective is to assess the market potential for the outputs of the proposed plant. This will help to understand if the pursuit of hydrogen production using geothermal plants should be encouraged or discouraged for industry.

1.5 Research Questions & Methods

In order to successfully conduct this thesis research, a main research question is essential. The main research question will guide and align the direction of this research. The main research question to be addressed is the following;

What is the state of the technological- and market readiness for green hydrogen production from geothermal power plants in the Netherlands?

In an attempt to answer the main research question, this question is accompanied by a set of sub-research questions. These help to set various milestones during this research. The accompanying sub-research questions have been sectioned into two categories.

Technology focused Research Questions

The first category relates to sub questions focusing on the technological aspect of this thesis, both geothermal and hydrogen related, and can be found below;

1. Which production methods, irrespective of their development phase, currently exist within the geothermal electricity generation domain?
2. What are the challenges and potentials for the Dutch Geo surface with respect to electricity generation?
3. How can hydrogen production systems be implemented in geothermal electricity generating power plants?

These sub-questions will address and research geothermal systems and how these systems can produce electricity to, in turn, produce hydrogen. Furthermore, hydrogen production methods themselves will be researched as well. These questions will be answered by conducting a *Desk Research*, conducting *Interviews with Experts* from external sources and performing an *Assessment Model*.

Market focused Research Questions

Secondly, sub-questions are categorized in relation to the market potential. These questions mainly relate to an assessment of the current and future market developments for both geothermal and hydrogen. The research methods for these questions will be a *Desk Research*, *Interviews with Experts* from external sources and performing an *Assessment Model*. The related sub-questions can be found below;

4. What is the current state of the overall hydrogen & geothermal market in the Netherlands?

5. What are drivers and barriers for the hydrogen and geothermal market in the Netherlands?
6. What are potential sales markets or applications for the commodity outputs of a geothermal plant producing hydrogen?

1.6 Thesis Overview

The following thesis is set-up in the following order; first, the research approach and research method will be addressed in the following chapter, chapter 2. Next, a literature review will be done in chapter 3. Following the literature review, the data collected from the expert interviews will be outlined. This is done in chapter 4. After the data collection chapter, a chapter will follow in which the knowledge base from the literature review and the expert interviews will be used to conduct a Technology Readiness Assessment (TRA). This is done in chapter 5. To conclude this thesis, chapter 6 will answer the research questions, assess the scientific contribution and reflect on the research itself and it's limitations. Furthermore, recommendations for further research will be done in the same chapter.

Chapter 2

Research Approach & Method

The following chapter will address the research approach and methodology of this thesis. First, the research approach will focus on how the research is to be conducted, which is of the exploratory type. The approach will entail the research steps taken in order to answer each research question. An approach for each individual research question can be found in section 2.1. A global overview of the entire research approach is shown in figure 2.1.

In figure 2.1, the rectangular shapes indicate an action whereas the oval shapes indicate a result, often a result following from the action before. Furthermore, five alternatively coloured rectangular areas indicate the five different main phases of this thesis. In order of occurrence these are; preliminary research, knowledge building, data collection, assessment & results and to finalize, conclusions and reflection.

Following the research approach is an elaboration on the research methods used for the approach. The various methods used will be elaborated on in section 2.2.

2.1 Research Approach

As mentioned, the research approach will be of the exploratory type. This approach will focus on how this thesis will be conducted step-by-step, in order to answer the sub- and main-research questions which were proposed in section 1.5. Therefore, a short research approach to each research question will be provided next. A more elaborate description of the type of research method mentioned for each research question will be provided shortly thereafter in section 2.2.

2.1.1 Approach for Technology focused Research Questions

As mentioned in section 1.5, the first three sub research questions are focused on the technological aspect of hydrogen production using a geothermal power plant.

SRQ1: Which production methods, irrespective of their development phase, currently exist within the geothermal electricity generation domain?

In essence, this question is related to the specific technological capabilities of geothermal plants as standalone technologies. The question targets where geothermal plant technology stands with respect to electricity generation, which from preliminary research is key for the production of hydrogen. Furthermore, the phrase '*irrespective of their development phase*', allows the question to also focus on future developments of geothermal plant technology.

Initial information on geothermal plants is retrieved through the method of literature review. Following this, the findings of the literature review will be introduced to an expert on geothermal

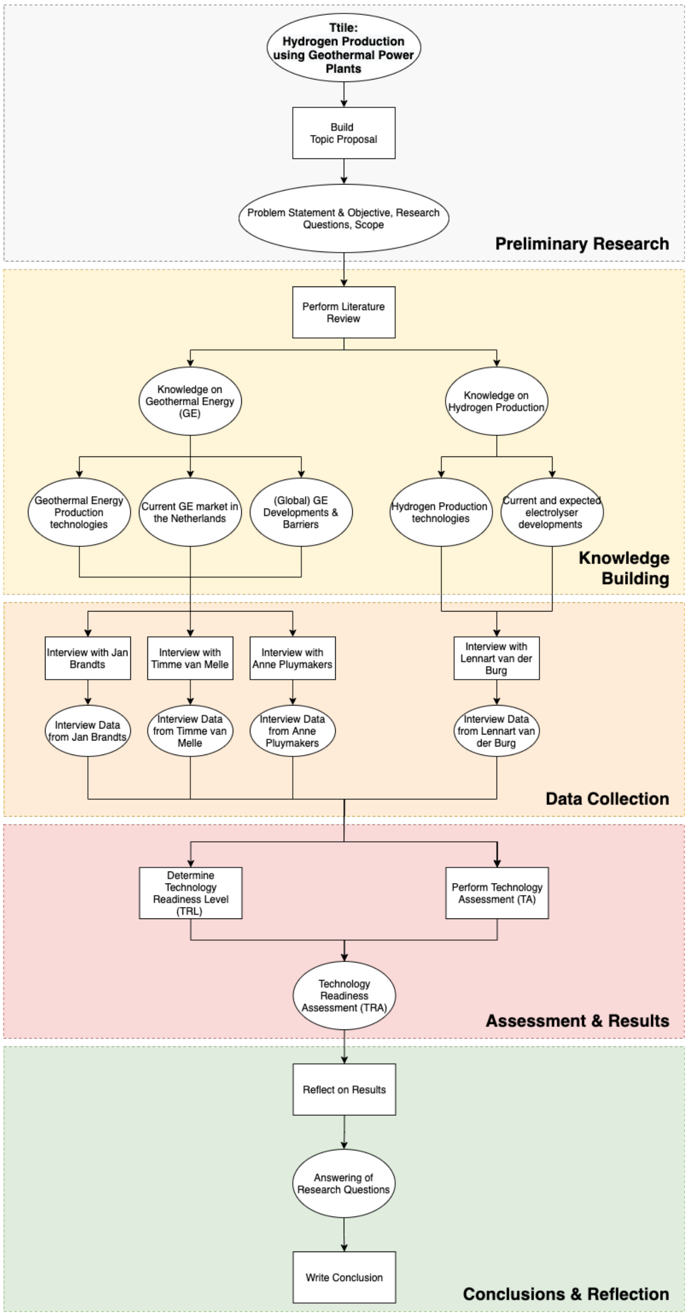

Figure 2.1: A global overview of the research approach for this thesis

energy, Jan Brandts from Engie, in order to verify the found information and to see if any relevant information is missing. Then, the technological capabilities of geothermal plants will be a part of the TRL framework performed in section 5.1. The assessment framework is performed using information gathered in the literature review and the interviews. The objective of the assessment is to be able to provide a complete as possible knowledge base. Therefore, allowing to answer this sub research question in the conclusion.

SRQ2: What are the challenges and potentials for the Dutch Geo surface with respect to electricity generation?

Whereas the previous sub research question focused on the technological capabilities of the geothermal plants, this sub research question focuses on the technological capabilities of the

Dutch geosurface. The question is set-up in such a way that it focuses on both the potentials and the barriers that could propel or slowdown the growth for the Dutch geothermal sector, as a result of Dutch geosurface developments.

Comparable to the previous sub research question, the approach will be to research the potential and barriers of the Dutch geosurface through a literature review. This literature will be verified and enriched through interviews conducted with experts on this topic. The experts are Jan Brandts from Engie, Timme van Melle from SCAN and Anne Pluymakers from the TU Delft. Their exact expertise on this subject will be elaborated on in section 2.2.1. Finally, the potential of the Dutch subsurface for ultra-deep geothermal activity will also be assessed in the framework performed in section 5.1. Again, this assessment will be performed using both the literature review and data retrieved from the expert interviews. The assessment will then allow to answer this sub research question, which is done in the conclusion of this thesis.

SRQ3: How can hydrogen production systems be implemented in geothermal electricity generating power plants?

This sub research question brings the attention to the hydrogen production aspect of this thesis. Through the literature review, the requirements and possibilities for hydrogen production are assessed. The information found is verified and further enriched through an expert interview. The interviewee is Lennart van der Burg from TNO, an expert within their hydrogen department, and focusing on electrolyser research and development. Finally, the knowledge gathered from both the literature review and the interview with Lennart is used to create the TRA on hydrogen production systems and what is required to implement the technology into a geothermal plant. Hence, the complete information found in the assessment framework will be used to answer this research question in the conclusion of this thesis.

2.1.2 Approach for Strategy & Market focused Research Questions

Following the technology focused sub research questions are three sub research questions (shown in section 1.5) which are focused on the strategy and market aspect of hydrogen production using a geothermal power plant.

SRQ4: What is the current state of the overall hydrogen & geothermal market in the Netherlands?

This question aims to understand where the current market stands with respect to general geothermal energy in the Netherlands. This is considered important as understanding of the current situation can form a basis to understand how the market might develop in the future. This question will be answered using information found through a literature review on the current geothermal market. This information will be verified and enriched through an interview with a geothermal energy market expert, Jan Brandts from Engie. Furthermore, an interview with geosurface explorer Timme van Melle, further enriched knowledge on where the focus of the market lies since the focus of geosurface explorers is argued to be in line with market focus as well. The Technology Readiness Assessment (TRA) conducted in chapter 5, uses the knowledge from the literature review and the data collected from the interviews. Completion of the TRA, allows for this sub research question to be answered in the conclusion.

SRQ5: What are drivers and barriers for the hydrogen and geothermal market in the Netherlands?

This sub research question is a question that follows naturally upon sub research question 4 as this question focuses on the drivers and barriers for the geothermal market to develop in future years. Such a question helps assess what is to be expected in the future, where opportunities lie for future geothermal plants and what could be detrimental to further development within the sector. This question is aimed to be answered using the expert interviews. This information is retrieved from interviews with experts such as Jan Brandts from Engie, Timme van Melle from TNO, Lennart van der Burg and Anne Pluymakers from the TU Delft. The data collected from interviews in combination with the literature review form the basis for the TRA framework which in return allows the researcher to answer this sub research question in the conclusion of chapter 6.

SRQ6: What are potential sales markets or applications for the commodity outputs of a geothermal plant producing hydrogen?

To strengthen the strategy for hydrogen production using geothermal plants provided in the concluding chapter of this thesis, it is argued to be necessary to understand what the sales market and applications of the geothermal plant outputs are. Since, if there is not a market, or the market is too competitive, then pursuing such a technology seems foolish. Therefore, also the sales market and applications is assessed using information retrieved from the interviews with Jan Brandts, Lennart van der Burg and Timme van Melle. Furthermore, the data from the interviews and additional information gathered during the TRA in chapter 5 allows for this question to be answered in the concluding chapter, chapter 6.

2.2 Research Methods

The following section will focus on the research methods used throughout this thesis. First, the qualitative interview data collection method will be addressed in section 2.2.1. Secondly, the assessment framework method will be addressed in section 2.2.2.

2.2.1 Qualitative Interview Data Collection

An interview can be considered as a qualitative method of data collection and strives to verify the technological findings of the literature review of the previous chapter.

This section will first elaborate on the reasoning for conducting expert interviews. Following this, the interview objectives will be addressed. Furthermore, an elaborate description will be given for the chosen interview method, a semi-structured interview method. The interview section will conclude with the method of data collection and coding.

Reasoning for Interview Research

There are various means of collecting qualitative data; observations, surveys and questionnaires, and, interviews. The choice for the qualitative data collection aspect of this thesis is the interview method.

Interviews have been chosen to be conducted since they allow for a more in-depth, personal and expert knowledge on specific phenomenon compared to high quantity and broader scope oriented methods such as questionnaires. Furthermore, observations of phenomenon in their (natural) surroundings are not required and could therefore be excluded for now. Interviews are also appropriate when little is already known about the research topic, which is currently the case for geothermal electricity and hydrogen production in the Netherlands. Hence, calling for expert interviews.

Interview Objectives

The objective of the conducted interviews during this research are fourfold. Firstly, to build upon, strengthen and amend to the knowledge and information found by the researcher regarding the respective topics of research in the literature review of chapter 3. Secondly, to help answer all sub research questions provided in 1.5. Thirdly, considering the interviews are conducted with a multitude of individuals with varying area's of expertise and with whom various topics have been touched upon such as technology, social acceptance and politics, amongst others, the interviews also have the objective to contribute to the assessment performed later in chapter 5. Finally, the fourth objective is to allow for the opportunity to gain unknown information or insights on current situations, developments or innovations in any area of expertise related to this thesis topic that which might have been missed beforehand.

Method of Interview

Following the objectives of the interviews, it is necessary to determine the method through which the interviews will be conducted. As lectured in the course *MOT2312 Research Methods* in the *MSc Management of Technology* by Dr. Ir. M. de Reuver, there are three distinct types of interviews that can be conducted; personal interviews, telephone interviews and self-administered questionnaires. Each type of interview has its respective (dis)advantages, related to costs, geographical coverage, staff requirements, anonymity, response rate, response completeness, depth and complexity, interview length, time, efficiency and level of bias. In order to restrain this thesis from becoming a thesis on interview methodologies, only the selected interview method will be further elaborated on; the personal interview. The personal interview type was selected due to the necessity of expert insights on the thesis scope as elaborated in section 2.2.1.

The personal interview type is an interview often done one-on-one in which specific questions can be asked directly by the researcher to the interviewee. The advantages of this type of interview are fourfold; the response rate to questions is high, questions can be further clarified and elaborated on if they do not seem clear at first, answers are often more complete as an interviewee can further argue their answers if needed, and finally, body language of the interviewee can be detected and analysed as an additional aid which allows the researcher to react to if necessary. Disadvantages for personal interviews also come in fourfold; high costs (often costs are in the form of time), a researcher is geographically limited, there might be a response bias from the interviewee in order to provide answers that the researcher wants to hear or a level of self-consciousness prohibiting them from truthful answers, and finally, confidentiality or anonymity is more difficult.

Besides the aforementioned types of interview, it is also possible to distinguish between the interview set-up. The possibilities are threefold; structured, semi-structured or unstructured. Again, for reasons similar to the reasons that restrained the elaboration of all research types earlier, only the selected interview set-up will be elaborated on; the semi-structured set-up. This set-up has been chosen due to the advantages that are accompanied with it; questions and interview topics that are deemed necessary to research are prepared before the interview in order to be able to obtain the relevant information, the set-up is flexible and gives room to touch upon topics during the interview that are relevant to the research but that were not on the researchers agenda beforehand, the questions asked can be tailored to new discoveries made during the interview, and finally, the obtained qualitative data from the interview can still be considered as reliable.

Hence, to shortly summarise, the interviews will be conducted in a semi-structured set-up with one-on-one personal interviews.

Data Collection & Coding

From the conducted interviews, new and additional information, or data, can be retrieved. In order to comprehend and process this data, a data collection method will be required. The data collection is primarily done in twofold; through a recording of the interview dialogue and by transcribing this dialogue thereafter. Needless to say, the recording and transcription is solely done after consent has been given by the interviewee. Should this not be the case, then the data collection will be done through manually taking notes during the interview and processing these notes thereafter. This, when used, can then be considered as a third method of data collection, although it is not favoured.

Once the data collection is completed using one of the aforementioned methods, it is essential to get a grasp on this data through coding. The goal of coding is to assign meaning to portions of the collected data and to confine data with similar properties to a group. This is up to the researcher and depends on the respective data. For example, in this thesis, all data collected from an individual interviewee that holds information regarding *geothermal energy* is accommodated under the section in the data collection chapter titled *geothermal energy*. The same holds for other overarching data topics that were addressed.

Interview Set-up

Due to the ongoing COVID-19 pandemic at the time of writing this thesis, the interviews have been conducted through a Microsoft Teams video conference. As described earlier, the interviews were of the semi-structured type. Therefore, per interview, varying topics with specific questions related to the interviewees expertise were prepared beforehand in order to guide the interview along the topics which the researcher argued to be necessary. However, the researcher allowed the interviewee to talk about any other topic or aspect that seemed relevant at the time or which followed logically upon a certain question. Hence, some topics were also addressed that were not prepared beforehand. The prepared topics and questions can be found in appendix A.

It should be noted that since both the interviewer and the interviewee are Dutch natives, the interview was conducted in Dutch. The questions and resulting answers that will be portrayed in the following section have been translated from Dutch to English by the researcher.

Interviewee Selection & Justification

The first interviewee goes by the name of Jan Brandts and works for Engie in the Netherlands. He has a MSc degree from the TU Delft in *Systems Engineering and Policy Analysis Management* (SEPAM) and started working for Engie in 2012 as a management trainee. His interests lay within the energy transition from his moment of graduation and his first projects were initially in the cold-heat storage sector (CHSS) as a project developer. In 2015 Engie wanted to pursue geothermal energy and raised the question internally; 'who would want to pursue this?'. Jan took this opportunity to start something completely new. Initially he started his geothermal adventures on his own, however in 2019 they had a team of 9 within Engie with Jan leading this team. After the acquisition of Hydreco Geomec [25], he now works in a team of around 35 employees. He is not the head of the newly founded team of 35. From the description above it seems almost self-explanatory why Jan was chosen to interview for this thesis as his expertise within the geothermal industry is evident. Furthermore, he was the pioneer within Engie regarding geothermal energy and hence has been through all stages of growth and development along the way. This gives him the most complete knowledge on the internal Engie business strategy and operations regarding this subject. Therefore, Jan is interviewed for both technology and market aspects regarding geothermal energy.

The second interviewee goes by the name of Lennart van der Burg and he works at TNO, the Dutch research institute for applied scientific research. Lennart works for the energy department at TNO which has around 900 researchers. This department works on multiple domains within the energy sector; wind, sun, biomass, carbon capture and storage (CCS) and policy. He himself is invested in research in the hydrogen domain, specifically in the hydrogen production research. For example, research into electrolysers. His background is in environmental economics and water technology. He has been at TNO for six to seven years of which the last three years in the hydrogen domain. His team mainly focuses on the technical aspects and improving the electrolysers. For example designing new membranes and electrodes for the current types of electrolysers but also for the second generations to come. Furthermore, his team also researches where they can implement their electrolysers and hence can be more market driven. They also test this in practice at for instance solar and wind farms onshore, but also offshore. Lennart was chosen as an interviewee due to his expertise on hydrogen production through electrolysis. Needless to say this is relevant due to the topic of this thesis; hydrogen production through geothermal plants. Being able to understand and research this technology, its application possibilities and future outlooks seems evident and cover a broad area related to the scope of this thesis.

Timme van Melle has 15 to 20 years of experience in the energy industry and is the third interviewee. Previously working for Essent, he worked in oil, gas and electricity markets but he has made his way into the renewable energy sector. The last 10 to 15 years he has been focused on energy systems as a whole, trying to understand how the entire process of energy systems can be reduced to zero carbon emissions. Hereby focusing on multidisciplinary aspects of energy systems such as calculations related to costs and energy network capabilities. Through SCAN he also has some experience with UDGE although he does mention at the start of the interview that he is no geologist, but merely well-known within the industry and knowledgeable enough to partake in discussions about it. The data collected from Timme will mostly be related to knowledge on geosurface exploration in the Netherlands as this is one of his main activities currently.

The final interviewee is Anne Pluymakers who is an assistant professor at the TU Delft in the experimental *Fluid-Rock Interaction* domain. She started as a researcher at the TU Delft in 2015 after finishing her PhD at the Utrecht University in 2014. Her expertise lies in research related to rock mechanics and the influence and interaction of rock with fluids. She was approached for this thesis initially to gather subsequent knowledge on characteristics, the potential and barriers for geosurface exploration and exploitation.

Furthermore, it can be noticed that each interviewee has a specific area of expertise and comes from a different sectors. Either they are more operationally focused or more research focused, or they are from the geothermal or from the hydrogen sector. This was done on purpose in order to cover the full spectrum scope of this thesis. Furthermore, the varying expertise and knowledge allows for the collection of both technology and market related data. This results in each interview to be unique and to contain varying topics and question asked. An overview of the varying topics and questions asked per interviewee can be found in appendix A.

2.2.2 Technology Readiness Assessment (TRA) Framework

Following the literature review which will be done in chapter 3 and the qualitative data collection through expert interviews, is the analysis of this thesis topic through combining two existing frameworks into one; the Technology Readiness Level (TRL) framework and the Technology Assessment (TA) framework. The former focusing on a specific technology maturity and the latter focusing more on an assessment of potential impacts and application of a technology. Together, formed under the overarching framework; *the Technology Readiness Assessment (TRA) framework*. Both the TRL and the TA will be elaborated on in the following sections.

Technology Readiness Level (TRL) Framework

As this thesis focuses on a nonexistent technology within the Netherlands as of the moment of writing it seems logical to assess where the various aspects of the technology itself stand with respect to development.

A well-known and richly researched framework that tries to gather an as complete as possible understanding of technology maturity is the Technology Readiness Level (TRL) framework developed by NASA. The TRL is a conceptual measurement tool that estimates technological maturity on a scale ranging from an *idea* to a *fully functional technology* [78]. TRL creates a technology eligibility evaluation for various parameters of a technology [9]. TRL can help in decision-making, creates technology performance objectives alongside the current state of the technology, and can argue barriers to be overcome for further development. Experts agree that TRL are the most common measure for assessing the readiness of new technologies or new applications of existing technologies to be incorporated into a product [36]. It should be noted that the TRL does not measure or assign a risk level to a project. Neither does it assess the ability to achieve cost or performance goals [13]. It is solely a fundamental means for evaluating the maturity of a technology and its ability to perform within a larger system [36].

The TRL is based on a nine level scale as shown in figure 2.2. A TRL rating is assigned to various parameters of a technology [56]. Looking at the scale, the various levels are tangible observations. Therefore, the Technology Readiness Level given to a certain parameter of a technology is based on if that tangible aspect has been achieved by the respective parameter or not [56]. For example, successfully achieving TRL 4 (technology validation in lab) does not move the technology to TRL 5. TRL 5 is only achieved once there has been an actual validation of the technology parameter in a relevant environment [56].

Figure 2.2: Overview of TRL's [8]

Each assessed parameter will be given an individual *Readiness Level* (RL) based upon the scale and tangible observations as described in section 2.2.2. From the various topic RL's, the minimum RL will be the RL of the overarching subject. This is argued to be logical as an entity is only as strong as its weakest link, irrespective of the level of development of other topics within. As an example, if topic A would receive a TRL of 4, topic B would receive a TRL of 8 and topic C would receive a TRL of 9, then the overarching TRL would be 4 as topic A would be leading.

In chapter 5, the researcher will use the TRL framework to assess the technological maturity of the four main parameters of a geothermal plant producing hydrogen in the Netherlands. These being; the geosurface exploration capabilities, the drilling capabilities, the geothermal plant capabilities and the hydrogen production capabilities. The TRL will be determined using the information from literature found in chapter 3 and data from the interviews in chapter 4. Hence, research, analysis and an objective viewpoint will determine the development phase and the level that a technology parameter is on. From this, and using the proposed TRL from the TRL scale in figure 2.2, each parameter will be assessed on its technology readiness.

However, for this thesis the researcher would also like to focus on other aspects besides solely the technological developments. In a paper by Vik et al. (2021), it is argued that the TRL has various limitations with the main limitation being that it focuses on technological developments and not enough on commercialisation and organisational aspects. They argue that *"technology is a multi-faceted subject and assessing technological readiness does not offer a comprehensive understand of a technologies maturity, nor what is necessary for a successful technology implementation"* [78]. Fundamentally meaning that the TRL alone does not consider the technology market environment..

Technology Assessment (TA) Framework

To accompany the TRL framework in the TRA, is the aforementioned TA framework. The TA attempts to anticipate future development of technologies and their possible market impacts and applications. The assessment can then be used to feedback into relevant decision domains [61]. The TA can be widely adopted in different domains such as private firms, sectors and government agencies [61].

This framework entails a methodology which somewhat writes a history of the future, or forecasting - a technique that uses known data to make argued guesstimates to determine the direction of future trends - which is supported by judgements of experts and data as will be done in this thesis [61]. This TA will build upon a knowledge base created in the literature review in chapter 3 and the data collected from the expert interviews in chapter 4 in order to create an assessment of future developments, market applications and impacts for a geothermal plant producing hydrogen.

Methodological issues regarding TA include the knowledge-control dilemma (as estimating future impacts and applications is speculative but constructed on a well-argumented base), and the distance between promoters of new technology (often insiders) and contestants (often outsiders) [61].

Justification for the Technology Readiness Assessment Framework

For this thesis, the researcher proposes to solely assess the technology and market aspects. A social acceptance aspect is disregarded for now as it is argued to be irrelevant at this moment in time since it could take multiple years for such a technological project to be initialised [20]. Hence, social influence should be assessed in a later development stage. Furthermore, for the same reasons, the researcher would also not like to pay full attention to the regulatory aspects. However, basic regulations and political aspects are regarded to be important to a certain extent and hence will be partly implemented within the technology assessment.
The TRA is considered to be a suitable framework in order to research and answer the sub- and main research question of this thesis. The combination of the TRL and the TA ensures that both the current technological maturity and the expected future technological developments, impacts and applications are assessed. In the eyes of the researcher, this TRA framework, creates a solid basis for decisions to be made.

Chapter 3

Literature Review

The following chapter will touch upon relevant literature for various aspects of this thesis.

3.1 Geothermal Energy

The following section will address literature related to Geothermal Energy Systems (GES). GES considers all types of plants involving geothermal actitivy such as pure heat extracting and electricity generation. It should be noted that, although GE is just one aspect of the overarching fusion of Hydrogen production and Geothermal Energy addressed in this thesis, the standalone GES is not the main topic of this thesis. Therefore, the depth of the literature review on GE will be more generic and solely aims to ensure enough information is presented to understand said fusion.

3.1.1 General Introduction on Geothermal Energy

Geothermal Energy (GE) is a non-carbon renewable source of energy and hence, considered as one of the energy sources to be used in the sustainable energy transition for the future [68]. GE is a renewable source of energy found in the form of heat which is retrieved from various depths within the earth's crust. Within this crust, the earths temperature generally increases around 3 $^{\circ}C$ for every 100 meters of depth. However, it should be noted that this is an average and can vary dependent on the location on earth. This is due to the earths crusts varying thickness and ground composition throughout. The heat emerges from the interior of the earth, which originates from the decay of radioactive materials within, resulting in a molten mixture that essentially generates and stores thermal energy.

Classifications

As of March, 2021, there is no uniform internationally accepted classification of various Geothermal Energy Systems for depth or temperatures. Various classifications can be found in literature, however these vary per country or institution [35]. Hence, for the continuation of this thesis, a set of three classifications for both depth and temperature has been defined in order to ensure consistency throughout.

Regarding the depth classifications, *shallow* GES will be regarded as no deeper than 150 meters, *deep* GES will range from 150 meters until a maximum of 4000 meters whereas *Ultra-Deep* GES will be all systems that extract heat from depths of over 4000 meters. Furthermore, literature mentions that the depth at which one needs to drill to exploit a certain amount of geothermal energy is not linear and varies around the world due to differences in crust compositions and thicknesses [28]. It is argued that geothermal gradients can vary from around 20°C per kilometer depth at northerly latitudes such as in Norway to around 40°C per kilometer at other locations across the globe. On average the gradient is around 25°C globally [28]. Hence, because the temperature of a production well is not linearly related to its depth, but can vary due to its location on earth and the earths crust thickness at that location, a separate classification for GES is based on the well temperature as well. Lower temperature wells (< 50°C) will be classified as *cool*, medium temperature wells are considered for the range of 50°C until 150°C and will be classified with the term *warm*. Higher temperature wells (> 150°C) will be classified as *hot*. An overview of the classifications can be found in table 3.1. It should be noted that a classification such as an Ultra-Deep cool well might be nonexistent (under 50°C Geothermal Well Temperatures (GWT) at a depth of over 4000 meters) due to the aforementioned geothermal gradients.

Depth / Temperature	< 150m	150m - 4000m	> 4000m
< 50°C	Shallow - Cool	Deep - Cool	Ultra-Deep - Cool
50°C - 150°C	Shallow - Warm	Deep - Warm	Ultra-Deep - Warm
> 150°C	Shallow - Hot	Deep - Hot	Ultra-Deep - Hot

Table 3.1: Overview of the classification for geothermal well depths and temperatures

Existing Geothermal Plants in the Netherlands

Due to the scope of this thesis, it seems logical to understand the potential geothermal classifications found in the Netherlands. Currently, there are around 21 installations producing geothermal energy as of the beginning of 2018. Taking a closer look at the geothermal locations provided by a national geothermal institute in the Netherlands, *Geothermie Nederland*, all but two of the 21 installations can be considered to be *Deep - Warm* installations according to the aforementioned classification. The other two are considered *Deep - Cool* installations. An overview of the respective power, well temperatures and well depths of the current installations in the Netherlands can be found in table 3.2.
As stated, the overview in table 3.2 provides geothermal installations currently in operation or in the final phases of their delivery. However, it should be noted that the company *Hydreco Geomec* acquired by ENGIE in 2020 [74], has another six projects in their development funnel that are related to geothermal installations or suitable location research [32].

3.1.2 Energy Production Technology

The driving force behind geothermal energy installations is heat that has been retrieved from within the sub-surface of the earth. This retrieved heat can be used for multiple purposes which are dependent on characteristics such as the retrieved temperature. Applications are heating, cooling or the generation *green electricity**.

Traditionally, geothermal electricity plants were built on the edges of tectonic plates where the availability of higher temperature geothermal resources was more abundant. This high temperature (> 150°C; *hot* classification as per table 3.1) was required to be able to produce enough water-based steam to drive electricity producing steam turbines, better known as *Rankine Cycle Turbines*. However, through the introduction of the so-called Binary Cycle Power Plant (BCPP) (which will be elaborated on later in this section), electricity generation from *warm* temperature (< 150 °C; table 3.1) heat reservoirs was made possible. Therefore, geothermal plants were

*Electricity generated with zero carbon emissions using theoretically unlimited natural resources such as wind, solar or heat, amongst others

Installation Name	Thermal Power [MW_{th}]	GWT [°C]	Well Depth [m]
Aardwarmte Vierpolders[a]	16	82	2200
Aardwarmte Vogelaer	18	85	2500
Ammerlaan TGI[b]	7	70	n/a
Agriport A7	14	90	2250
Het Grootslag Andijk	14	92	n/a
Duijvestijn	8	70	2300 - 2950
Geopower Oudcamp	18	95	2800
Geothermie de Lier	16	87	2400
Hoogweg Aardwarmte	15	60	n/a
Floricultura Heemskerk	10	100	2700 - 2900
Green Well Westland	11,5	85	3000
Haagse Aardwarmte Leyweg [a]	7	76	n/a
Aardwarmte Koekoekspolder	7,4	73	1950
Mijnwaterproject Heerlen	n/a	28	± 500
Nature's Heat	16	85	2500
Trias Westland[c]	25 - 45	90	2300
Trias Westland 2	15	90	n/a
Van den Bosch 1 & 2	9	60	1600
Van den Bosch 3 & 4	7,3	70	1800
Wayland Energy	18	67	2000
Greenbrothers	6 - 9	25 - 45	500 - 1250

[a]Owned by Hydreco Geomec
[b]The first project to deliver heat to both Dutch greenhouses and private homes simultaneously
[c]Initially meant to go to 4000 meter depth, however this was later deemed economically unfeasible

Table 3.2: Overview of the geothermal plants in the Netherlands [34]

applicable in a wider geographical area than solely along the traditional edges of tectonic plates [4].

The innovation that drove the emergence of lower temperature geothermal power production was the introduction of closed loop intermediary fluids that have a lower boiling point than water [39]. In principle, the energy production using these intermediary fluids is the same as the aforementioned water-based steam flash plant. The intermediary fluids are brought to a certain pressure and temperature until they are *flashed* and evaporated into a steam, which in turn powers a turbine. This process is known as an Organic Rankine Cycle (ORC). The intermediary fluids however are cooled after exiting the turbine, to then be re-heated again later on in the system to re-evaporate and power the turbine. Hence, the intermediary fluids are in a closed system. The fluids are heated using the heat retrieved from the *warm* geothermal reservoirs. A schematic overview of such an ORC in a BCPP is provided in figure 3.4.

As mentioned in previous paragraphs, there are various types of plants available to produce heat and electricity from the subsurface of the earth. Regarding geothermal power generation, there are currently four options. These are elaborated on below and are accompanied by a short description;

Direct Dry Steam Plants

These plants use the traditional water-based low pressure, high volume steam to drive the power producing turbines. The steam temperature required is 150°C or higher [20]. A simple schematic overview is shown in figure 3.1.

Flash Plants

Flash plants are similar to dry steam plants and the most common geothermal electricity plants in operation today. The difference is in the method of steam creation. Flash plants use a process called *flashing*, where high pressure, high temperature water is rapidly released into a low pressure reservoir. This rapid pressure release causes the high pressure water to vaporize or *flash* into a steam which in turn drives a turbine. Flashing can be done once, twice or thrice, depending on the starting temperature of the water or steam as each flash decreases the temperature. Flash plants work best with starting temperatures greater than 180°C [20]. A simple schematic overview is shown in figure 3.2.

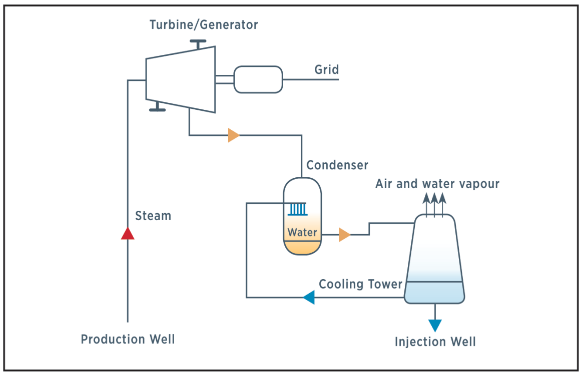

Figure 3.1: Simplified dry steam plant [20]

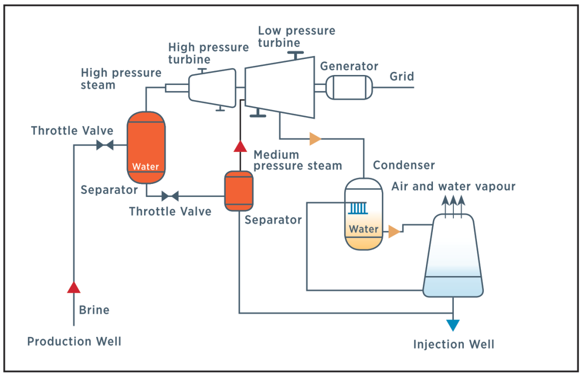

Figure 3.2: Simplified double flash plant [20]

Binary Plants

Binary geothermal power plants are similar to conventional fossil or nuclear plants in that there is a working fluid incorporated in the plant system that undergoes an actual closed cycle [81]. Binary plants are plants that operate well in geothermal fields and depths with warm to cool temperatures as per the classifications of section 3.1. This is due to the aforementioned ORC, the use of an intermediary fluid (with a boiling temperature that is well below that of water) in a closed loop cycle as an alternative to water-based steam. In principle, these plants work similar to flash plants. The main difference is that binary plants use the geothermal heat to evaporate the intermediary fluid into a steam, which then drives a turbine. Typically, binary plants operate using geothermal well temperatures of 100°C until 170°C. Lower temperatures are possible, however this greatly reduces the efficiency of the system [20]. Comparing these operating temperatures to the current operational plants in the Netherlands shown in table 3.2, it seems that these systems could be applicable, or already used, in the Dutch geothermal climate. A simple schematic overview is shown in figure 3.3.

In a study performed by DiPippo (2007), the efficiency of binary plants was studied for various GWT. This is an important aspect as it is key to understand at which GWT a plant can or cannot be economically feasible with respect to the return of investment timeframe, a key issue for project developments. DiPippo compared existing BCPP with the ideal theoretical thermodynamic cycle. However in this research, he also considered the fluid from the geothermal well to not be an isothermal fluid (an assumption that a fluid remains at the same temperature during flow operations), but a fluid that cools as it is transferred up to the plant and working fluid cycle [19]. Hence, coming to a more theoretically and practically just conclusion. DiPippo concluded that for case studies with GWT between 100°C and 140°C, the thermal efficiency of

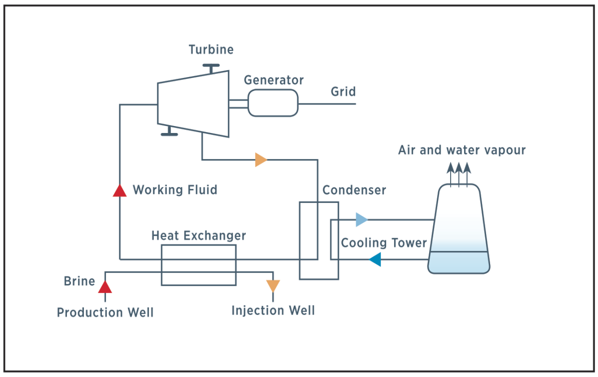

Figure 3.3: Simplified BCPP [20]

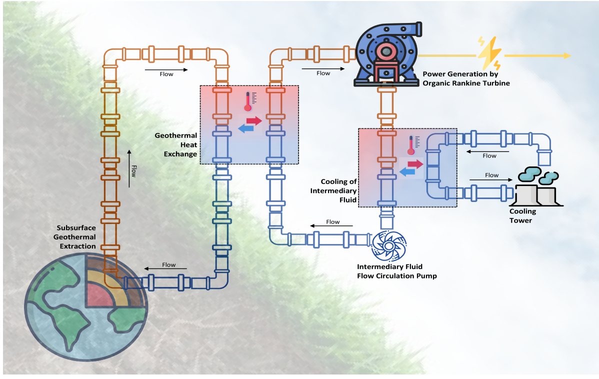

Figure 3.4: Schematic of a BCPP with an ORC

a BCPP is only between 8% to 10% [19]. However, the maximum theoretical thermal efficiency based on the ideal triangular cycle, which is comparable to an ideal carnot cycle, is shown in the fifth column of table 3.5. Relatively to its theoretical maximum, the BCPP has an efficiency of 58% ± 4% for the aforementioned temperature range. The results of the study on six existing BCPP can be found in table 3.5 [19].

Plant and location	Cooling method	T_H (°C)	T_0 (°C)	η_{th} (%)	$\eta_{th,mx}^{TRI}$ (%)	η_{rel} (%)
Brady Bottom Cycle, NV, USA	ACC	108	16.8	8.0	13.6	59
Heber SIGC, CA, USA	WCT	165	15	13.0	24.8	52
Husavik Kalina, Iceland	WOT	122	5	10.6	17.4	61
Miravalles Unit 5, Costa Rica	WCT	165	23.9	12.8–16.3	19.2	67–85
Nigorikawa, Hokkaido, Japan	WCT	140	13	9.8	18.2	54
Steamboat, NV, USA[a]	ACC	152	23	7.9	14.4	44

ACC, air-cooled condenser; WCT, water cooling tower; WOT, water once-through.

Figure 3.5: Relative efficiencies for several geothermal plants [19]

As mentioned, Binary Cycle Power Plant (BCPP) thermodynamically exchange the heat from a geothermal source to an intermediary working fluid with a low-boiling point which is incorporated in a closed cycle within the plants system. An example of an intermediary working fluid is *isobutane*, which is used in a geothermal binary plant located in *Steamboat Springs* in Nevada, USA. The isobutane fluid has a boiling temperature of -12°C (11°F). The exchange of heat from a *warm* geothermal source (50°C - 150°C) hence can ensure that the working fluid is exchanged to a steam. This steam in turn powers an electricity producing turbine.

However, one can imagine that the aforementioned isobutane working fluid, used in the Steamboat Springs geothermal plants, is not the only possible working fluid in existence. Cao et al. (2020) conducted a research on the evaluation and optimization of different working fluids in novel geothermal plants using an electrolyser which is fed by a two-stage ORC. For their research they primarily focussed on four organic working fluids named; Isopentane, R123, R141b and n-pentane. A few relevant thermophysical properties of the aforementioned working fluids are shown in Table 3.3.
It is interesting to note the difference in boiling point temperature between the proposed working fluids used in the research conducted by Cao et al. (2020) in Table 3.3 and the isobutane working fluid used in the Steamboat Springs BCPP (-12°C) [38]. Furthermore, there are papers stating that BCPP can operate on multiple working fluids with lower boiling temperatures such as propane(-42°C), more commonly known as Liquefied Petroleum Gas (LPG). However, butane has a 9% higher energy content as a gas which would seem as a more important measure than

Properties	Isopentane	R123	R141b	n-pentane
Molar Mass [$\frac{kg}{kmol}$]	58.12	152.90	117.00	72.15
Density [$\frac{kg}{m^3}$]	2.44	1464.00	1234.00	620.80
Boiling Temperature [K]	301.1	300.97	305.0	309.2
Boiling Temperature [°C]	27.95	27.82	31.85	36.05

Table 3.3: Relevant thermophysical properties of the proposed working fluids [13]

the boiling temperature. Also, the higher boiling temperature for isobutane allows for a lower effort to bring the working fluid back to a fluid within the closed-loop cycle. It is interesting to note the significant difference in working fluid boiling temperatures proposed by Cao et al. (2020) and fluids such as the isobutanes and propanes, hence proposing that if it is chosen to build a BCPP, this is to be investigated more extensively.
Furthermore, Cao et al. (2020) concluded that the choice of the working fluid did not greatly affect the production rates of their proposed BCPP. However, still mentioning that R123 performed slightly better at the lower temperature ranges of their Geothermal Well Temperatures (GWT) (±185°C), which is still significantly higher than current GWT in the Netherlands provided in Table 3.2. Finally, Cao et al. (2020) concluded that an improvement of 40% in the total output rate can be obtained for an increase of 30°C in GWT.

Enhanced Geothermal Systems

One of the main challenges for the aforementioned geothermal plants, is the economic feasibility. Mainly resulting due to the depth that one needs to drill to be able to access the temperature required to efficiently run the plant. Especially if we scope towards a country such as the Netherlands, which geographically is not close to the edge of any tectonic plates as this is where higher temperatures are more widely available and easier to access.

To overcome this, Enhanced Geothermal Systems (EGS) has been developed. EGS allows geothermal plants to extract heat from areas under the ground which are normally too dry and impermeable for geothermal systems. It works around the issue of areas lacking in natural permeability or fluid availability by drilling into these impermeable areas and injecting fluids into these areas under high pressure with the idea of re-opening or enlarging some pre-existing fractures [29]. This technique is similar to *Fracking* which is often used in the oil & natural gas industry and a proven drilling technique [7]. However, it is often frowned upon for apparently causing earthquakes. It is argued that EGS does not cause these issues as it does not require the same levels of pressure as fracking does and operates mainly on the natural temperature difference between the hot rock and fluids which creates a more natural expanding and contracting environment. Essentially, it can be regarded as *re-watering* a dry area under the earth's crust.

This technique could potentially be interesting if there are areas in the Dutch subsurface that have significant temperatures relatively close to the surface but low permeability.

Innovations & Conceptual Geothermal Plants

Due to the increasing interest and installed capacities of geothermal plants globally, but mainly in the United States, developments in types of geothermal plants are evolving as well. Often times, new geothermal plants, follow from the barriers or challenges of other. The same holds for the concept geothermal plants from the company *Eavor*.

Eavor has developed a geothermal plant that removes the necessity of a deep water reservoir and solely relies on a heated rock environment. This allows for their system to, theoretically, be installed anywhere in the world. They do this by using the main benefits of a BCPP. However, instead of using the warm water from a reservoir to heat an intermediary fluid at the surface, they use the hot rock at depth and heat the intermediary fluid below the ground through multiple laterally installed pipelines in a closed system with turbines above ground [17]. In essence, they take the closed loop system from a BCPP that is usually above ground, and enlarge and install it below ground. A schematic is shown in figure 3.6. With a first testing phase of this concept being done in Bavaria, Germany, Eavor is looking to commercialise. However, the costs of the first phase alone are already estimated to be 200 million euros and the complete project is expected to be 2.4 billion euros upon completion [17].

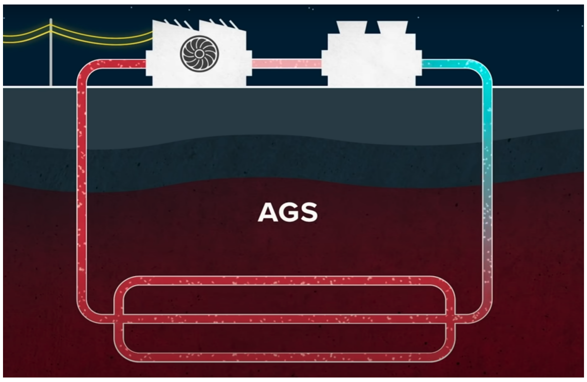

Figure 3.6: The Eavor AGS concept [17]

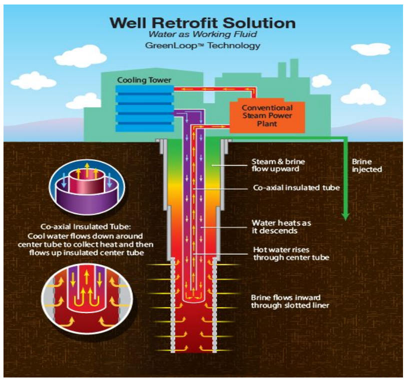

Figure 3.7: The Greenloop AGS concept [17]

A less Capital Expenditures (CAPEX) intensive geothermal concept is the concept developed by the company *Greenfire*. Greenfire aims to use existing oil and gas wells where all information is available on the depth and temperature of the hole in order to reduce costs and hence to ensure that payback times are reduced significantly. By modifying these existing and abandoned wells, they propose to implement a vertically oriented closed-loop system, again based on the BCPP idea. Also, similar to the Eavor concept, they do not rely on water reservoirs to be present as the hot rock at depth is expected to heat the intermediary fluid in the closed loop system. A schematic of this concept is presented in figure 3.7.

A third and final concept is one of the company *Sage Geosystems*, which was founded in June of 2020 by former oil and gas industry veterans.
They realise that there is not one single optimal geothermal design solution that is applicable for all applications and all subsurface environments, therefore they have multiple solutions. One these is a concept that implements elements of both AGS and EGS. Initially, their idea is to drill a conventional well which through EGS is fractured and then filled with a highly conductive fluid instead of traditional water. This fluid, since highly conductive, can transfer high temperatures from far below the depth of the well, up towards the well inlet. Within the well itself a vertical closed loop system is built similar to the system of Greenloop. However, the Sage system is more efficient as it allows for higher temperatures to interact with the closed loop system [17]. A schematic of the Sage concept is shown in figure 3.8

In essence, although concepts, innovations and ideas such as these within the geothermal industry make the idea of geothermal energy everywhere in the world less futuristic as the dependency on water reservoirs because less of an issue.

Sustainability & Emissions

Geothermal Energy (GE) is deemed as a proven sustainable source of heat. Using GE instead of natural gas as a heat source, on average, results in a reduction of 88% of CO_2 emissions. CO_2

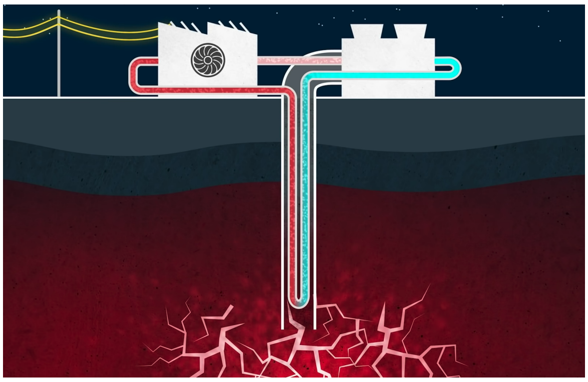

Figure 3.8: The Sage AGS & EGS concept [17]

emissions can be almost completely eliminated for a GES once the electricity used to power the systems within the plant, such as pumps for the production and injection wells, are powered by green energy [33].

An example in the Netherlands on emission reductions due to GE can be found in *Floricultura Heemskerk* plant which was introduced earlier in table 3.2. According to the owners, the introduction of this geothermal plant is saving the usage of 5.000.000 cubic meters of natural gas each year, or 9.000 tons of carbon dioxide [27]. To bring into perspective, that is equivalent to the consumption of just under 21.000 barrels of oil [3]. Although a welcome reduction, it is still a minor development compared to the 825.000 barrels of oil used by the Netherlands per day in 2019 [70].

Intermittency & Consistency

A common issue addressed with leading green renewable electricity producing systems such as wind and solar farms, is the intermittency of these systems. Intermittency is regarded as the extent to which energy production capabilities of a power plant are unintentionally low, often due to availability of the driving power source. For example. due to inconsistent (high) wind speeds for wind farms or varying solar radiation (due to clouds or seasonal earth rotation) for solar farms.

Hence, one of the leading advantages of GE over other renewable energy sources such as wind and solar energy, is its continuous year-round availability [20] and therefore high capacity factor. The Energy Information Administration (EIA) in the United States of America, one of the leading countries in the geothermal industry, has been keeping track of the capacity factors of various (renewable) energy sources on a month-to-month basis. From their data, it can be seen that GES have a capacity at an average between 72% and 75%, and are only second to nuclear energy at over 90% capacity [21]. whereas, wind energy struggles to achieve capacity factors over 40%, solar struggles to even utilize 30% of capacity. Do note that the aforementioned percentages correspond to capacity factors on US soil. Capacity factors can differ depending on location. This holds for wind, solar but also for geothermal energy production.

Therefore, due to the geographical scope of this thesis, it is also interesting to understand the situation in the Netherlands. According to the *Centraal Bureau voor de Statistiek* (CBS), a data collecting authority in the Netherlands, capacity factors for onshore wind farms have not exceeded 30% [15]. whereas offshore wind farms have not exceeded 45% [16]. Likewise, solar farms in the Netherlands under perform significantly with respect to capacity factors, averaging only about 10%. Geothermal energy in the Netherlands is estimated around the same capacity factors as mentioned earlier in the United States, at around 75% [51].

3.1.3 Geothermal Market

As this thesis strives to provide a strategic plan towards implementing Hydrogen Production Systems (HPS) in Geothermal Energy Systems (GES), it is deemed essential to understand how also the GE market is expected to develop in future years. This section will provide an overview of the expected global and national markets. Although the global market is not part of the main scope of this thesis, it is argued to be relevant for this section as global market developments and technology innovations can affect the Dutch market potential.

In May of 2018, a consortium of four organisations; *Stichting Platform Geothermie*, *Dutch Association of Geothermal Operators (DAGO)*, *Stichting Warmtenetwerk (WN)* and *Energie Beheer Nederland (EBN)* published a document titled *Master Plan Geothermal Energy in the Netherlands* which will be named MPGE further onwards. It should be noted that the main focus of the MPGE is on heat generation in contrast to electricity generation, which is more essential for the main topic of this thesis. However, the MPGE does mention electricity generation possibilities of Geothermal Energy Systems (GES) in the Netherlands. It is stated that for electricity generation, geothermal energy needs to be extracted from depths of more than 4000 meters where Geothermal Well Temperatures (GWT) exceed 130°C [33].

Hence, a potential challenge for electricity generation using GES currently, is that there is a rather extensive amount of information available on surface data for depths under 4000 meters due to past oil and gas drilling activities, but not enough on depth beyond 4000 meters. For example, more than 4000 boreholes have a depth greater than 1000 meters on land in the Netherlands ever since the first drilling began in 1886 [49]. However, in comparison, only 41 boreholes have achieved depths of over 4000 meters and only six have gone deeper than 5000 meters. An overview of the amount of drilling operations in the Netherlands is shown in the schematic in figure 3.9. This figure shows where the current focus lies regarding drilling operations. One can conclude that this focus barely goes below ultra-deep depths of 4.000 meters. In figure 3.9 light blue dots correspond to oil and gas drilling operations below 4000 meters, dark blue dots correspond to oil and gas drilling operations above 4000 meters, whereas the red dots indicate drilling operations specifically conducted for geothermal operations.

Nevertheless, the consortium does acknowledge that more knowledge on greater depths could prove to be an important driver for geothermal electricity generating technology and therefore, become important for production of sustainable green energy. However, as mentioned, the generation of electricity is not a main aspect of the MPGE presented. One should note however that, therefore, this does pose as an interesting topic to research further and can possibly help amend the MPGE.

As of 2018, the production of geothermal energy (although mainly in the form of heat and not electricity) was in the range of 3 petajoules*. With respect to market development, the MPGE estimates a GE production increase to 50 petajoules in 2030 and more than 200 petajoules in 2050 [33].

Existing Geothermal Binary Plants

Under the pretext of learning from the experiences of others, it seems essential to assess existing Binary Cycle Power Plant (BCPP). The amount of operational BCPP is not extensive, as there

*1 petajoule per year can heat around 20.000 households. The total demand of heat in the urban environment is 400 petajoules per year.

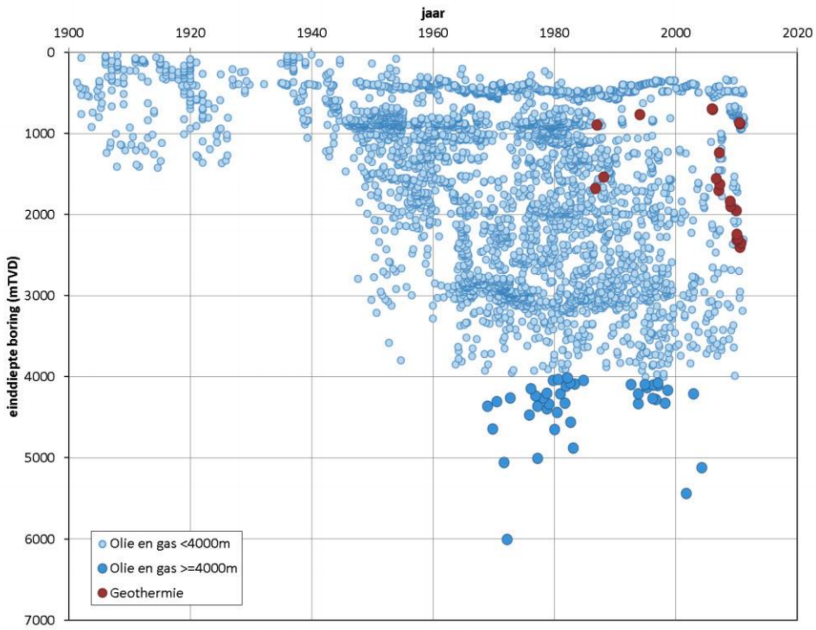

Figure 3.9: Schematic overview of drilling operations and depths against time in the Netherlands [49]

are only 12 that have an installed capacity of over 10MW and are operational as of April 2021 globally. An additional three plants are hybrid binary-solar PV power plants which predominantly focus on electricity production through a binary process (binary capacities: 85,7%; 80,3%; 65,3%).

Furthermore, developments in existing flash and dry steam geothermal power plants are the addition of binary cycles to waste heat from the preliminary flash and dry steam cycles. This increases the total capacity of the respective power plant (binary capacity: 1%; 1,8%; 13%; 28,3%). For example, geothermal flash electricity plants in Kawerau, New Zealand and Wairakei, New Zealand, use the separated brine (which can still be at a temperature of over 100°C) after the initial flash cycles of the geothermal plant, to boil the intermediary working fluid in a binary cycle to drive additional turbines [10].

An overview of existing Binary Cycle Power Plant (BCPP) can be found in table 3.4. Most of the BCPP plants are located in the United States. In later stages of research, it would be interesting to contact a few of these BCPP in order to learn from their developments and operations.

Potential & Growth

Using the publicly available deep surface data from oil and gas exploration and production in the Netherlands, the Dutch research institute for applied scientific research (*Toegepast Natuurwetenschappelijk Onderzoek* (TNO)) analysed the Dutch geothermal potential in 2012. The potential was assessed to its technical and economic potential until depths of 4000 meters. The assessed potential for electricity production was rated at around 34 Petajoules (PJ) per year, or 9,5 TWh per year [50]. Whereas the total electricity consumption in the Netherlands was estimated at 120 TWh per year in 2017 [14], amounting to around 8% of the total electricity need in the Netherlands. However, it should be noted, that these estimates do not consider the entirety of the Dutch geothermal potential, as not the entire subsurface of the Netherlands has been mapped. Furthermore, the aforementioned production potential only assesses the potential for depths that allow for electricity generation.

Installation Location	Power [MW]	Owner	Cooling Method
Blue Mountain, USA	50	Nevada Geothermal Power	-
Brawley, USA	13	Ormat	Water
Heber Complex*, USA	89	Ormat	Water
Mammoth, USA	29	Ormat	Air
McGinness Hills	90	Ormat	Air
Ngatamariki, New Zealand	82	Mercury	-
North Brawley, USA	13	Ormat	Water
Ormesa (OG I & OG II), USA	40	Ormat	Water
Don A. Campbell, USA	41	Ormat	Air
Puna, USA	38	Ormat	Air
Raft River, USA	11	Ormat	Water
San Emidio, USA	11	Ormat	Water
Salt Wells, USA	18	ENEL	-
Te Huka, New Zealand	23	Contact Energy	-
Cove Fort, USA	25	ENEL	Water
Olkaria III, Kenya	139	Ormat	Air
Platanares, Honduras	35	Ormat	Air
Jersey Valley, USA	10	Ormat	Air
Steamboat Complex, USA	70	Ormat	Air & Water
Tungsten Mountain, USA	26	Ormat	Air
Tuscarora Power Plant, USA	18	Ormat	Water
Amatitlan, Guatemala	20	Ormat	Air
Zunilla, Guatemala	23	Ormat	Air
Neal Hot Springs, USA	22	Ormat	Air

Table 3.4: Overview of existing BCPP [44]

However, the geothermal potential is far greater when also considering the re-use of waste heat from electricity producing geothermal plants alongside electricity production. For example, if there would be an introduction of ultra-deep geothermal systems in the Netherlands, plants such as binary- and flash-plants could be retrofitted with so-called *low temperature bottoming cycles*. These use the redundant low temperature heat after electricity generation for heating applications such as normal heat demand that Dutch GES are used for today. Combining the electricity and heat production in the same plant would naturally further increase plant efficiency [20].

Furthermore, in a research conducted by Li et al. (2014) on the comparison of GES with RES such as wind and solar using data from the World Energy Assessment (WEA), it was determined that the availability of GE is far greater than solar and wind together. Nevertheless, the overall installed capacity compared to the potential capacity of GE, and the increase in the 5 years prior to the research conducted in 2014, is trailing greatly compared to solar and wind. An overview of their findings are provided in table 3.5.

Energy Type	Energy Potential (GW)	Installed Power (GW)	Increased Power Last 5 Years (GW)	Installed Capacity (%)
Solar	49900	139	116	2.4
Wind	20300	318	159	5.5
Geothermal	158500	12.0	1.10	0.21

Table 3.5: Comparison of global RES [52]

Subsurface Exploration Tool: ThermoGIS

To bring the known information into perspective, TNO has created a tool to visualize the geothermal potential of the Dutch subsurface. The tool, called *ThermoGIS*, is a publicly available web-based geographic information system whose main purpose is to support industry and government with the development of Geothermal Energy Systems from the Dutch subsurface [73]. As mentioned, the main contributor to ThermoGIS is TNO. ThermoGIS provides maps that entail information on subsurface layer compositions, depth, thickness, permeability and temperatures of potential aquifers in the Netherlands. Furthermore, using TNO's in-house analytical techno-economic calculations, they can provide estimated information on the economic, technological, power and thermal potential of the various known subsurface locations throughout the Netherlands.

A minor introduction of what the the ThermoGIS tool offers is shown in figure 3.10 and figure 3.11. For example, figure 3.10 shows the Geothermal Well Temperatures (GWT) of an aquifer known by the name of the *Dinkel Subgroep* (DCD). The respective GWT depths are shown in figure 3.11. From these two figures, a potential GWT between 160°C and 170°C lies underneath the area around Rotterdam and The Hague. However, these temperatures are obtained at depths of around 5000 meters which have not been achieved as of today as mentioned earlier. Potentially more achievable depths of 3000 until 4000 meters provide GWT of 120°C until 140°C for the Rotterdam and The Hague area. Do bear in mind that the above example is just a single snapshot of the ThermoGIS tool. Area's other than the aforementioned Rotterdam and the Hague area are also visible through adjustments of tool inputs. The above merely demonstrates its applicative and informative potential.

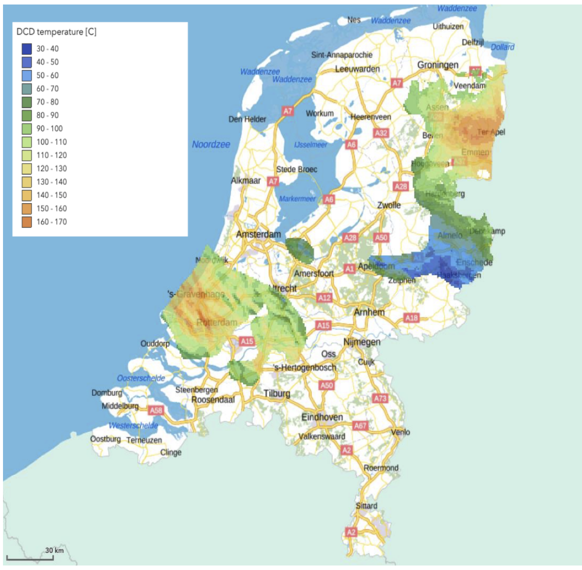

Figure 3.10: GWT in the Carboon subsurface

Figure 3.11: Relative GWT depths in figure 3.10

Barriers

Although GE potential is available, the acceleration of GES implementation has been lagging compared to the aforementioned RES such as wind and solar. Following from section 3.1.3, the Li et al. (2014) paper tried to discover the reasons why geothermal power generation has been lagging behind wind and solar. The main barriers to geothermal development as of today are threefold; financial, social-environmental and administrative [20].

Firstly, the financial barriers. Geothermal plant developments require large Capital Expenditures (CAPEX) investments before any certainty can be created for the potential of a plant site regarding exploitability and hence, profitability [20]. This is often related to ground research and test hole drilling which is necessary and can cost multiple upfront millions with little success certainty as surface research alone is often not decisive enough to present conclusive data. Therefore, geothermal sites are often based on argued *guesstimates*. This barrier is argued to be overcome from governmental financial injections in uncertain geothermal site research. Taking away the risk and hence increasing the incentives for private developers. However, governments can only take this risk upon themselves to a certain extent as well.

Secondly, social-environmental barriers form from the necessity for social and environmental impact assessments of plant sites. These assessment can require significant amounts of time and effort [20]. Furthermore, as often times geothermal plants can be built close to or within residential areas, this can lead to social demonstration of plant developments, sometimes irrespective of impact assessment results. Further increasing barriers and project delays.

Thirdly, are the administrative barriers related to issues such as licensing, permits, regulations, assessments and research. These aspects need to be addressed carefully as, for example, certain regulations can significantly delay projects if not adjusted correctly for innovations such as those happening in the geothermal domain [20]. Even within the Netherlands, geothermal energy is relatively new and often still operates according to old oil- and gas regulations, which ultimately could be irrelevant or unnecessary regulations. However, it should be noted that this barrier might have already been overcome as the Dutch government as reviewed the old oil- and gas regualtions for geothermal energy as of 2021 [6].

3.2 Hydrogen Production through Geothermal Power Plants

Following the previous literature review section on GE, this section will focus on the second and main fragment of this thesis; hydrogen production. This section of the chapter will elaborate on basic hydrogen theory, its classifications, production methods, potential suppliers and developments and innovations in the domain. Furthermore, this section focuses on answering sub research question 3 as proposed in section 1.5 through a literature review;

7. How can hydrogen production systems be implemented in geothermal electricity generating power plants?

3.2.1 General Introduction on Hydrogen

Roughly 75% of all mass on earth consists of hydrogen, making it the most abundant chemical element known to man. However, hydrogen does not occur naturally as a standalone element and can only be found in a compounding configuration with other elements in liquid, gas or solid form. The most well-known configuration is hydrogen (H_2) compounded with oxygen (O), better known as water (H_20). Furthermore, the hydrogen element is often compounded with carbon elements, creating hydrocarbons such as natural gas (CH_4) [1].

When in its gaseous form and mixed with oxygen, hydrogen is a highly flammable and explosive gas that can be spontaneously triggered by a spark or heat ($>500°C$). Additionally, hydrogen is the lightest element known to man. The combination of molecular weight of hydrogen and its explosive properties allow hydrogen to have an energy density (under elevated pressure levels) that is almost three times higher than natural gas. 120 megajoules (MJ) per kilogram (kg) for hydrogen over 45 MJ per kg for natural gas [76].

Production Methods

As mentioned earlier, hydrogen molecules are found in compounding configurations with other molecules such as natural gas. The natural occurrence of pure hydrogen molecules is not as abundant as its existence and therefore, it needs to be separated from its configurations. This is can be done through various hydrogen production methods which will be shortly listed and explained below for general knowledge;

1. *Thermochemical Production Methods*
   Thermochemical production methods focus on separating atoms from their molecular structure. The most common thermochemical, and hydrogen production process in general at the moment of writing, is Steam Methane Reforming (SMR). This method uses two successive high-temperature steam reactions (between 700°C and 1000°C) to separate the carbon molecules from the hydrogen molecules in methane gas (CH_4, also known as natural gas) [24]. This method is not deemed relevant for this thesis and hence will not be further elaborated on due to its production method resulting in carbon emissions and its widespread use in the current hydrogen economy. Additional thermochemical methods are coal gasification, biomass gasification and a solar thermochemical method. For reasons similar to SMR, these methods will not be elaborated on.

2. *Biological Processes*
   In such processes, microbic bacteria and algae can use sunlight and organic matter to produce hydrogen through biological reactions [24]. Such technologies are also deemed sustainable and a green method for producing hydrogen, however still in early stages of research and development and unrelated to this thesis topic to elaborate on.

3. *Electrolytic Processes*
   Electrolytic processes use a process called electrolysis to split hydrogen and oxygen from a water molecule [24]. The main source of energy for this process is electricity and hence, if the electricity is produced in a green and sustainable manner, can result in a green and sustainable hydrogen production method. Therefore, this process will be elaborated on in section 3.2.2 to research the possibilities in combination with electricity produced using geothermal plants.

However, keeping the focus of this thesis in mind, (green) hydrogen production through geothermal systems, a more elaborate focus will be put on the electrolysis method as this method can, theoretically, produce green hydrogen through the generation of green electricity by a geothermal system. Knowledge and focus points from the earlier section focusing on types of relevant geothermal plants, the Binary Cycle Power Plant (BCPP), in the Netherlands will be kept in mind as well.

3.2.2 Electrolysis

Regarding the second main topic of this thesis, green hydrogen production, this section of the literature review will highlight the relevant knowledge on this topic. As mentioned, electrolysis requires electricity, a direct electric current (DC), to allow for a chemical reaction that separates the hydrogen and oxygen molecules in water, which would not occur otherwise. Electrolysis happens through a set of electrodes, the cathode (negative) and the anode (positive), which is embraced by an electrolyte. An electrolyte has to be a good conductor, meaning it can carry an electric current but hence can be various types of materials. In the case of hydrogen production, it is often water. By setting an electric current on the two electrodes, ions are transferred through the electrolyte. In the water electrolysis case, these ions are either H^+, OH^- or O_2^- [30]. A membrane finally separates the resultant gases H_2 and O_2.

Types of Electrolysers

There are three different types of electrolysers producing hydrogen; the acidic Polymer Electrolyte Membrane (PEM), the Alkaline and the Solid Oxide Electrolyte (SOE). A schematic overview of the working principle of these three electrolysers is shown in figure 3.12.

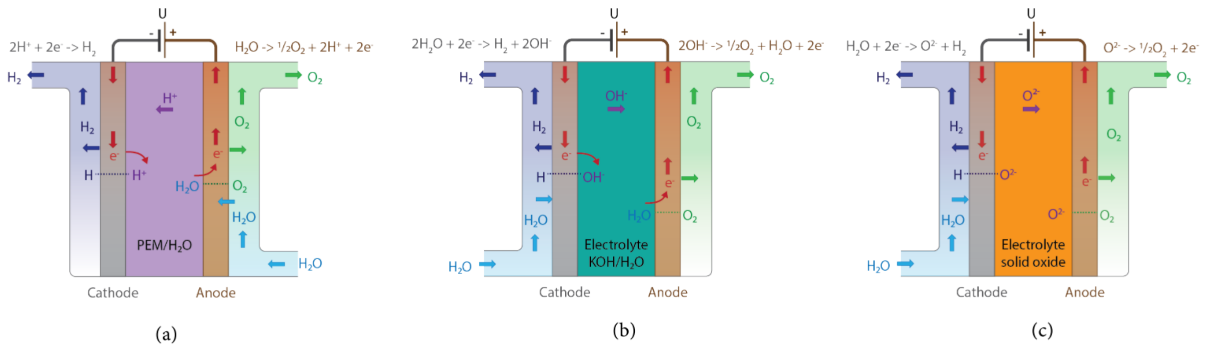

Figure 3.12: (a) the PEM; (b) the Alkaline; (c) the SOE [30]

From Guo et al. (2019) we learn that the PEM and Alkaline electrolysers are similar in their structure. The main difference is that a PEM uses a *thin-film electrode assembly* which the Alkaline does not. Furthermore, Guo et al. (2019) states that the Alkaline electrolyser is a mature technology with a low CAPEX and can deliver production capacities that are well-suitable for large-scale hydrogen production facilities. Their production capacities are a factor 2.5 larger than their PEM counterparts ($1000\frac{m^3}{hr}$ over $400\frac{m^3}{hr}$) [37]. However, the comparison paper does state that Alkaline electrolysers have the disadvantages of having a relatively slow start-up, are corrosion prone, have a complicated maintenance scheme and the devices themselves contain a significant amount of components which make it complex [37]. Therefore, they argue that the PEM is the electrolyser of the coming years as, although production capacity is currently lower, they solve the issues addressed for the Alkaline electrolyser. PEM electrolysers start up fast, are not prone to corrosion, require only simple maintenance, operate at lower temperatures (50°C to 80 °C and are less complex than Alkaline electrolysers [37]. However, high CAPEX and expected lifetimes of the PEM electrolyser being half of the Alkaline electrolysers still prohibit exponential developments for PEM. Regarding the SOE, Guo et al. (2019) state that these electrolysers were barely available commercially at the time of writing and underdeveloped.

Electrolysers Developments

It will be interesting to look at electrolysers in development or available commercially in order to assess the combination of hydrogen production through geothermal power.

Gallandat et al. (2017) amended and reproduced a list of electrolyser suppliers that was initiated by Bertuccioli in an earlier phase. This list is shown in table 3.6 and provides an overview of potential electrolyser suppliers in the case that a Ultra Deep Geothermal Energy (UDGE) plant with hydrogen production is constructed in the Netherlands. However, it should be noted, that this list is last updated in 2017 and hence, should a UDGE plant be constructed, the developments of Alkaline and PEM electrolysers will most likely be far superior to the electrolysers provided in table 3.6. Therefore, this table should currently only be used for an *as-is* situational sketch.
As one can see from table 3.6, there are only a few suppliers of electrolysers available in the Western market. Also, Gallandat et al. (2019) failed to incorporate electrolyser suppliers from Asia. This is because very little is known about such activities in that market according to Gallandat et al. (2019). However, they do state that companies in China and Japan are developing

Company	Country	Type	Model	Capacity $[\frac{Nm^3}{hr}]$	H^2 Purity [%]	Elec. Consump. $[\frac{kWh}{kgH_2}]$	Efficiency [%]
Acta	Italy	Alkaline	EL1000	1	99.94	53.2	74.0
Erredue	Italy	Alkaline	G256	170	99.5	59.5	66.2
Hydrogenics	Belgium	Alkaline	HyStat60	60	99.998	58.2	67.7
Idroenergy	Italy	Alkaline	Model120	80	99.5	62.7	62.8
Nel Energy	Norway	Alkaline	A485	485	>99.9	42.5 - 49.3	79.9 - 92.6
McPhy	France	Alkaline	McLyzer	60	>99.5	57.8	68.1
Teledyne Energy System	USA	Alkaline	EL-N	500	99.99	N/A	N/A
Wasserelektrolyse Hydrotechnik	Germany	Alkaline	EV150	220	99.9	59.1	66.6
Areva H2 Gen	France	PEM	E120	120	99.99	53.8	73.2
H-TEC Systems	Germany	PEM	EL30/144	3.6	N/A	55.4	71.1
ITM Power	UK	PEM	HGas1000	132	99.99	N/A	N/A
Proton OnSite	USA	PEM	Hogen C30	30	99.99	65	60.6
Siemens	Germany	PEM	SILYZER200	225	99.5	N/A	65 - 70

Table 3.6: Overview of electrolyser suppliers and their Key Performance Indicators (KPIs) [30]

electrolysers. For this research, analysing and committing research to various Asian electrolyser suppliers is argued to be out of the scope of this research as it is more focused on the technological assessment and possibilities within the geothermal domain. However, it should be noted that, with the economic growth of China, this market would be an interesting topic to dive into for another research within this domain.

In recent years there is also a relatively new electrolyser type by the name of Anion Exchange Membrane (AEM), with currently only one manufacturer worldwide; Enapter. In essence, AEM works under the same principles as the three described earlier, using electrodes to create an electron transport through membranes in an electrolyte. However, unlike a traditional Alkaline electrolyser, a single AEM cell is separated into two *half-cells* by an anion exchange membrane. Each half-cell consists of an electrode, a gas diffusion layer and a bipolar plate [23] as shown in figure 3.13. Multiple cells can be connected in order to create a *stack*. This set-up allows the hydrogen and oxygen to be produced under pressures of 35 bar and 1 bar respectively [23]. This pressure difference ensures a very high purity of 99.999 % when dried. Enapter also claims that their modular electrolysers produce 500 $\frac{NL}{hr}$ (normal liter per hour) at the aforementioned values while only requiring 6.0 kWh of energy per liter [23]. Comparing this with the electrolysers presented in table 3.6, the Enapter AEM requires only around a tenth of the energy that existing Alkaline and PEM electrolysers (as 1 kilogram of water is equal to 1 liter).

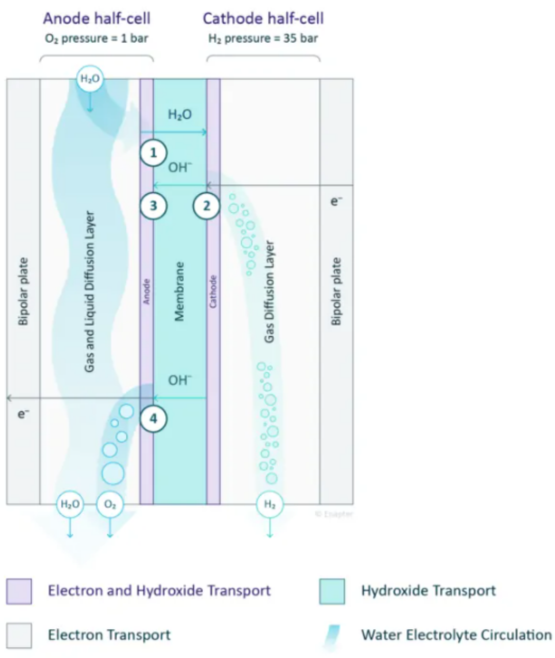

Figure 3.13: Schematic of AEM Electrolyser [23]

Chapter 4

Data Collection

4.1 Interview Results

The following section will provide the results obtained from the conducted interviews. Each interviewee was an individual with an own expertise and hence, most interviews are unrelated to one another. Expertise was selected upon relevance to the thesis scope and topic and will be elaborated on within each individual subsection. Hence, they were chosen based upon the researcher's objective judgement sampling. Judgment sampling is a form of purposive sampling and is often used to retrieve rather specific information which is otherwise not easily accessible [66]

4.1.1 Interview Results - Jan Brandts (Engie)

This section will focus on the actual interview and the takeaways from it. The following is a summary of what was asked and what was answered. If direct quotes from Jan were used, this will be stated in between quotation marks. The takeaways are categorized into the topics as they are identified in appendix A. Note that the first topic, related to personal questions and the introduction of Jan has already been elaborated on in the section titled *Interviewee Identification* in section 2.2.

Geothermal Energy at Engie

At first, Geothermal Energy (GE) at Engie was a funnel of potential projects and idea's whereas Hydreco Geomac, as of this moment to be mentioned as solely Hydreco, was the market leader. Hydreco however was linked to a public party called *Brabant Water* which possessed a limited amount of money for projects. That is where Engie was able to step in and hence the acquisition was decided upon. Engie also had developers whereas Hydreco was able to ensure the implementation and exploitation of the GE alongside their own respective developers as well.

The length of a GE project is often extensive as well, potentially taking six years from the initial idea until the first moments of drilling. Even before actually drilling the first hole and deciding to put 20 to 25 million euro's into a project, a team could have already spent one to two million euro's in costs related to working hours and research. During the course of the first six years arrangements would be made regarding permits, grants, ground research, long term exploitation contracts with customers, arranging and designing the heat distribution network, tenders and so on. This period can not be greatly shortened as most aspects of such a project have extensive lead times before decisions are made on aspects such as the permits or grants.

Ultra Deep Geothermal Energy

Engie and Jan's team are looking into Ultra Deep Geothermal Energy (UDGE) alongside their main geothermal research and projects. However, for them the largest problem of UDGE is that there is a lack of information about it and the knowledge on the geosurface of the Netherlands. According to Jan, UDGE is a gambling game at the moment. The way that it would work now is that you take a set of idea's on potential drilling locations, which you argue but cannot fully back up to be interesting, and hope for the best once you start test drills. More often than not the result would be negative, but the investment of this initial test drill is nevertheless significant and has to be earned back at some moment in time again. As long as the knowledge on the geosurface of the Netherlands is not improved, this *gambling* business model does not seem like a successful one.

Interestingly enough, without any influence of the researcher, Jan mentions the potential combination of UDGE for the production of electricity and heat together;

"You would never do it [Ultra Deep Geothermal Energy] solely for electricity production, but always in a combination of heat with electricity production as a byproduct."

However, Jan does mention that he wonders if that alone is a reason to go into UDGE. Following this, the researcher mentions that he does not consider electricity production to then be a byproduct but the main product of UDGE through an Binary Cycle Power Plant (BCPP) with heat as a byproduct after the electricity production cycles. As a reaction, Jan mentions that the existing UDGE plants that he knows of always have heat as the main business case and have electricity production as the byproduct. The higher temperature heat would then be used for the big industries requiring high temperatures for their respective processes. The business case there then is that they can perform these processes using a sustainable and green source of heat compared to more carbon emitting processes used traditionally.

As a reaction to the aforementioned *gamble* of the Dutch geosurface, the researcher asked Jan why the knowledge is so scarce. The researcher also mentions the *ThermoGIS tool* which maps the various layers of the Dutch geosurface well, which was elaborated on in section 3.1.3. Jan clarifies that he knows this tool well. Jan replies that ThermoGIS is good in mapping the various types of rock layers in the surface, but that it is not capable of identifying the flow of fluids or other substances. Why that is not possible he does not know. Nevertheless, that flow is the one thing that you require for an undertaking such as UDGE. Therefore, although relevant information, the ThermoGIS tool does not benefit all too much on identifying interesting drilling locations. Furthermore, if one would find a location with a pocket of water, it is still unclear how difficult it will be to retrieve that fluid. Is the pressure at such a level that it will come to the surface by itself or is it necessary to pump it up manually? Those factors are factors that ThermoGIS can not clarify, it does not map the so called permeability of the surface so test drilling is required to find out.

Nevertheless, Jan says that they use the ThermoGIS tool extensively and they work together closely with TNO as well. The tool combines subsurface pictures with existing drilling data from past oil and gas drilling operations. Also, some locations have lots of drilling holes due to the expectancy of gas there at the time since the Netherlands is a gas country. However at some locations there are barely any drill holes. This does not mean that there is not any water, there just was not enough gas to be profitable in the past, which was the main focus. Hence, these so-called *dry wells*, locations with not enough gas could still be interesting locations to research with respect to water. Currently there is also a program called *Seismische Campagne Aardwarmte Nederland* (SCAN), with a mission that focuses on identifying the properties of unknown subsurface areas in the Netherlands. They strive to create a complete picture of the

Dutch subsurface [65].

An interesting lesson that the researcher can take from the previous paragraphs, is that it will be interesting to further research subsurface identifying methods. A method that could supply in permeability and flow assessment of the subsurface could greatly reduce risks for UDGE. Following the identification of SCAN, they will be contacted for an interview as well during this thesis as they are expected to have more knowledge on the missing subsurface knowledge.

Seasonal Demand & Production

During the interview with Jan the topic of seasonal demand as studied in the literature review was also addressed. Jan stated that in the summer months the demand for heat does reduce. Especially in the built environment this demand decrease is measured. Due to the decreased demand, the plant is often shut down as it is difficult to decrease the production amount with for instance 10%. It can be adjusted slightly, but not so much. Often a geothermal plant is on or off. Although the shutting down of the plants in the warmer months allows for maintenance, it is a problem as revenues are absent throughout these months as well.

Therefore a way to bridge the shutting down of a plant is welcome. The researcher proposes the aforementioned idea of a BCPP that produces electricity alongside heat and if that would be an option. Furthermore that if the electricity demand decreases as well, the plant could produce hydrogen in order to keep capacity factors of the plant as high as possible. As a reaction to this, it sounds like an ideal world and if it would work then that would be great. Theoretically this idea is possible. However, Jan logically states that that is not all that is necessary. He states that even if you would have a BCPP that produces electricity and heat, you need to question yourself if it would make sense to implement a hydrogen producing electrolyser into the plant as well. Since if the hydrogen would only be produced in the two or three months that demand for electricity and heat is low, this means that the Capital Expenditures (CAPEX) and Operational Expenditures (OPEX) of this added electrolyser needs to earn itself back in this short period of time. Greatly influencing its business case.

However, what is interesting is the increased capacity factor. A geothermal plant has large upfront CAPEX and low OPEX. Preferably you would therefore want to run the plant as much hours as possible to get a Return on Invesment (ROI) as soon as possible. Nevertheless, the increased depth almost increases production cost exponentially for a BCPP which then again could counter the aforementioned benefit of a higher capacity factor.

Organisation

Organisationally, Jan stated that the geothermal department within Engie is solely focusing on the depths on which most of the information is available. So often times these will be area's where there have been significant amounts of oil or gas drilling. Interestingly enough, often times these drill holes go to around the 3000 meter range, which is where gas is mostly found. This means that they often skip the 500 meter to 2000 meter depths. Jan mentions that the 500 to 2000 meter range could still be interesting due to the greater chance of water flow since the rock is less compact, although temperatures would be lower.

Hence, within the organisation you can notice that they are not focusing on being the leader or taking the lead with respect to UDGE research or projects. Mostly, the risk is too high and information on ultra deep surfaces are too scarce to act upon for now. Nevertheless, they do follow news and updates related to UDGE. Hence, to answer interview question 5B, their focus is currently solely on geothermal heat where knowledge is more available. This also partly answers question 5E in which one could conclude that they take a low risk or risk mitigating role.

Related to interview question 5D, opportunities with foreign projects, the team in the Netherlands itself does not work together with foreign projects. However, there are projects related to UDGE within other Engie country offices such as a plant that Engie ahs in Indonesia. Jan mentions that the business case for using hydrogen as a means of storage could be interesting there, since due to bad or no existing infrastructure, Engie first needed to implement an entire infrastructure of road, electric and pipeline networks to be able to build and process the outcomes of the plant itself. Here a hydrogen based storage system on-site could potentially be an interesting business case as this would eliminate the pipeline infrastructure throughout the country. Then transporting the produced energy from the plant through hydrogen tanks over roads.

From a short research performed after the interview with Jan an article was found to solidify Jan's statment on the aforementioned build of infrastructure leading to significant cost increases and time consumption of an Indonesian geothermal plant. The article quoted Supramu Santosa, the CEO of *PT Supreme Energy* on the journey to the Muara Laboh, geothermal power plant in West Sumatra, Indonesia in which Engie was a partner [31], and stated the following;

> *"Before drilling, we first had to build a road to the mountain. The length of the road is approximately 30 km. For that alone it will cost around USD 30 million. This activity took three years, especially since the Muara Laboh PLTP had to be built in the mountains."* - Supramu Santosa

Social & Political

In order to fully implement a sustainable geothermal energy infrastructure within the Netherlands, albeit solely for heat or also more related to UDGE, there needs to be social and political backing as well. Especially if we further upon aforementioned aspects such as the risks related to the unknown geosurface information in the Netherlands.

The researcher asked Jan if there is a chance to involve Dutch politics for subsidiaries and risk reduction in for instance geosurface exploration, hence relating to question 6B. In essence, if the information was available which would allow companies to extract a new sustainable energy source from the earth, then that would be of interest to the government, would it not? Jan agrees. He mentions a discussion between the government and the stakeholders involved in the geothermal market which he has shared with the researcher. This discussion discusses what is required for geothermal energy to take off. One is subsidiaries but also mechanisms to mitigate risks for ground research. If the government truly wants to give UDGE a chance, then they can not expect the market to invest tens of millions of euros in a gamble. So the collaboration and discussions are there, they are just rather slow.

Additionally, a barrier for UDGE currently are the policies and regulations. The current geothermal market works according to *de Mijnbouwwet* (the Mining Law). It has been updated in 2002 and focuses on *laws related to researching and extracting minerals and other mining related activities* [69]. However, the updated version from 2002 mainly focuses on the extraction of oils and gases and not so much on geothermal activities according to Jan. Therefore, for geothermal research, researchers sometimes need to take safety precautions and follow certain regulations which are irrelevant to geothermal practices but which do require extra time, organisation and finances. Although sometimes unnecessary. It would be interesting if this is changed to lower the safety regulations, finances and time when possible for less deep geothermal activities. The same however holds for UDGE. There are discussions to change these regulations to be more applicable for geothermal practices as it is a growing entity but they are currently not available. So, potentially this can help ensure UDGE to be interesting, when the time is right.

Market

Jan has been rather critical on UDGE, mainly also because of the high-risk aspect of it. At the moment you just do not know what you are going to get once you start drilling. However, all risk and financial aspects aside, he thinks that if it would work it would be a great development for the sustainable market. Especially because high temperature geothermal developments can help decarbonize the entire process industry which are reliant on higher temperatures. So in that respect there would be a market. The same holds for green electricity, the market for green electricity is there due to the Paris agreement and further developments regarding the sustainable economy.

To answer question 7A, Jan is unsure about the business case with respect to the pricing of geothermal electricity compared to other green electricity producers such as wind and solar PV systems. So he still questions its competitiveness and the possibility for subsidiaries for UDGE. Nevertheless, deep geothermal energy is a proven business case in the Netherlands, so potentially UDGE can be in the future as well. Especially since there are existing binary plants that are functional in other areas in the world such as Iceland en the United States as shown in table 3.4. Although keeping in mind that they do achieve higher temperatures at shallower depths, simplify the business cases for these plants.

4.1.2 Interview Results - Lennart van der Burg (TNO)

This section will focus on the actual interview and the takeaways from it. The following is a summary of what was asked and what was answered. If direct quotes from Lennart were used, this will be stated in between quotation marks. The takeaways are categorized into the topics as they are identified in appendix A. Note that the first topic, related to personal questions and the introduction of Lennart has already been elaborated on in section 2.2 titled *Interviewee Identification*.

Hydrogen & Electrolysis

To understand where Lennart's and TNO's focus lies at the moment within the hydrogen domain, question 2A was questioned. The main focus of TNO's research within the hydrogen domain is mainly on the technical aspect. They focus on how hydrogen is produced by looking, researching and developing new membranes and electrodes which can be applied to existing but also to next generation electrolysers. However, they also look into where and for which applications they can implement the electrolysers that they are developing, such as developing electrolysers for offshore applications and applications in heavy industry. This helps find and overcome challenges in order to be able to scale up in a later stage.

To be able to consider electrolysers and hydrogen production as a product of a BCPP, it is essential to understand what the effects of production of hydrogen would be. Therefore, a combination of question 2C and 2E was asked which was related to electrolyser efficiencies and developments. According to Lennart, developments are really taking off. He stated that in the two months preceding the interview, they have achieved more than they did in the entire year before. This is mainly due to a significant increase in the capacity of people and parties working on such developments. Internally within TNO but also externally. Regarding efficiency developments progress is also evident with electrolyser efficiencies at TNO improving from 60% to 70% or 75%. However, it should be mentioned that these figures are regarding the small scale test beds. The next step is to show that efficiencies can be met for large scale facilities and the industry level. Furthermore, they need to see if the materials that they invented are producible at larger quantities and larger dimensions. It will be important to find producers that can deliver such quantities. In short, the technical innovations are definitely promising and available, they just need to be scaled, tested and implemented in larger quantities which is the challenge to overcome next.

Considering the technological developments and innovations for electrolysers there is, unfortunately, a huge gap between ambitions and what is currently actually being done. Lennart states this in response to question 2D, regarding the 6GW production ambition in 2024 and the 30GW ambition in 2030 of the EC. With respect to the 170MW mentioned in the article, the production capacity has grown to 300MW globally as of May 2021. Nevertheless, the Netherlands is severely lacking behind its production goals. Not just for electrolysers, but regarding renewable energy production and carbon emissions reductions in general according to Lennart. Ambitions are one aspect, but not acting on these ambitions in an orderly manner is another. There are little to no differentiating laws, subsidies, tax abatement's or financing to an acceptable level. Therefore, to increase production twenty-fold by 2024, a lot more needs to happen then just the plans and ideas proposed currently, there should be more action. Lennart does mention that he can see the price of the European Union Emission Trading Scheme (EU ETS) rising - *a permit system that caps the amount of CO_2 emissions an entity can emit. These permits can be bought and sold between entities wanting to emit more or less CO_2* -, as is the carbon tax. However, he is missing a true outspoken commitment to renewable fuels that could increase and fuel investments and innovations within that sector.

Business Case & Market

In light of question 3A, it should be noted that hydrogen is not a new phenomenon in the Netherlands, it is already used in significant amounts of quantities throughout. You can find it in refineries for fuels, for plastic production and so on. However, it is all on a carbon emitting gas basis and not in a green or blue manner. If we only look at green hydrogen, through Steam Methane Reforming (SMR), then the market is almost non-existent. In the Netherlands there are around 300 cars that are fueled by hydrogen but other than that, there is not really a demand for (green) hydrogen at the moment. Hence, making the business case for projects as the one proposed difficult. Once there is a mandate or some sort of forced change from grey to green hydrogen, then the demand will be enormous. For example, take a look at Tata Steel, they require around 3GW of hydrogen, imagine their demand would be altered to even a small percentage of green hydrogen. Hence, the demand for hydrogen is not non-existent but that for green hydrogen currently is.

So, imagine that a mandate or certain policies would be implemented which stimulate the use of green hydrogen, an interesting variation to question 3B is, how easily or quickly can industry make that change in the future? According to Lennart, scaling is possible but is not sure how quickly that can happen. As an indication he mentions that currently, electrolysers are still being built by hand. Large players in the electrolyser industry, companies such as *Thyssenkrupp* or *Siemens*, still build the cells by hand as these only just left the Research and Development (R&D) phase. This labour intensive process currently makes building large hydrogen GW producing plants difficult as an average Polymer Electrolyte Membrane (PEM) produces 3MW, hence requiring around 400 PEM stacks with each stack containing around 500 cells. It will take a while if all of this is done by hand. Then considering, that that means you only have the stacks, not anything else that the plant needs. Currently there are plans to build electrolyser producing automated plants in 2023 or 2024 but that means that you do not even have the actual hydrogen producing plant past those years. So in short, it can take a significant amount of years before the green hydrogen production market will accelerate. The previous can be regarded as an answer for question 3E.

Regarding a comment from the researcher if electrolysers or hydrogen producing facilities could not just be implemented into existing energy producing plants, Lennart mentioned that they would require new facilities and infrastructure. But this infrastructure can be coupled into the existing systems and infrastructures so besides the actual new facility itself, not too many adjustment need to be made.

Following the aforementioned, the interview focused on other barriers or challenges that are arising for hydrogen or electrolysers in general, relating to questions 3C and 3D. Lennart stated that there are significant barriers and challenges. Besides the mandates and topics already spoken about, is the topic of raw materials. Electrolysers require the materials iridium and platinum for their electrodes. Both which are rather scarce materials globally. At the current scale this is not a problem yet, but with the prospects of scaling in the future it is. At a GW scale, electrolysers would require all of the iridium currently available globally, hence creating a problem. Also iridium is a byproduct of platinum and the increasing demand has greatly increased prices for both. The current price for iridium is around 185.000 euros per kilogram. Now of course, more mines could be opened in the future and more geosurface research could be done to find more mining locations but as it stands now, this proves to be a large barrier and challenge for expansion. But can be possibly fueled by increased demand.

Seasonal Variation

The researcher speaks about the idea of a combination of a geothermal binary plant producing electricity and residual heat with an electrolyser as a means to keep capacity and production factors of the entire plant high. As an answer, Lennart says that in the basis, green hydrogen is expensive. The electrolysers themselves and hence the CAPEX is expensive, which currently is at around 1.5 million euros per MW capacity. So preferably you would want these systems to be working as much as possible. Therefore, using them just to overcome the lower demands of the plants in the summer does not sound profitable. The same holds for example for wind- and solar hydrogen production. For solar on land in the Netherlands they only run for 20% of the time which logically, is rather costly. Furthermore, you also need to be able to store it which again is costly and energy intensive. However, Lennart and TNO expect the price per MW for an electrolyser to decrease fivefold to around 300.000 euros per MW for the system in the future.

Political

In reaction to the answer in the final paragraph of the *Hydrogen & Electrolysis* section, the researcher asks, if he understands correctly, that the problem of electrolyser and renewable energy growth currently mainly lies with policy makers? Lennart confirms, that is the core of the problem at the moment. The technology is developed, available and can be scaled. The main reasons why it is not scaling as of yet is the significant levels of risks that there is for various involved party's. That risk can be averted through actions and policies that can be put forward by policy makers.

So the technologies need more and higher subsidies? is the response of the researcher. Lennart does not fully agree with this statement. He states that there are multiple options besides subsidies; prohibit the use of combustion vehicles, prohibit the extraction of oil, set up a mandate to have a certain percentage of green fuel around. A compliance of green synergies if you must. Higher CO_2 taxes or other tax abatement's and then finally of course also subsidies. So it needs to be a balance of a multitude of factors. Only subsidies would not help an innovative company since when the subsidy would stop then all the work stops as well, there need to be more incentives then just subsidies. The previous two paragraphs hence focus on questions 5A & 5B.

4.1.3 Interview Results - Timme van Melle (SCAN)

This section will focus on the actual interview and the takeaways from it. The following is a summary of what was asked and what was answered. If direct quotes from Timme were used, this will be stated in between quotation marks. The takeaways are categorized into the topics as they are identified in appendix A. Note that the first topic, related to personal questions and the introduction of Timme has already been elaborated on in the section titled *Interviewee Identification* in section 2.2.

SCAN

In response to question 2A, Timme starts with mentioning the *white spots* in the Netherlands - referring to areas of the Dutch subsurface with little to no information - which were flagged prematurely as areas with no natural gas deposits and hence were not further researched by related companies. However,he states that no natural gas does not necessarily mean that there is no potential for geothermal heat. Hence, to determine if geothermal heat is available, SCAN is working to collect data on these unknown areas through activities such as seismic ground research and drilling. Often times, drilling follows up on seismic research as drilling can provide more accurate data on topics such as permeability.

However, in reply to question 2B, Timme mentions that SCAN does not focus on *Ultra-Deep* layers, their focus lies at a maximum depth of 4.000 meters. Nevertheless, Timme mentions that the effort to also retrieve seismic data from depths of up to 6.000 meters is relatively low and therefore they can and often will also provide data at these depths. It is just that it is not their focus area.

All of the data on these measurements are publicly available and can be found at the *Nederlandse Olie- en Gasportaal* (NLOG). However, it is specific geological data which requires certain applications or software to analyse alongside expert geological knowledge. This shortly answered question 2C.

Ultra Deep Geothermal Energy

There is a consortium that is focusing on UDGE in the Utrecht area called Geothermie Oost-Utrecht Duurzaam (GOUD) of which the execution is partly in hands of the same party controlling SCAN, which is Energie Beheer Nederland (EBN). Hence, SCAN and GOUD use the same technologies and research process. However, the main difference is their focus area. As SCAN focuses on depths up to 4.000 meters, multiple ground layers and hence on geothermal heat, GOUD focuses on UDGE and one specific layer in particular, the *dinantien* layer. The above hence answering question 3A.

In response to the follow-up question, question 3B, Timme mentions that there are many layers that are relevant for deep geothermal heat but that there is currently only one which they might highlight to be exploitable for UDGE, which is the dinantien layer. This layer itself is not permeable, however it is a layer that could potentially be fractured at certain locations which would make it potentially suitable to extract hot water (see table 3.1) from and hence allow for UDGE exploitation. The exact location and depth of this layer is still unknown, however SCAN has published 12 papers containing research substantiated guesstimates of the characteristics and locations of this layer which are also publicly available from the SCAN database. Timme still questions the rate of success of such projects due to the incompleteness of data and, even if the exact location of this layer is found, its permeability and water extraction potential. According to Timme, there is an estimated 15% chance of success in the case that a party would start drilling, to find a suitable *fracked* location and make it economically feasible at the same. Therefore, he says it is essential to mitigate risks and uncertainties during exploration and therefore, before drilling operations begin, as drilling can already cost between 30 and 100 million euros.

Following the above, the researcher asks if risk mitigation then, is also one of the objectives for SCAN with respect to geothermal energy in general. Well yes and no. Yes in the sense that they also perform research in such layers as the dinantien, however, they do not focus on drilling to depths deeper than 4.000 meters and therefore will not provide information on for instance permeability. If potentially, the top layers of the dinantien rise above 4.000 meters then they could and might, however until now that is not the case. Nevertheless, Timme mentions that even if this would happen, it is difficult to tell if the data found for a layer such as the dinantien at, let's say, 3.000 meters can be extrapolated to a depth of 5.000 meters. These kind of topics make this research and the UDGE domain in general rather difficult, uncertain and costly.

Question 3C was asked as a result of the above explanation from Timme, his response was that momentarily, the technology just is not available. It is, again, possible to make well argued guesses from seismic data on cracked areas in between various layers that have seen significant movement over the years, which is also where the 15% guesstimate is based on which was mentioned earlier. Yet, the technology is not at the level, so to say, that you can take a picture and you see almost everything that is relevant to see. The invention of such a technology would solve most barriers for geothermal energy in general. However, Timme is unaware and does not know of any developments or expected innovations to come in the geophysical domain. Hence, it would be interesting to contact someone with more knowledge on geophysics in order to answer question 3D.

Social & Political

As EBN, SCAN is a part of, and has influence in, policy making regarding geothermal energy. SCAN is executed according to a plan written by TNO and EBN which was granted a subsidy by EZK. Hence, from this, one can definitely say that the government supports the activities performed with respect to geothermal energy as EZK subsidises the current research to UDGE through the aformentioned grant. So, essentially you could argue that EZK is also interested and active in the UDGE domain hence answering question 4A.

With respect to conventional geothermal energy and question 4B, Timme states that the backing of the government is there to some extent for UDGE. But he notes that it is different and less than conventional geothermal activities as that is already a proven technology. Conventional is being done today, the required depths are relatively accessible, the possibilities are more available and risks are lower. If we are talking about UDGE, Timme states that full support for that is still rather uncertain. It is at least not something which can be found high on the agenda regarding the energy and heat transition for the coming years.

One social and public concern for EBN and UDGE in general in the Netherlands is that, although they support further research into UDGE, they are concerned about how UDGE is presented in various media channels as being the solution to all energy problems in the world and that solar and wind energy should be disregarded altogether. Since yes, theoretically, the energy is there but it needs to be found, proven and collected first. Therefore, he feels that publicly it is being oversold as *the* solution to all global warming problems, answering question 4C.

Regarding the business aspect and hence question 4D, Timme states that besides the barriers mentioned in earlier paragraphs, which were mainly related to technological capabilities and high risks, is that as of yet, no one has taken the opportunity to be the first-mover within the UDGE domain in the Netherlands. So far all has solely been limited to discussions and a few drilling experiments, however no-one has taken the lead in investing tens of millions euros in such a project, which potentially already says enough for now. Additionally, at this moment, there are no policies stimulating electricity production using geothermal energy as we can see in the policies for wind and solar. Such policies can be found in the *Stimulering Duurzame Energieproductie* (SDE; Renewable Energy Stimulus) policies of the Netherlands.

Market

According to Timme, if UDGE projects would take off, he sees the market initially for it being in the high temperature, steam market. He would not write off electricity production from UDGE completely, but he would definitely not classify it as the primary commodity. Timme mentioned, it would initially help more to reduce carbon emissions of carbon intensive industrial processes which require higher temperatures of heat before using heat to produce electricity at a certain low percentage efficiency. For example, the markets that Timme mentions to be potentially interesting for UDGE are for instance industries that boil potatoes, sterilise milk, make paper or comparable. Industries that mainly only require temperatures in the range of 150°C. Therefore, answering question 5A.

In response to question 5B, Timme starts with the baseload energy production argument which is often used for geothermal energy against energies such as wind and solar. Timme states that although the baseload is pleasant, you also want an energy source that can be increased to accompanying spikes in energy demand which is trickier for geothermal plants. So that is another argument why he does not see electricity production happening for UDGE as it can not deliver spike in production capacity at certain moments in time. In addition, Timme mentions investments done in Germany for sustainable energy production which were withdrawn due to the massive investments that UDGE required to complete the business case. The only location where he sees the business case for electricity production happening is in countries such as Iceland and Italy, where so to speak, the warm water comes to the surface almost by itself. In the Netherlands, electricity production would only happen in the case that there is so much extra heat production from a geothermal well that plants are not able to sell all of the heat to heat consumers first. Furthermore, currently electricity is ideally produced using water steam at temperatures of 700°C to 800°C which are temperatures that UDGE is definitely not going to achieve. The higher the temperature, the more efficient the electricity producing turbines are. So even if UDGE can power such turbines, the efficiency is going to be rather low.

4.1.4 Interview Results - Anne Pluymakers (TU Delft)

This section will focus on the actual interview and the takeaways from it. The following is a summary of what was asked and what was answered. If direct quotes from Anne were used, this will be stated in between quotation marks. The takeaways are categorized into the topics as they are identified in appendix A. Note that the first topic, related to personal questions and the introduction of Anne has already been elaborated on in the section titled *Interviewee Identification* in section 2.2.

Ultra Deep Geothermal Energy

After introducing the topic and objective of this thesis to Anne which can be related to question 2A, she mentioned that hydrogen and electricity production from an UDGE geothermal plant is technically seen as one of the options for the energy transition. However, she does point out immediately that for it to be successful, it is dependent on numerous (often local) circumstances. In the Netherlands there are, to her knowledge, 18 deep geothermal locations which have depths between 2.000 and 3.000 meters from which temperatures between 70°C to 90°C can be retrieved. Occasionally, also temperatures of 100°C can be retrieved. To her understanding, a plant requires well over 100°C and high levels of fluid flow to produce electricity and hence also hydrogen. Hence, electricity generation would indeed require deeper depths. Anne mentions that the deeper one drills, the lower the permeability gets and hence the flow, simply because the pressure from above increases. So for a UDGE plant to be effective, you would need to go deeper, have relatively high fluid flow or, in the case that fluid flow is low, you you need a relatively high pressure to retrieve the fluid from such depths.

Subsurface Exploration

In relation to question 3A, Anne's response is that it is true that there is no catalogue entailing various levels of permeability across the subsurface of the Netherlands or Europe. Mainly because predicting such aspects is incredibly difficult. However, there is some information available on fluid compositions scattered across various locations in Europe from former drill sites of, for instance, oil and gas sites. Following this, Anne does mention a project that she is currently working on in collaboration with other researchers called the *REFLECT* project. One of the goals of this project is to create a geothermal fluid *Atlas* of the European subsurface. They do this by processing the aforementioned data that is known one fluid compositions. The REFLECT project is ongoing and not near to completion as of today. Also, she notes, there is not an extensive database that contains enough information to complete such an Atlas at the moment and data needs to be retrieved from various databases from various countries and institutions. Nevertheless, it is a start for a fluid composition overview and hence somewhat positive for UDGE, although very minor.

As was mentioned by Timme van Melle as well, Anne mentions that the problem with seismic research and assessing permeability is that it is not possible to see what exactly is in the ground. Permeability has no characteristics which can be measured from a distance. Mainly a result of the manner of seismic research. This is because seismic waves can only assess when there is a change in density, but they can not assess which density, material or fluid it is. What type of ground it is, is essentially a well substantiated guesstimate based on former data and knowledge. As Timme mentioned, to really understand what is at a certain depth in the ground, researchers still need to drill down and retrieve samples. Furthermore, Anne mentions that it is also difficult to estimate sometimes at which depths one is drilling, as it can not always be assured that a drill goes straight down into the ground.

Drilling Operations

According to Anne, it is also possible to create permeability artificially. This is done through a technique called fracking (which has also already been mentioned in the literature review in section 3.1.2). According to Anne, fracking has had a bad reputation in recent years, mainly in the United States, due to the consequence of earthquake taking place. However, fracking at 4.000 or 5.000 meters is different to most fracking done today and is not comparable according to Anne. Another option to besides fracking is to use existing fault lines. However, she does state that the risks for earthquakes are more evident and form a large problem of this. As a result, she mentions that significant amounts of research in the deep geothermal domain currently research ways to perform such activities without causing a higher risk of earthquakes. This paragraph shortly touched upon question 4A.

In response to question 4B, Anne says that technically it is possible to create *deviated wells* (drilling at various angles and in various directions). However, how difficult, what extra cost and risks are beyond her knowledge and expertise. on this topic. She does however doubt the possibility of the Eavor concept (figure 3.6), as drilling upwards is incredibly difficult. Also, potentially drilling down from two varying locations to form a closed loop beneath the ground is argued to be unfeasible as finding both pipelines and drilling to the exact same location is, in general, incredibly difficult. However, the *Sage Geosystems* concept seems possible as essentially fracking could be done anywhere. Although, the risk of earthquakes would be significant.

Market & Politics

During the interview, the broad economic feasibility was shortly discussed, relating to question 5A. Anne mentioned that currently, geothermal energy is significantly more expensive than alternatives. Mainly because oil and gas is incredibly cheap relatively. Anne mentions one of her lectures that she gives at the university in which students are required to assess the business case for hydrogen storage compared to alternatives. She mentioned that the conclusions from such business cases and lectures is that renewables such as hydrogen are often times nowhere near the price of oil and gas alternatives. Greatly prohibiting growth. Therefore, she too mentions the necessity of carbon taxes which has been heard before in earlier interviews. Otherwise, energy forms such as hydrogen are nowhere near competitive. Furthermore, a problem with developing a geothermal market is that there is just less money to be made from it while risks are high. Initiatives such as SCAN can provide preliminary research, but if no one decides to take the risk of actually drilling, then the technology will not develop the way it could. The geothermal energy domain is a relatively poor domain compared to others such as oil and gas. The aforementioned can be related to answering question 5B.

Following the above, Anne also mentions a story about a horticulture grower in the province of Limburg in the south of the Netherlands which has an effect on geothermal politics and market. In Limburg, there was a grower who decided to build his own small geothermal plant in order to heat his greenhouse. Consequently, earthquakes happened within a few hundred to a few kilometers distance from the plant. As a result of this situation, the regulations changed to prohibiting the build of small geothermal plants, further hampering potential developments in this domain. Although a single, small story, this shows the influence of insignificant upfront ground research and lacking regulations currently for harnessing geothermal energy in the Netherlands.

However, other than the above, Anne mentioned that she is not one to speak about economic aspects as that is not what her personal research focuses on. She is mainly focused on how rocks break and when and how fluids can travel through them.

Chapter 5

Technology Readiness Assessment (TRA)

The following chapter will use the knowledge basis of the literature review in chapter 3, the data collected from the expert interviews in chapter 4 and further relevant knowledge gained from literature searches throughout the assessment to perform the Technology Readiness Assessment (TRA) as explained in section 2.2. The TRA will be conducted in the same order and using the same methods as was presented earlier in section 2.2. Hence, first the Technology Readiness Level (TRL) will be analysed followed by the Technology Assessment (TA).

Furthermore, throughout this thesis it has come forward that hydrogen production using UDGE can potentially result in configurations of electricity and heat production as well. Hence, for the following assessment these outputs will be taken into account as well.

5.1 Technology Readiness Level (TRL)

In order to determine the technology maturity of hydrogen production through UDGE in the Netherlands, the four main technology parameters are analysed. These are argued to be the technical geosurface knowledge, the ground drilling capacity, the type of geothermal plant and the hydrogen producing electrolysers. The maturity is done through the aforementioned Technology Readiness Level (TRL) framework which was explained in section 2.2.2.

5.1.1 Geosurface Exploration

The first technological topic to be assessed is geosurface exploration. It seems evident to understand what the available resources are below the surface before any actions regarding geothermal energy can be conducted. Resulting from the conducted interviews in the data collection phase of this thesis, it seems clear that the major barrier to implementation for UDGE currently, is the lack of knowledge of the Dutch geosurface. Both Jan Brandts (Engie) as Timme van Melle (SCAN) formulated this to be the main point of concern regarding geothermal energy in the Netherlands.

Currently, the technology that assesses the subsurface at multiple kilometers depth is insufficient. It lacks the capabilities to identify the permeability and availability of fluids of the subsurface at depth. The main method to retrieve such necessary information for UDGE is through a trial-and-error gamble of drilling to a certain location and seeing what is there. Even locating drinkable groundwater at shallow depths below the surface is difficult to identify and is often done using landscape indicators such as deep valleys, trees and rock types or simply by drilling test holes

[72]. Where the former is not applicable for ultra-deep depths, the latter is an uncertain and cost- and time intensive method. Hence, this greatly influences the level of risk and therefore, the willingness to proceed with projects such as UDGE. Nevertheless, it is possible to identify various layers of rock and the temperatures of the rock at depths of 6 kilometers. Therefore, providing a detailed set of information on these aspects found in a tool called ThermoGIS as explained in section 3.1.3.

Furthermore, it should be noted that the Dutch geosurface is relatively undiscovered. The areas that have been discovered and often heavily researched are areas that were expected to contain natural gas. Often located in the northern provinces. However, the research done at these locations were focused on gases and not on fluids and therefore potentially relevant to reassess for this cause. In order to further discover the Dutch subsurface, the program SCAN, as elaborated on in section 4.1.3, has been established. SCAN is striving to fill the voids of so-called *white spots* of Dutch geosurface knowledge. Using seismic research, SCAN will be able to map the various rock layers under the surface. This knowledge on rock layers can aid in making well-educated guesses of areas that might allow for greater levels of permeability and water flow.

However, as explained by Anne Pluymakers from the TU Delft in section 4.1.4, the capabilities of seismic research are limited to rock layer identification. This is due to the fact that seismic activity works on the principle of refraction, better known as *Snell's Law*. Contrasting rock layers allow for this refraction more and therefore, allows for identification. However, water does not refract more from primary depth A to a secondary depth B, as it is the same fluid with the same density throughout and therefore the identification of water in the surface from seismic research is more complicated.

Although the topic of fluid discovery technology limitations in the subsurface has been addressed multiple times, Anne Pluymakers does mention a project currently in operation in the EU called *REFLECT*. REFLECT strives to create an overview, or an *Atlas* as they call it, of the EU subsurface fluid environment and hence to identify economically viable geothermal energy sites. They are doing this in order to encourage the development of sustainable geothermal plants by mitigating the risks of subsurface uncertainty [59]. Their focus also lies with electricity producing Geothermal Well Temperatures (GWT) although currently, the currently assessed depths are not *Ultra-Deep* but are within the scope for the future. To quote;

"The REFLECT project aims at geothermal fluid data for temperatures > 80°C. So, we are looking for data of deep wells. From what was collected up to now, I see that most of the wells are between 2 and 3 km deep. I do not see any ultra-deep wells yet in our database."

Furthermore, the data collected by REFLECT should be able to reduce CAPEX by improving predictions and knowledge of chemical reactions and subsurface movement of rock below the surface which are typical problems for geothermal plants. Their operations are through assessing results from deep drilling and extrapolating results of the drilling in a predictive model across a larger area. The REFLECT project and research can hence provide a significant positive impact to future geothermal and Dutch subsurface knowledge developments, which currently is one of the major challenges. At the moment, the transfer of REFLECT results is done through the participation of power plant operators and owners as project owners [59]. Therefore, developments should be monitored continuously by Engie if they should choose to pursue UDGE.

To summarise, the challenge with subsurface knowledge currently is the lack of capabilities to assess permeability and fluid flow at depths of over 4.000 meters. This challenge already unfolds at shallow depths. Therefore, resulting in high levels of uncertainty for current UDGE locations in the Netherlands. Nevertheless, with the SCAN and REFLECT project establishments, this is currently being researched. Although SCAN's focus does not lie on the ultra-deep depths, they will still map these depths as well. Furthermore, REFLECT might prove to be a game changer with respect to geothermal fluid knowledge at deep (and potentially ultra-deep in a later stage) depths. However, as the level of these developments is still in the researching phase and proof of working concepts other than trial-and-error through drilling boreholes are unavailable, the TRL for geosurface exploration is still in the experimental research level, level 3, as per section 5.1. Aspects that would provide an increased TRL for this part would be an increase of data on the Dutch subsurface allowing for clearer conclusions as to where there is and where there is no ultra-deep geothermal potential.

5.1.2 Drilling

The step that will follow the moment that geosurface exploration capabilities are developed sufficiently enough to be able to identify potential geothermal wells at ultra-deep depths of around or over 4.000 meters, therefore providing GWT of more than 100°C, is the step of drilling. Once a suitable geothermal well is found, its potential will need to be retrieved. In comparison to subsurface geothermal well exploration, drilling technologies have seen many innovative developments throughout the decades following the initial oil drilling operations in 1859 [5].

In the oil and gas industry, vertical and directional drilling are the key technologies that have been driving the exploitation of hydrocarbon resources. In essence, they are also important for exploiting deep geothermal energy [54]. Initially, drilling in ultra-deep depths in the oil and gas industry resulted in unstable tools as an effect of heat-related damages to the electronic boards [54]. Currently however, drill bits such as *Tungsten Carbide Insert* (TCI) have been developed specifically for deep geothermal drilling, to be able to drill through hard rock and access steam wells exceeding 260°C [54]. It should be noted that there are also additional drilling techniques designed for lower temperatures and softer rock such as *Water Based Mud* (WBM) drilling (± 200°C), however going into details of specific drilling techniques is beyond the scope of this thesis. Therefore, merely the maximum technological limitations for drilling are mentioned.

Besides vertical deep drilling, drilling can also be performed in the horizontal direction or any required direction (directional drilling) for that matter. Referring back to the conceptual geothermal power plants presented in section 3.1.2 of the literature review, horizontal drilling can present the possibility of constructing conceptual plants such as the Eavor Advanced Geothermal System (AGS). As mentioned in the interview with Anne Pluymakers from the TU Delft in section 4.1.4, horizontal drilling is a technology well developed and possible. As the application of these techniques have been successful in various petroleum extracting industries [54]. However, drilling *upwards* back to the surface made her doubt the technical possibility or argue its significant difficulty at the very least.

To summarise, it is clear that through petroleum industries, drilling techniques have been through a number of innovations in order to extract the maximum potential out of subsurface petroleum fields. Often times, challenging drilling techniques to overcome deeper and hotter depths. Therefore, it seems that there are little to no *technical* limitations regarding drilling operations in the Netherlands to the necessary geothermal depths of 4.000 meters to 6.000 meters. Hence, the TRL for drilling is set to the highest level, level 9 as the actual technology has been proven in an operational environment, as per section 5.1.

5.1.3 Geothermal Plant

From the literature review in chapter 3, a distinction was made between the four main geothermal power plants; direct dry steam plants, flash plants, binary plants and enhanced geothermal plants. The two first mentioned are argued to be irrelevant due to their minimum Geothermal Well Temperatures (GWT) requirements of 150°C which are significantly higher minimum requirements than their BCPP counterpart. Also, these GWT are argued to be the most unfeasible in the Netherlands at the current time, given the current state and knowledge of the Dutch geosurface and already discovered geothermal wells provided in table 3.2 in the literature review. From the information in the aforementioned table, the highest temperature GWT found in the Netherlands, at the moment of writing, is 100°C found at the Floricultura Heemskerk plant.

Furthermore, as mentioned in section 5.1.1, the lack of knowledge on the geosurface forms a major issue. As the capacity of the geosurface and the amount of time, energy and cost that is required to get to a certain depth can greatly influence the economic feasibility of a geothermal project, a Binary Cycle Power Plant (BCPP) is arguably the most relevant type of geothermal plant to consider for the Netherlands from a technological and geosurface standpoint. Due to the use of the intermediary closed-loop fluids, BCPP can operate with lower GWT temperatures (starting at 100°C) than dry steam plants (>150°C) and flash plants (>180°C). Temperatures proven to be available and accessible, by Floricultura Heemskerk, in the Netherlands.

Potentially, with increased research from entities such as SCAN, geothermal wells could be found at depths just under the depths of the Floricultura Heemskerk plant, greatly increasing the efficiency of a BCPP. These smaller increments of depth would seem more technologically feasible than trying to access locations with GWT of over 150°C which would allow for use of dry steam or flash plants. Hence, further substantiating a choice for a BCPP. Alongside the argument for recommending BCPP in the Netherlands due to the lack of high GWT at achievable depths, is the significant increase of research and development regarding BCPP over recent years. BCPP is the newest geothermal energy technology and, in recent years, has been the geothermal plant type of choice for the vast majority of newly installed geothermal plants around the world [60].

With respect to efficiency of a BCPP, the study that was also highlighted in the literature review, addressed a thermal efficiency of a case study of the *Brady Bottom Cycle Plant* in Nevada, USA, to be 8%, with a relative effiency of 59% compared to the theoretical maximum of a plant with a GWT of 108°C. This specific plant was interesting to mention as it is a BCPP that is operated using a fairly low GWT. The GWT is relatively close to current geothermal plants in the Netherlands and therefore it could be potentially feasible to have such a plant in the Netherlands as well. Although the efficiency of the Brady plant is rather low, its technological feasibility could still show a promising outlook for such a plant in the Netherlands. Furthermore, it should be kept in mind that the *amount required and cost of fuel* of a BCPP does not increase with lower efficiencies as there is no price on geothermal heat. However, the level of efficiency is of course relevant to the payback period for the plant as a higher efficiency can result in a lower OPEX and a lower CAPEX.

Accompanying the benefit of being operationally more efficient in low GWT locations, the BCPP also provides the advantage of being a closed-loop system in comparison to more conventional geothermal plants such as the dry steam and flash plant. As a result, geofluids, the warm fluids extracted from depth, are not brought into contact with the upper ground atmosphere. This is environmentally advantageous as bringing geofluids to the surface can result in the escape of elements stored in the earth for years. Gases that can be present when extracting geofluids are gases such as nitrogen and carbon dioxide [12]. Furthermore, besides the presence of gases, 95% of geofluid compositions themselves contain dissolved constituents such as chlorides, sodiums and sulfates [12]. Keeping these geofluids in a closed loop within the ground that they are extracted from and re-inserted into, ensures no leakages of geofluids can contaminate potential soils and drinking water wells.

Alongside existing geothermal plants, the literature review also shortly touched upon various conceptual geothermal plants. Although their are plans to bring some of these concepts into operation, such as the concept from the Eavor company in the state of Bavaria, Germany, these plants are argued to still be to conceptual to assess technologically. Mainly because a successful idea on paper does not necessarily mean a successful physical design. Also, as was mentioned in the interview with Anne Pluymakers, the Eavor idea seems to be rather challenging technologically but not completely unfeasible.

Nevertheless, in relation to the technological feasibility and readiness of electricity producing geothermal plants in the Netherlands, it seems that the most relevant type of geothermal plant is the BCPP. This type of geothermal plant is the latest innovation within the geothermal energy generation domain and accounts for most of the newly installed geothermal plants across the globe in recent years. Already making up just around 33% of all geothermal plants across the globe and over 62% of the geothermal plants in the United States alone [77]. Therefore, the plants themselves are technologically feasible, deployed and proven in an operational environment. Hence, the TRL of the most relevant geothermal plant for the Netherlands, the BCPP, is argued to be the highest TRL, level 9.

5.1.4 Hydrogen Production

Following the TRL's related to the first main topic of this thesis, geothermal energy production, the second main topic, hydrogen production is assessed in the following section. As mentioned, this thesis solely focuses on the production of green hydrogen which should be kept in mind throughout the following assessment.

In order to produce green hydrogen using a geothermal plant, the geothermal plant will require significant amounts of electrolysers. As mentioned by Lennart van der Burg in section 4.1.2, electrolysers are currently still mainly being built by hand. Large scale automated electrolyser assembly lines are only expected to be built come 2023 or 2024. However, keeping in mind aforementioned time spans of building a geothermal plant in the Netherlands, as mentioned by Jan Brandts in section 4.1.1, could already take six years from the idea to the first drilling phase. Hence, automated assembly lines for electrolysers could potentially be available come the moment of an UDGE geothermal plant in the Netherlands. Furthermore, as was touched upon in the literature review and later on also mentioned during the interview with Lennart van der Burg, there are only a few commercial suppliers of electrolysers available in the western market.

However, developments are starting to accelerate, as key players in the industry are clearly focusing on developing large scale multiple megawatt hydrogen producing electrolysers. For instance, according to a report from *Aurora Energy Research*, the global electrolyser market is expected to expand to over 200GW in the coming twenty years of which 6GW are expected in the Netherlands [67]. Additionally, current 1MW to 10MW projects are expected to be replaced by electrolyser projects in the range of 100MW to 500MW [67]. The french firm *Air Liquide*, recently opened their new 20MW electrolyser plant in Quebec, Canada in January of 2021 [53]. Hence, developments are clearly being undertaken.

Furthermore, as was described by Cao et al. (2020), the capabilities of an electrolyser system integrated in a geothermal electricity plant are largely dependent on the electricity output of said plant. Since electrolyser hydrogen production levels are practically completely dependent on the proper supply of electricity. Therefore, Cao et al. (2020) state that hydrogen production is mainly dependent on the electricity output of the plant, referencing to a research done by Yuksel et al. (2018) into a geothermal power plant for hydrogen production. Yuksel et al. (2018)

concluded that the key drivers for hydrogen production were the GWT and working fluid in the closed loop cycle of the geothermal plant. A GWT increase from 130°C to 200°C resulted in an increase of hydrogen production by 1100% due to an increase in electricity production of 800% from 1000kW to 8000kW [82]. Therefore, the question regarding this thesis and perhaps the technology readiness of hydrogen production through a geothermal plant again comes back to the capabilities of the geothermal plant to produce electricity, instead of the capabilities of the electrolysers. Besides the aforementioned, it is interesting to shortly note the efficiency of electrolysers, as this logically has an effect on the overall geothermal plant. From the literature review, most electrolyser efficiencies were regarded to be around 70%.

Regarding hydrogen production costs, an IRENA report on green hydrogen cost reduction [46], stressed that as of 2020, electrolyser development costs are still considered highly expensive in both CAPEX and in OPEX compared to fossil fuel counterparts. The same was concluded from the interview with Lennart van der Burg where he also mentioned current electrolyser prices to be around one and a half million euros per MW with an expected price of around 300.000 euros per MW in the distant future. Nevertheless, the electrolyser costs compared to fossil fuels still significantly affect the business case for any green hydrogen producing plant nowadays. Furthermore, the mentioned PEM electrolyser from the literature review in chapter 3, which was regarded as the more promising type of electrolyser for the future although current production capacity is lower, is still 50% to 60% more expensive than the alkaline electrolyser [46]. The SOE was barely regarded in the IRENA paper as cost consideration are more challenging since developments are much further from commercialisation. The two main cost estimate barriers for electrolysers are regarded as; the lack of availability of data on electrolyser developments from producers and cost estimates boundaries are not consistent when data is available. With the latter, the paper means the boundaries of the electrolyser which are considered for the cost estimate such as; is the full system considered or is only the fuel cell stack considered [46].

To summarise, it seems that literature shows that in essence hydrogen production technologies are available although still mainly in the development phase. Large scale commercialisation roll-out of production plants still seem years away as was also mentioned by Lennart van der Burg. However, it seems that electrolyser developments are continuous and accelerating for the future and multiple megawatt electrolyser plants are demonstrated in relevant environments although that on a large scale. Also, the main drivers for hydrogen production through geothermal plant efficiencies and production capacities are more related to the geothermal plant capacities and less to electrolyser capacities. Therefore, hydrogen production through electrolysers powered by geothermal plants are currently argued to be at a TRL of 6, which is the highest of the development phases as per section 5.1.

5.1.5 TRL Results

In order to be able to conclude the TRL, it is argued to be logical to shortly conclude each parameter and compare. How the overall TRL was to be determined was also mentioned in the TRL methodology section on in section 5.1.

To help remind the reader; "Each assessed parameter will be given an individual *Readiness Level* (RL) based upon the scale and tangible observations as described in section 2.2.2. From the various topic RL's, the minimum RL will be the RL of the overarching subject. This is argued to be logical as an entity is only as strong as its weakest link, irrespective of the level of development of other topics within. As an example, if topic A would receive a TRL of 4, topic B would receive a TRL of 8 and topic C would receive a TRL of 9, then the overarching TRL would be 4 as topic A would be leading."

Therefore, according to the above, the overall TRL regarding the four main parameters for the hydrogen production using a geothermal plant technology were a 3 for geosurface exploration, a 9 for drilling, a 9 for the geothermal plants and a 6 for hydrogen production. Therefore, the overall technology would only score a 3.

5.2 Technology Assessment (TA)

The following section will provide the technology assessment for the relevant aspects of the proposed ultra-deep geothermal plant. The aspects to be addressed are; the market for green hydrogen itself, the potential electricity market and the pure heat market. Furthermore, the technology assessment will touch upon political aspects which influence the market of the aspects proposed. The assessment is done in light of the Paris agreement goals set to be achieved by the year 2050. The technology assessment, will build upon the literature review of chapter 3 and the data collected from the interviews performed in chapter 4.

5.2.1 Hydrogen

The first subsection will focus on the market of the potentially produced green hydrogen from the geothermal plants. There are three main potential market applications for green hydrogen as shortly mentioned in the literature review; (heavy) industry, mobility and energy storage [75]. These will be further addressed later on.

Currently, green hydrogen is regarded as almost nonexistent in the renewable energy sector. Such statements seem clear from renewable energy strategy papers such as the one on the hydrogen vision and strategy from the year 2030 until 2050 for the province of *Zuid-Holland*. This paper states that the hydrogen market for the province encompassing the highest population density in the Netherlands is still clearly in the testing and start-up phase for hydrogen applications [79]. During this phase, they are testing various hydrogen applications and potentially required infrastructures with *grey* hydrogen, as according to the paper, there is currently no public hydrogen infrastructure or any hydrogen regulations to control such a market [79]. This greatly influences the possibility for the Dutch industry to create a value chain for production, distribution and exploitation activities. However, although testing is currently done with grey hydrogen, the province envisions this to be the precursor of green hydrogen with an intermediate step using blue hydrogen along in the process. It is argued that the current developments with grey hydrogen is what will create the current nonexistent market for green hydrogen in the future towards 2050.

Although the above is mainly focused on the hydrogen vision of the province of Zuid-Holland, this vision is in collaboration with other provinces and with foresight of goals set by the Dutch government and the Paris agreement. Hence, is argued to hold for the Netherlands as a whole. Furthermore, collaborations are also happening internationally with respect to infrastructure developments between countries. As it is argued that the hydrogen economy is not one pursued by the Netherlands alone and international collaboration can strengthen scaling activities, lower financial risks and provide knowledge sharing [79].

Industry

One of the main energy consumers and carbon emitters in the Netherlands, the (heavy) industry, is expected to and essentially obligated to reduce carbon emissions to a net zero level. This is where an important opportunity lies for green hydrogen because hydrogen itself as a commodity is not new within industry processes. Currently, grey hydrogen in the Netherlands is an important raw material in the petrochemical industry as was mentioned by Lennart van der Burg. It is mainly used for the production of ammonia which in return is mostly used to produce various types of fertilizers. In the Netherlands, the industry emits around 13 million tons of CO_2 per year as a result of grey hydrogen production from natural gas. To compare, 13 million tons of CO_2 is equivalent to all CO_2 emissions due to electricity usage in Dutch households in 2018 [55]. Logically, a replacement of this with green hydrogen has a major influence on the total emissions of the Netherlands. Furthermore, hydrogen can be used to replace fossil fuels such as coal and natural gas in production processes which require high temperatures (>600°C) as well.

Main barriers for using green hydrogen currently in industry is it's low level of availability which is a result of relatively low availability of green electricity sources. Furthermore, the price of green hydrogen for industry processes is significantly higher than that of natural gas produced hydrogen, which again, is also a result of low availability of green electricity sources. However, the hydrogen market itself is existent. Hence, for the future, as the goal of 2030 is to produce 70% of all electricity in the Netherlands through green energy sources [55], the availability and possibility for green hydrogen production will be significantly better as well. Therefore, allowing industry to use green hydrogen in production processes more dominantly and hence creating a market for the green hydrogen produced from the proposed geothermal plant.

Mobility

Besides industry, mobility practices are well-known and main contributors to greenhouse emissions. Mobility can be regarded as any type of transport vehicle by land, air or sea.

In the market domain of sustainable automobiles, developments in recent years have mostly seen Battery Electric Vehicle (BEV) emerging. The majority of the literature reviewed concludes BEV transportation to be dominant over potential hydrogen Fuel Cell Electric Vehicle (FCEV) for two reasons [11]. First, due to the theoretical limitations of hydrogen in small applications and secondly, due to the continuous developments of BEVs in current markets. The theoretical limitation of FCEVs is a result of the efficiency along the value chain, as to power an FCEV, renewable energy needs to first be converted to hydrogen, then compressed, transported and/or stored, then transformed back to electricity within the FCEV and its drivetrain. As it stands today, this results in an efficiency of 38% for the full value chain of an FCEV. Compared to a current 80% efficiency for BEVs [62]. Therefore, FCEVS require more than twice the energy as BEVs. Also, making FCEVs currently significantly more expensive to operate than BEVs. Furthermore, BEVs have the backing over FCEVS of practically all automobile manufacturers worldwide except for *Hyundai* and *Toyota* who do have FCEV models. Finally, infrastructure and investments for the FCEV market is practically non-existent compared to that for BEVS in recent year [11]. However, this is also partly due to the non-existence of green hydrogen as a power source compared to more readily available green electricity from renewable sources such as wind and solar. Hence, due to the aforementioned, a market for green hydrogen (potentially produced from geothermal power) within the automobile industry is unexpected.

Where there might be more of a future for green hydrogen in the mobility domain, is for heavy duty vehicles. Vehicles such as trucks, trains, ships, buses and airplanes. The reason for this is directly related to their size and workload, or energy demand [55]. The required energy for most heavy duty activities requires battery volumes that are multiples in size and weight of the actual vehicle themselves. This is hence where literature sees potential for hydrogen powered fuel cells as its energy density is superior to that of batteries [55]. Hence, allowing for significantly higher amounts of energy to be used for operations. Nevertheless, the current market for heavy duty powered vehicles is relatively non-existent as well although there are multiple developments within this domain. For instance, American based firm *Plug Power* is focusing on fuel cell applications for forklifts [64], the aerospace department of the TU Delft is extensively researching a hydrogen powered aircraft called the *Flying V* [18], ship yards are experimenting with hydrogen powered ships [63] and the Dutch-American company *Hyzon* has introduced its first functional hydrogen powered heavy duty truck with an order backing of over 1500 trucks in its portfolio [57]. Therefore, although currently relatively non-existent, the heavy duty vehicle market fueled by (green) hydrogen is expected to grow significantly in the net-zero emission future.

Seasonal Storage

One topic addressed multiple times during the conducted interviews in chapter 4, is the topic of producing hydrogen in times of lower electricity or heat demand than the full capacity of a geothermal plant. As was stated by Jan Brandts, heat demand from current deep geothermal plants does indeed reduce over the warmer summer months. This is mainly seen in the built environment. As a result of this reduced demand, the current plants are often shut down in the summer months. They are shut down as it is difficult to reduce production levels by a certain percentage. A plant is basically on or off, there is barely an in between. Hence, this means that there is an absence of revenue generation in the summer, greatly influencing the profitability and payback period of the complete geothermal plant.

A solution proposed to overcome the summer months shut down is one of the two main topics of this thesis; hydrogen production. Theoretically and ideally, the proposed solution seems as an excellent proposal. However, Jan was mainly concerned about the market and business case related to this solution. As according to the aforementioned IRENA report on green hydrogen cost reduction, the costs of hydrogen producing electrolysers are still considered highly expensive compared to fossil fuel and some renewable energy alternatives [46]. Furthermore, the previous statement did not consider seasonal operation of an electrolyser. The proposed solution, operating in the summer months in order to increase the capacity factor of the geothermal plant essentially increases the payback period of the electrolysers by a factor of four when considering a summer period of 3 months. Therefore, the reasoning behind this proposal seems weak.

5.2.2 Electricity

One of the potential outputs of a Binary Cycle Power Plant (BCPP) is electricity. In recent years, the pressure on the electricity grid in the Netherlands has grown extensively due to an increase of electricity demand and hence, electricity production. Also, the manner of electricity distribution has changed as well. The demand increase is partly a result of changing consumerism; the rise of BEVs, electric cooking and an ever increasing online world for many aspects of life. Furthermore, the electricity production is often more concentrated. Where earlier a few large well-positioned electricity plants delivered electricity through a network of cables across the country, the electricity is now, as the dependency on renewable energy grows, often provided through concentrations of solar- and wind farms in sparsely populated areas [48]. These renewable energy sources often result in *grid congestion*, essentially meaning that the available electricity grid is unable to process all of the electricity loads produced by the plants during peak operations.

This congestion is a market that a geothermal plant can tap into, as the BCPP would ensure a consistent level of electricity output throughout a continuous period in the case that this would be its main output. Furthermore, although dependent on the results from REFLECT and SCAN activities, it is possible that the location for a BCPP could be nowhere near the current locations of solar- and wind farms in the Netherlands. Hence being beneficial to grid congestion due to the reason mentioned in the previous paragraph. Also, as Jan Brandts mentioned and various literature alongside current market developments show, the market for green electricity is ever increasing due to the Paris agreement goals and hence on that basis, it can be argued that there is a market for geothermal electricity as well. However, Jan did argue the price competitiveness of UDGE electricity compared to that of solar- and wind farms due to needing to drill to ultra-deep depths to access electricity producing GWTs which will be expensive. However, BCPP can potentially still go through many technical developments in the future, allowing for reduced costs.

In the interview with Timme van Melle, geothermal electricity generation was spoken about as well. On this topic, Timme mentioned that he understands that the electricity generation is possible theoretically, but if the idea of an ultra-deep BCPP would happen, he would not regard it as the primary commodity to be produced. The same was essentially said by Jan as well; UDGE would never be done solely for electricity production, but always (as a byproduct) with heat. However, in a calculation done by the Dutch authority for emissions (*Nederlandse Emissie Autoriteit* (NEA)), a group of ten heavy industry companies were identified as accountable for over 50% of all CO_2 emissions of the heavy industry. Amongst these ten companies, six are electricity power plants which run on natural gas [22]. Therefore potentially questioning the statements made by Jan and Timme as electricity generation being an irrelevant market since an UDGE BCPP could conduct the same practices as these six heavily polluting companies but in a fully sustainable manner. Although with current technologies the production output of an UDGE plant would be significantly lower than the aforementioned natural gas powered plants. However, this could be considered as a technological or GWT implication which could still be further researched and developed to produce higher outputs. Due to this, the sustainable electricity market should still be considered as an interesting market for an UDGE plant.

5.2.3 Heat

Following the hydrogen and electricity markets, the final output of a UDGE BCPP would be heat. This would hold in all three proposed configurations; pure hydrogen production, pure electricity production and pure high temperature heat output. For former two configurations, the heat output would solely be as residual heat of temperatures ranging between 40°C and 50°C. The pure high temperature heat output has already been addressed earlier as potentially the more logical primary output commodity for such a plant. As in reality, heat is the exact resource which is retrieved from the earth in such a system. Heat is also the main commodity being produced from the existing geothermal power plants in the Netherlands today. Markets for which heat could be relevant for are; (heavy) industry, the built environment and the horticulture industry. Hence, these will be further assessed.

Industry

Starting off with the (heavy) industry, thereby focusing on the pure hot temperature heat output which theoretically is at 120°C at 4.000 meters depth and increases by 30°C for every 1.000 meters. In the interview with Timme van Melle, in which the focus was mainly on UDGE geothermal energy, he stated that if such projects would be realised in the Netherlands, then the high temperature heat and steam market is the market that would be most ideal for such a plant. An identical statement was made by Jan, who mentioned that most of the existing UDGE projects that he is aware of have heat as their main output and can generate electricity as a byproduct.

Furthermore, when taking a look at sustainable developments within the Netherlands, heavy industry will be required to make the transition to more sustainable production processes in the near future by using sustainable inputs for their processes. In the earlier mentioned calculations of the NEA, besides the electricity producing companies, there were companies in the refinery, chemical and steel business. These businesses mostly use temperatures for their processes which can be considered well above the temperatures that can be delivered by a UDGE plant in the Netherlands. For instance, to produce diesel in a refinery, temperatures between 220°C and 350°C are required, whereas kerosine requires temperatures between 175°C and 260°C [2]. To produce steel, temperatures well over 1000°C are required [47] and, to produce (heavy) *Naptha*, temperatures between 80°C and 175°C are required [58].

> Naptha is used; to dilute heavy crude oil, as a fuel in commercial applications such as cigarette lighters, camping stoves and oil lanterns and it is a crucial component in the production of plastics. [26]

As stated these temperatures are mostly well out of range for applicable geothermal wells. However, a potential geothermal plant at 4.000 meters tapping into a 120°C geothermal well could deliver a base temperature for such processes. Making the basis of refineries, chemical industries and steel manufacturers more sustainable which would greatly affect their carbon outputs. Keeping economical aspects aside, Jan Brandts did argue this to be a great development for the industry market in a sustainability sense as well and could imagine this market to be available for geothermal heat.

Besides the most polluting companies in the Netherlands, industries mentioned by Timme van Melle such as those that boil potatoes, which sterilise milk (requiring 70°C for fresh milk or 130°C for pasteurised milk [80]) or produce plastics can be considered interesting markets for hot temperature heat. Industries mostly focusing on temperatures in the range of 100°C to 150°C. A smaller market, but a market to provide heat for nonetheless.

One implication for the aforementioned industries might be distribution of industry locations. Whereas hydrogen and electricity production allow for production *on-site*, the above described markets evidently will be scattered across various locations. This could greatly influence the delivery of heat at required temperatures as transportation through pipelines across significant distances could result in temperature losses, decreasing efficiency and revenue streams for such a plant. As the production of the plant would be mostly dependent on the accessibility of a suitable geothermal well, the choice of location could greatly influence the sales market of the plant.

Built Environment

The second market to be addressed regarding heat is the built environment market. A market already well-known to the geothermal industry and mostly only requiring temperatures around 50°C. Due to these required temperatures, the built environment should mostly be regarded as an extra market which can be exploited for the residual heat of processes requiring higher temperatures. Therefore, logically, it should not be regarded as a main market for an UDGE geothermal plant. Nevertheless, still a market to be mentioned as the benefit of geothermal heat in the built environment is it being more efficient, more cost effective and more direct than other renewable energy such as wind and solar which would need to convert electricity to heat first.

Horticulture

Finally, the horticulture market. For this market, much of the same applies as was shortly mentioned in the previous built environment section. This market has already been in development since 2008 when the first drilling took place to geothermal heat for the industry. Most deep geothermal plants in the Netherlands which were mentioned in the literature review of chapter 3 and which were shown in table 3.2 are focused on this market. Geothermal plants with geothermal wells at depths of 2.500 to 3.000 meters use the water at these depths to heat greenhouse horticulture facilities. Often times, the temperatures retrieved from these depths (75°C to 90°C) are well above the required temperatures for horticulture. As a result, the existing facilities are already combined to deliver heat to the built environment that surround the plants. Therefore, due to the required temperatures, the horticulture market, much like the built environment market, should not be regarded as a main market for an UDGE geothermal plant. However, it can be interesting to source residual heat to this market.

5.2.4 Political

Markets are not only influenced by the demand of consumers in sales markets but also by politics. Politics can stimulate, regulate or discourage certain markets through legislations and regulations such as taxes, production capacities and emissions capacities. Additionally, they can also offer subsidies and set goals that need to be met by the industry. These aspects will be elaborated on in the following section in order to determine if they are stimulating or discouraging UDGE plants in the Netherlands.

Paris Agreement & Dutch Political Developments

Mentioned before in this thesis, are the targets set by the Paris Agreement in 2015. The Netherlands has politically ensured its commitment to a decarbonised future and, as a consequence, has set targets in its national climate agreement in order to achieve said targets. These targets ensured an acceleration in the energy transition in the country with billions of euros to be invested over the current decade [40]. Although, mainly focusing on renewable energies, such as solar and wind, which are unrelated to the renewable energy forms proposed in this thesis. Nevertheless, geothermal energy is considered an important partner in achieving the set targets. With ambitions of *Platform Geothermie* increasing the production of 3 petajoules (PJ) of geothermal energy in 2018 to 50PJ in 2030 and over 200PJ in 2050 [33]. Where 1PJ is equivalent to 278GWh [71] or 20.000 households and the demand for heat is around 400PJ per year. Ambitions which exceed those of parliament but are deemed achievable as a result of recent development activities and the latest potential estimates [33].

Besides geothermal activities, is the importance of the role of hydrogen within these targets and agreements. The Dutch are already at the forefront of European policy initiatives by kick-starting a hydrogen revolution by building various infrastructures in key strategic locations for Europe [40]. The Dutch hydrogen ecosystem already entails a broad range of hydrogen technologies in various aspects of the hydrogen value chain. From research institutes and industrial partner developments within the domain, to electrolysis producers and applications in various sectors such as road, industry and maritime [40]. Additionally, it is evident for Dutch politics to propel green hydrogen adoption as they are current Europe's second largest (grey) hydrogen producer [40].

Subsidiaries & Tax Abatement's

For most new, innovative and disruptive technologies it can often require a significant amount of resources to ensure successful adoption. From the conducted interviews with Jan Brandts, Lennart van der Burg, Timme van Melle and Anne Pluymakers, one aspect that stood out and was mentioned in each interview was the topic of funding, competitiveness and costs of an UDGE plant producing electricity and/or hydrogen. The commodity outputs of such a plant need to compete with existing carbon based alternatives such as natural gases and oils.

Therefore, it seems essential by everyone interviewed that in some shape or form, subsidies and tax abatement's would greatly benefit the technology. Jan mentioned, for geothermal energy to take-off, subsidiaries could be a mechanism to mitigate risks for ground research. He does note that discussions with policy makers are ongoing regarding these subsidies but they are rather slow and can take a significant amount of time. The same was said by Timme, who stated that the backing of the government is there to some extent for UDGE. However, it is less than the backing for conventional geothermal activities focusing solely on deep heat producing geothermal plants. In his opinion, this is mainly because conventional geothermal activities are already a proven and in order technology, greatly lowering the risks for governments as well. In a way this can be considered as a vicious circle regarding risks. Additionally, Anne mentions that there is less money to be made in the geothermal market and prices cannot compete with carbon alternatives. Due to this fact, it might be necessary for politics to initiate aspects that lower the competitiveness of these carbon alternatives such as carbon taxes and emission capacities. As currently, the renewable and hence, geothermal market cannot seem to compete.

Regarding hydrogen, Lennart stated that the reason green hydrogen production is not being scaled is due to the significant risks for producers. In his opinion the technology themselves is developed, available and can be scaled if adopted. It is just that the risks need to be averted. In his opinion, the solution does not lie solely with providing more and higher subsidies. He stated that it should be a balance of a multitude of factors such as; prohibiting the use of combustion vehicles, prohibit the extraction of oil and gases, set up stringent mandates, introduce carbon taxes and other tax abatement's and of course finally also subsidies. Only subsidies is not enough, there need to be other incentives for producers and consumers to make the switch to a more sustainable form of energy.

Legislation & Regulations

The paper *Master Plan Geothermal Energy in the Netherlands* [33] written by *Geothermie NL* was already shortly touched upon earlier and in the literature review in chapter 3. This paper from 2018 devoted a significant portion to argue the appropriate legislation and regulation structure for geothermal energy in the Netherlands. As geothermal energy in the Netherlands is young and growing, they argued that the current political structure is inadequate and needs to be better matched and tailored with future developments. A somewhat simialar statement was done by Jan Brandts, in his interview shown in section 4.1.1, where he stated that a barrier for UDGE currently are also the policies and regulations as it is somewhat outdated and is based on older activities which do not always apply to current geothermal activities.

Regarding legislation and regulations, Geothermie NL proposes to undertake two actions; further development and implementation of industry standards, and collaborate closer with EZK and other competent authorities to facilitate rapid processing permit applications and necessary amendments to current legislation and regulations [33]. The latter is arguably the most interesting as currently legislation and regulations pose several bottlenecks for geothermal proposals. Related to slow permit application processes due to lack of assessment standards, risk control standards according to nuclear energy legislation and allowing for improved methods of testing methods.

Furthermore, a process which already began in 2018, is an amendment to the *Mining Act*. Amendments that have been proposed to be altered are for instance, allowing for permits to apply to a wider geographical range of the subsurface and above-ground area and providing more specific descriptions of the assessment criteria and content for a permit as these were often lacking [33]. Additionally, Geothermie NL proposes amendments to further regulations such as the *Heat Act*, the *Building Decree* and the *Nuclear Energy Act* which are sometimes related to (sub)-surface activities which took place before geothermal activities did. Hence, sometimes these regulations are unrelated to geothermal activities and can hamper geothermal developments.

Policy

With respect to policy the sector needs coordination and optimisation of planning and environmental policy between various branches of government [33]. According to the master plan, the geothermal sector would greatly benefit from more coordination between these branches as currently these do not always work together effectively on a national, regional and local level [33]. Policies can be contradicting from level to level as different stakeholders are involved in different processes. Collaboration between stakeholders across levels needs to be found as a result. Furthermore, developments of tools such as ThermoGIS are required to form a strong basis for permit applications. Also, policies should be in place to ensure that subsurface are not exhausted over time but are used optimally.

In the future, advisory roles should be implemented further during permit applications [33]. Hence, structured training should be provided for advisors in order to ensure that they give clear advice and understand assessment criteria for policies and permits as this is lacking currently.

Chapter 6

Conclusions

The following chapter shall be the concluding chapter of this thesis. This thesis was aimed at answering the main research question;

What is the state of the technological- and market readiness for green hydrogen production from geothermal power plants in the Netherlands?

To accompany the main research question, two sets of three sub-research questions were created to help answer the main research question. The first set was related to technology focused questions;

SQ1 Which production methods, irrespective of their development phase, currently exist within the geothermal electricity generation domain?

SQ2 What are the challenges and potentials for the Dutch Geo surface with respect to electricity generation?

SQ3 How can hydrogen production systems be implemented in geothermal electricity generating power plants?

Additionally, the second set was related to strategy and market focused questions;

SQ6 What is the current state of the overall hydrogen & geothermal market in the Netherlands?

SQ5 What are drivers and barriers for the hydrogen and geothermal market in the Netherlands?

SQ6 What are potential sales markets or applications for the commodity outputs of a geothermal plant producing hydrogen?

The main- and sub-research questions were researched and answered by gathering information through the literature review presented in chapter 3, and by collecting data through the conducted expert interviews which were presented in chapter 4. Subsequently, the literature review information and interview data were combined to perform an assessment in chapter 5.

6.1 Answering the Sub-Research Questions

SQ1 Which production methods, irrespective of their development phase, currently exist within the geothermal electricity generation domain?

There are four fully developed types of geothermal plants which are capable of producing electricity; direct dry steam plants, flash plants, binary cycle power plants and enhanced geothermal systems. Of these, the first two are regarded as irrelevant for the Dutch geosurface climate as they require minimum temperatures of 150°C which seems improbable to be achieved in the near future for the Netherlands. Furthermore, their technology is somewhat outdated in comparison to the binary cycle power plant. The working principle of this plant is essentially the same as that of a flash plant. However, this type of plant utilizes a secondary working fluid with a boiling temperature in the range of around -10°C and 30°C which is heated by the geothermal fluid through a heat exchanger in a closed loop. As a result, a binary cycle power plant is operable anywhere from 100°C with a thermal efficiency of around 8% and hence requires less geosurface depth to be operable. Higher geothermal well temperatures of course do still result in better efficiencies. Furthermore, enhanced geothermal systems also play into being operable at lesser depths ensuring less drilling costs and therefore increasing economic feasibility. Enhanced geothermal systems using the technique of *fracking* to access impermeable areas which are filled with a fluid to be heated by the earth and which hence, can be extracted later. Essentially *re-watering* a dry subsurface area. This technique is also interesting for the Dutch subsurface although socially often frowned upon due to its supposed proneness to creating earthquakes.

Shortly, conceptual geothermal plants were researched as well. Three were identified. First, the Eavor concept, which focused on creating a binary cycle power plant closed loop system with an intermediary low boiling point working fluid as well, however, they propose to install the closed loop heat exchanger system within the subsurface at depth, simplify and improving the heat exchange. Secondly, the Greenloop concept. This concept also created a closed loop working fluid system, however they propose to vertically install such a system into existing, former oil and gas, boreholes. Therefore eliminating drilling costs and hence, increasing economic feasibility. Thirdly, the Sage concept. This concept combines the concept of enhanced geothermal systems with the Greenloop concept. Essentially fracking under and around existing boreholes to introduce a heated fluid and placing a vertical closed loop system into that borehole. It should be noted that the presented concepts are still concepts and nonexistent currently throughout the globe. Although the Eavor concept is trying to run a test phase in Germany in the near future.

SQ2 What are the challenges and potentials for the Dutch Geo surface with respect to electricity generation?

Theoretically there is potential, as the geosurface temperature increases on average by 30°C for every kilometer of depth. However, based on what is actually known at the time of writing, the current potential is barely available, known or researched. This has to do with the challenge of assessing the Dutch geosurface at depths that could possess the required geothermal well temperatures to be able to power geothermal plants, such as the binary cycle power plant, to produce electricity. Little is known about the permeability and accessibility of the geosurface at the required depths of around 4.000 meters. Furthermore, it should be noted that most parties which are exploring the geothermal domain are not focused on these depths either, such as SCAN and REFLECT. Their main focus lies well above the 4.000 meter line. Even if their focus would be on the relevant depths for this thesis, they could not fully map the geosurface potential. To assess the true potential, parties would need to physically drill to certain depths in order to create a trustworthy assessment. Hence, the challenge and barrier to understand the true potential lies in the technology capacity.

SQ3 How can hydrogen production systems be implemented in geothermal electricity generating power plants?

Essentially, this seems to be relatively uncomplicated. A hydrogen production system would merely need to be connected to the output of the geothermal power plant which, as stated by Lennart van der Burg, would not require to many adjustments. However, easier said than done than just *plugging in* into an existing plant. A hydrogen production plant would need to be built in the vicinity of the geothermal plant and relevant infrastructure would need to be built. But in essence, it is possible.

SQ4 What is the current state of the overall hydrogen & geothermal market in the Netherlands?

The current geothermal market is clearly focusing on decarbonising the heat market. All existing geothermal plants in the Netherlands solely output heat. This could be clearly seen in figure 3.9 which showed all drilling depths in the Netherlands focused on oil and gas but also on geothermal energy. The deepest geothermal energy focused drilling operation did not exceed 2.500 meters. Therefore, operations are far from what is required for electricity generation.

Furthermore, political aspirations regarding geothermal activity were mentioned to be focused on shallow to deep geothermal projects and not on ultra-deep geothermal projects. The focus of governmental actions regarding sustainable electricity generation are clearly focused on renewable energies such as wind and solar. The same holds for geosurface exploration as was mentioned earlier. Hence, to answer this question, the current state of the geothermal market is focused on heat and not on electricity or hydrogen production.

SQ5 What are drivers and barriers for the hydrogen and geothermal market in the Netherlands?

The main driver for a geothermal market is clearly the energy transition that the Netherlands is pursuing. Geothermal energy is able to provide net zero energy, mainly in the form of heat. Tax abatements, environmental policies and more sustainable legislation and regulations in favour of renewable energies can greatly fuel the geothermal market. Furthermore, the heat market mainly consists out of natural gas and does not have many other contenders that are carbon free. This creates an interesting market for geothermal energy although this does not relate to this thesis' topic of electricity and hydrogen production.

Interestingly enough, this is also one of the main barriers. Geothermal energy is not considered, researched and politically fueled as much as renewable such as wind and solar. This creates barriers for geothermal plant producers and exploiters to build geothermal plants. Competing fuels, when considering electricity production, are much cheaper than electricity production through geothermal plants. The same holds for geothermal heat in comparison to natural gas heat. Furthermore, further research into technologies such as those required for geosurface exploration are not widely supported and often relatively small compared to political backing from other energy sources.

SQ6 What are potential sales markets or applications for the commodity outputs of a geothermal plant producing hydrogen?

The three possible outputs researched for a geothermal plant are; hydrogen, electricity and heat. It seems evident that electricity, and therefore hydrogen production as well, should not be regarded at the moment and in the near future as economically feasible outputs for an UDGE plant. The efficiencies and cost for each process is regarded as unfeasible. However, market applications related to heat could be rather interesting as in this market, mainly natural gas and grey hydrogen is currently used, which are carbon emitting. Therefore, considering UDGE plants producing temperatures of 100°C, interesting markets could be applications in (heavy) industry such as diesel and naptha production in refineries, plastic production and milk sterilisation. Furthermore, residual heat could be applied in markets where shallow and deep geothermal plants are currently operating as well such as the built environment and horticulture. However, the economic feasibility of providing heat to the mentioned markets has not been researched and it is recommended to do so in succession of this thesis.

6.2 Answering the Main Research Question

What is the state of the technological- and market readiness for green hydrogen production from geothermal power plants in the Netherlands?

As a result of the TRA, the technological and market readiness were assessed and analysed. In order to answer the main research question, both will be addressed below.

In regard to the technology readiness of green hydrogen production from geothermal power plants in the Netherlands, four parameters were assessed; geosurface exploration, geosurface drilling, geothermal plant types and hydrogen production methods. For each parameter, a TRL was determined according to the framework proposed in chapter 2. As a result of the assessment, the TRL's for each aforementioned parameter were level 3, level 9, level 9 and level 6, respectively.

Hence, it can be concluded that the main barrier on a purely technology readiness basis for the proposed technological system is the geosurface exploration parameter. It seemed clear that the geosurface exploration capabilities at depths required for UDGE ($\pm$ 4.000 meter) is far below the required capabilities. Also, the current focus of geosurface exploration of involved institutions in the Netherlands is primarily until depths of around 2.500 to 3.000 meters and often even less deep than that. Also, the data that can be retrieved from exploration at relevant UDGE depths, or from most depths in general, can not always clearly conclude that hot water or brine is available or not. In order to allow for exact knowledge on what is below the surface, regardless of depth, drilling to the location which is argued to be potentially interesting is required. As a result, finding a suitable location for an UDGE plant is financially a high risk undertaking. Other parameters such as the drilling capabilities and the geothermal plant types were considered to be technologically ready. For drilling this is a result of past oil and gas developments. Regarding geothermal plants the proposed BCPP is one that is operational in various locations across the globe and hence, on a technology level, considered to be ready as well. Electrolyser developments are still in a state of research & development currently, but considered to be scaled to multiple MW sizes in the future.

Furthermore, in the case that an UDGE power plant would be constructed in the Netherlands, this research questions if that plant should focus on green hydrogen production. For green hydrogen production, electricity generation by the power plant is required. However, electricity generation efficiencies of (existing) geothermal power plants are remarkably low, at around 8% thermal. Given the efficiency of the best electrolysers on the market (65% to 75% efficient) results in a round trip efficiency for hydrogen production from geothermal plants at around 5.6%. Note, that this does not even consider storage, transportation and the efficiency for consumption of hydrogen. Hence, this is a topic of the quality and capabilities of the geothermal plants. Whereas most RES such as wind power turn work into electricity, which in return could be turned into (high temperature) heat, it seems illogical to use geothermal heat at 100°C to produce electricity when the heat it retrieves from the earth is already an interesting and demanded commodity itself. Therefore, co-generation of hydrogen, electricity and heat in a geothermal power plant is argued to be potentially irrelevant for the Netherlands as other RES could be potentially better and more relevant for electricity generation. In essence, RES such as wind energy and geothermal energy are in different playing fields.

Regarding the market assessment conducted, the three output markets were considered; green hydrogen, electricity and heat. Regarding green hydrogen, opportunities lie in the heavy mobility sector and in the (heavy) industry sector. However, regarding the former, the heavy mobility sector for green hydrogen is currently still in development and large amounts of applications are few. Nevertheless, many developments are being made and (green) hydrogen is considered as one of the main contenders to decarbonise this sector in the near future. With respect to (heavy) industry, this is considered to be the most relevant sector to pursue, as this sector already uses significant amounts of grey hydrogen as of today. Therefore, being able to provide green hydrogen to decarbonise this sector when it would be readily available, is argued to be most interesting. Comparable to the aforementioned for green hydrogen, the same holds for green electricity generation although production through a BCPP is inefficient as previously mentioned. Finally, of the three outputs of an UDGE geothermal plant, it was already argued earlier that it would be more logical to consider pure heat as a main output in comparison to a co-generation plant. High temperature heat retrieval could be interesting to look further into in the future once geosurface exploration tools such as REFLECT and SCAN can provide more complete information on ultra-deep depths. As in the over 100°C market, geothermal energy could be the only sustainable contender and interesting for industries requiring high temperatures for their production processes.

6.3 Scientific Contribution of Research

During the preliminary research of this thesis it seemed clear that UDGE was a non-existent technology within the Netherlands. Also, no previous research was found that focused on this topic. The information that was available on GE, was focused on depths at a maximum between of 2.500 meters and 3.000 meters. Furthermore, in light of the Paris Agreement and the climate goals being pursued by the Netherlands, researching novel carbon neutral energy such as hydrogen is key.

This thesis is a first attempt at researching the possibilities of green hydrogen production using the renewable energy source, geothermal energy. This research focused on identifying the technological maturity of various parameters which are involved in such a system. The research showed that, in a technological maturity sense, that primarily the geosurface exploration parameter is a significant barrier for further development of UDGE. Without ultra-deep depths, GWT necessary for electricity generation, and hence hydrogen production, can not be achieved. Also, thermal efficiency levels of the full hydrogen production cycle is worrying at 5,6% for a 100°C GWT.

Furthermore, this thesis assessed how the technology could develop in the future and what the possible market impact and applications could be if such a system would become reality through a technology assessment. This showed that if an UDGE plant would be built in the Netherlands, the main application should not be on hydrogen production, neither should it be a byproduct. The most relevant output would be heat in order to help decarbonize (heavy) industry.

The scientific contribution of this thesis was hence a first attempt at assessing green hydrogen production using geothermal energy in the Netherlands. Researching where opportunities lie or where significant barriers prohibit development.

6.4 Research Reflection

As this thesis strove to assess green hydrogen production using geothermal energy in the Netherlands for the first time in a scientific research, it is important to reflect on the research itself.

Research Approach & Method

This thesis initially built its knowledge base on existing literature on geothermal energy plants around the world, in order to gain an understanding of the requirements, necessities and implications for operating such a plant. Furthermore, it researched current geothermal energy operations in the Netherlands. Finally, knowledge on hydrogen production was gathered to help understand how hydrogen production could potentially be implemented or incorporated in a geothermal plant.

Following this knowledge base, two research methods were adopted; data collection through semi-structured interviews and a Technology Readiness Assessment (TRA). The TRA is a combination of two frameworks, the Technology Readiness Level (TRL) and the Technology Assessment (TA). As a result, the TRA in essence is an assessment which assesses the maturity and capabilities of a technology and how one can expect this technology to develop and be applied in the future. As the objective of this thesis was to understand if and how hydrogen production could be implemented in geothermal energy systems, which in return allowed to recommend if and how Engie should or should not pursue this type of technology, it is argued that the exploratory research approach using the methods described above is sufficient to come to a conclusion in light of that objective.

As this topic of research is a first in the Netherlands, it was considered to be important to first lay out the general technological maturity and potential future market applications and developments in order to create a basis from which further research could build upon in more depth should that be relevant. Although sufficient, the approach is not perfect. Limitations will hence be considered next.

6.5 Research Limitations

Limitations in the approach of this research will be addressed here. Limitations are related to the semi-structured interview data collection, the TRL framework and the TRA framework.

Limitations of Semi-Structured Interview

First, regarding the semi-structured interview data collection. This thesis interviewed four experts in different domains of expertise. The interviewees were selected upon the domains that they worked in and seemed relevant at the time of contacting them. These domains were; geothermal energy at Engie (Jan Brandts), hydrogen production (Lennart van der Burg), subsurface exploration (Timme van Melle) and subsurface research (Anne Pluymakers). One limitation is that these experts are mainly focused technological aspects related to this thesis topic. However, since this thesis also assesses market applications such as (heavy) industry, it would have been beneficial to contact individuals working in the sectors analysed as well. The same holds for contacting government officials regarding their renewable energy research focus, operators of existing non-UDGE geothermal plants in operation in the Netherlands or operators of existing BCPP in other countries. Furthermore, it could have been beneficial to speak to more than one expert per domain in order to create some sort of validation on what another expert would have said. However, it proved that each interview was a time-consuming undertaking as well regarding contacting and waiting for a response, preparing the interview, conducting the interview and processing the information after the interview which affected the amount of interviews done.

Limitations of Assessments

Regarding the first assessment, the TRL, a limitation of the framework is assessing the in-depth of topics to be regarded for the assessment. For example one topic which was assessed was the geothermal plant maturity. This is a rather broad topic and could be assessed in more detail per geothermal plant type for instance. Limitations of the TA were regarded to be the difficulty in estimating future impacts, applications and developments as although these can be as well argued as possible, it is still speculative assessment. In light of the TRA framework, a limitation is the focus of the assessment on mostly the technological maturity, development and application. This framework does not assess aspects which influence the success of a technology implementation such as regulations, social acceptance and financial aspects. Nevertheless, this would allow for future research and was argued to be more relevant in the event that hydrogen production using a geothermal plant in the Netherlands would be more technologically mature.

Lack of Knowledge & Experiences

As mentioned, this thesis is the first research (to the researchers knowledge) about hydrogen production using geothermal power plants in the Netherlands. Although therefore a relevant topic, it also limits the knowledge on which this thesis could build upon as their is a lack of experience on this topic within the Netherlands. This thesis therefore partly builds upon literature and knowledge from outside of this thesis scope such as geothermal plant developments from other countries. This hence also identifies a strong recommendation for further research regarding this topic; UDGE knowledge import or knowledge sharing. A recommendation that would be well suited for the institutional domain of Dutch policy makers regarding RES. To further collaboration with countries, companies and other establishments excelling in geothermal energy.

6.6 Recommendations

Recommendations for Engie

The short and concise recommendation for Engie is that they should not pursue or develop their geothermal energy systems to implement hydrogen production systems. The reasons for this are threefold.

First and foremost, to produce hydrogen through electrolysis, a plant would require electricity generation. In order to be able to produce electricity, a geothermal plant would require at least 100°C to sufficiently power its turbines using a binary cycle closed loop system. However, this is the minimum and would result in an efficiency close to 8% thermal which is remarkably low. Considering the electrolysis efficiency of around 70%, the roundtrip hydrogen production efficiency would amount to 5.6%. Note, that this does not even consider storage, transportation and the efficiency for consumption of hydrogen which would further reduce overall efficiency.

Secondly, the geosurface exploration capabilities at depths required for UDGE is far below the required capabilities. Focus on geosurface exploration is clearly primarily until depths of around 2.500 to 3.000 meters. Also, the data that can be retrieved from exploration at lower depths can not always clearly conclude that hot water or brine is available or not. That would require drilling to a location which is argued to be potentially interesting. As a result, finding a suitable location for an UDGE plant is financially a high risk undertaking.

Thirdly, due to the aforementioned efficiencies, hydrogen production through geothermal plants is considered as not competitive compared to other green hydrogen production processes in relationship to cost effectiveness. This is largely due to the extra process involved; from heat, to electricity, to hydrogen. Whereas, for instance, a wind energy process would only require electricity to hydrogen.

Nevertheless, higher temperature heat retrieval could be interesting for Engie to look further into in the future once geosurface exploration tools such as REFLECT and SCAN can provide more complete information on ultra-deep depths. In the over 100°C market, geothermal energy could be the only sustainable contender. Therefore, although it was not the main topic of this thesis, it is argued to be a relevant technology to keep monitoring in the coming years.

Recommendations for Further Research

Recommendations for research that should follow this thesis are fivefold; focus on heat markets for UDGE, further research in subsurface fluid identification and exploration methods, continue Dutch geosurface exploration of ultra-deep depths, research regulatory incentives for geothermal energy developments, research cost competitiveness of geothermal energy in relation to other renewable energy sources.

Although the main topic of this thesis was focused on hydrogen production through UDGE which seems an illogical market to pursue, it should be pointed out that ultra deep geothermal plants should not be deemed unfeasible overall. Once geosurface exploration technologies are developed further and high risks can be taken away, then such a plant may be possible. Also, the focus market for such a plant should then be on heat as this is a market where there is a large market for net zero heat and competing alternative technologies would be few.
From the TRL assessment it seemed clear that the subsurface fluid identification and exploration is one of the main barriers currently for UDGE. Which in return is hence also one of the main barriers for hydrogen production from geothermal energy. The main implication of this is that researchers can not identify fluids from above the surface and that drilling to depth is required to understand what is truly in the ground. This results in high costs and uncertainties and hence in low incentives for geothermal energy at (ultra-deep) depths. Further research and support for institutions such as REFLECT are of utmost importance to introduce ultra-deep geothermal energy within the Netherlands.

Besides subsurface fluid exploration, the geosurface rock layer exploration in the Netherlands is not fully mapped either. Furthermore research and exploration in such domains can help identify potentially relevant areas for ultra-deep geothermal energy. Hence, research and support for institutions such as SCAN should be considered as well.

This thesis did not focus on regulatory aspects of a hydrogen producing geothermal plant in the Netherlands. Adding regulatory research into topics such as carbon taxing to the created TRA framework of this thesis could provide a broader picture and could provide extra incentives to further research into (ultra-deep) geothermal energy. For instance, for industry then requiring green hydrogen or sustainable heat sources.

Furthermore, this thesis and TRA framework does not provide a full focus on financial and cost competitiveness of UDGE in comparison to current markets and other renewable energy sources. Further research into the potential cost competitiveness of such an UDGE plant in the event that it would exist would be a strong addition to this research.

It seems evident from the above that there is a lack of experience and knowledge regarding UDGE power plants in the Netherlands. A final recommendation, as was already shortly mentioned in a previous section on the research limitations, would hence be to establish larger knowledge sharing platforms regarding this topic, most specifically in the geosurface exploration and geothermal power plant building domain.

Appendix A

A

A.1 Prepared Interview Topics & Questions for Jan Brandts

1. **Personal**

   A. Could you shortly introduce yourself? For instance, who you are, what you do at Engie, what your expertise is and what your experience is within this domain.

2. **Geothermal Energy at Engie**

   A. Engie acquired Hydreco Geomac last year, can you tell me a little bit more about the current projects in your portfolio?

   B. What are the plans for the future, which projects will you be working on and realising?

3. **Ultra Deep Geothermal Energy**

   A. What are the prospects for Hydreco Geomac and Engie regarding Ultra-Deep Geothermal Projects?

   B. How do you analyse the Dutch geosurface? Is there a collaboration with external parties regarding this?

   C. Could you tell me more about the Trias Westland project that had the intent to start an Ultra-Deep plant to four kilometers depth. What happened there? What did you learn? What were difficulties or reasons to stop?

   D. How would you rate the Dutch geosurface in general? What is known about it? What does Engie know or its partners?

   E. Are you familiar with a tool created by *TNO*, ThermoGIS? How would you rate its information? Do you use it at Engie? How reachable are the various layers depths and temperatures?

   F. Is Engie familiar or involved in any Binary Cycle Power Plant (BCPP)? What do you know about these types of plants and is there any ongoing research on BCPP?

4. **Seasonal Demand & Production**

   A. I can imagine that there is a fluctuation in demand for geothermal energy in the form of heat during seasons such as the winter and the summer. How does this unfold in reality for your projects?

   B. The proposed hydrogen storage system from electricity generation in a BCPP is argued to be a solution for the fluctuating demand and hence to keep plant production levels consistent throughout an entire year. What is your view on this?

5. **Organisation**
   - A. How should I visualize the current set-up of your team or organisation?
   - B. Does your team currently focus solely on geothermal heat or is a department also working on innovations such as BCPP Ultra-Deep plants?
   - C. What collaborations is Engie in regarding geothermal energy?
   - D. Do you also follow and discuss opportunities with foreign projects of other firms? Or is the focus truly more in the Netherlands and sharing of knowledge scarce?
   - E. Is there time, money and space to research higher risk aspects of geothermal energy such as geosurface scanning? Or does Engie take a more risk mitigating role in this domain?
6. **Social & Political**
   - A. Do you have any information or insights on the social aspect of geothermal energy? For example, how is it regarded amongst the general public?
   - B. What is the Dutch political systems view on geothermal energy? Is it highly subsidized or not at all? Is it encouraged or is the focus more on other energy system developments?
   - C. If any, what are the barriers regarding geothermal energy? Financially, socially, politically, technologically or anything else that pops up?
7. **Market**
   - A. What is your view on the development of the geothermal electricity market compared to systems such as wind and solar energy?
8. **Other**
   - A. Is there anything that comes to mind what I have not asked or that might be relevant to this research?

A.2 Prepared Interview Topics & Questions for Lennart van der Burg

1. **Personal**
   - A. Could you shortly introduce yourself? For instance, who you are, what you do at TNO, what your expertise is and what your experience is within this domain.
2. **Hydrogen & Electrolysis**
   - A. What is your and TNO's main focus of research on at the moment regarding hydrogen?
   - B. How can electrolysis be implemented in a geothermal plant? Would it be as easy as just connecting such a system to the electricity output or are special requirements applicable?
   - C. What is the efficiency of (the best) electrolysers today and which would that be in your opinion?
   - D. I read an article about you from November of 2020 in *De Ingenieur* in which you stated that production costs need to be lowered significantly to reach the production goals of the European Commission (EC) of 6GW of hydrogen in 2024 and 40GW in 2030 [45]. Currently it is only at 170MW. What is your view on that now and have their been noteworthy developments since then?

E. What is your expected efficiency growth or capacity growth of electrolysers in the foreseeable future? How much theoretical growth is there?

3. **Business Case**

   A. What is your opinion on the hydrogen business case currently?

   B. What is your view on the green hydrogen market for the foreseeable future?

   C. What are the major barriers for expansion besides costs currently for electrolyser developments?

   D. In the aforementioned article in *De Ingenieur* I read about a shortage in a raw material called Iridium [45], how great of a problem is that to developments? Are their replacements?

   E. Is the market fueling hydrogen developments? For instance with are heavy duty vehicle companies

4. **Seasonal Variation**

   A. One idea I have currently is to propose to produce hydrogen through electrolysis in the summer months to bridge the lower demand in that period and keep capacity factors of the plant high. What is your view on such an idea?

5. **Political**

   A. How is hydrogen being handled in the Netherlands politically in your opinion? Are there policies fueling its development? Or could it be better?

   B. In the *De Ingenieur* you mention that the EC needs to enforce more European wide policies to ensure collaboration within the market. Could you elaborate on more specific aspects on this?

6. **Other**

   A. Is there anything that comes to mind what I have not asked or that might be relevant to this research?

A.3 Prepared Interview Topics & Questions for Timme van Melle

1. **Personal**

   A. Could you shortly introduce yourself? For instance, who you are, what you do at SCAN, what your expertise is and what your experience is within your domain.

2. **SCAN**

   A. What is SCAN?

   B. What is the main focus of SCAN and are their long-term goals?

   C. What do you do with your data measurements?

3. **Ultra Deep Geothermal Energy**

   A. Since you mention that you also map Ultra-Deep depths, do you work together with parties such as GOUD? Or any other parties?

   B. What is your opinion on UDGE based on the work that you do?

   C. Why is it necessary to drill to depth? Why can the current technology not assess permeability or availability of water at depth?

D. In your opinion, should the focus not lie more on subsurface exploration innovations from above the surface rather than the current state of research?

4. **Social & Political**

   A. SCAN is working on behalf of the Dutch *Ministry of Economic Affairs and Climate Policy* (EzK), to what extent do they support the activities of SCAN?

   B. To what extent does EzK support UDGE?

   C. How would you compare public support to other renewable energies such as wind and sun?

   D. How would you compare business support to other renewable energies such as wind and sun?

5. **Market**

   A. Imagine UDGE would exist, how do you envision the market for it?

   B. What is your opinion on the idea of electricity production with hydrogen production as a capacity factor increasing byproduct?

A.4 Prepared Interview Topics & Questions for Anne Pluymakers

1. **Personal**

   A. Could you shortly introduce yourself? For instance, who you are, what you do at the TU Delft, what your expertise is and what your experience is within your domain.

2. **Ultra Deep Geothermal Energy**

   A. What is your opinion on UDGE?

3. **Subsurface Exploration**

   A. I have spoken to Timme van Melle at SCAN, who works on subsurface exploration. However, they do not focus or are able to assess permeability and fluid characteristics of the subsurface. Could you explain why a somewhat identical system does not exist for permeability?

4. **Drilling Operations**

   A. Could you elaborate on the aspects of drilling which are relevant for UDGE depths?

   B. The concepts described in the literature review of section 3.1.2 are shortly described. What is your opinion on these concepts?

5. **Market & Politics**

   A. Could there be a market for UDGE?

   B. In your opinion, what would be necessary to stimulate the geothermal market?

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