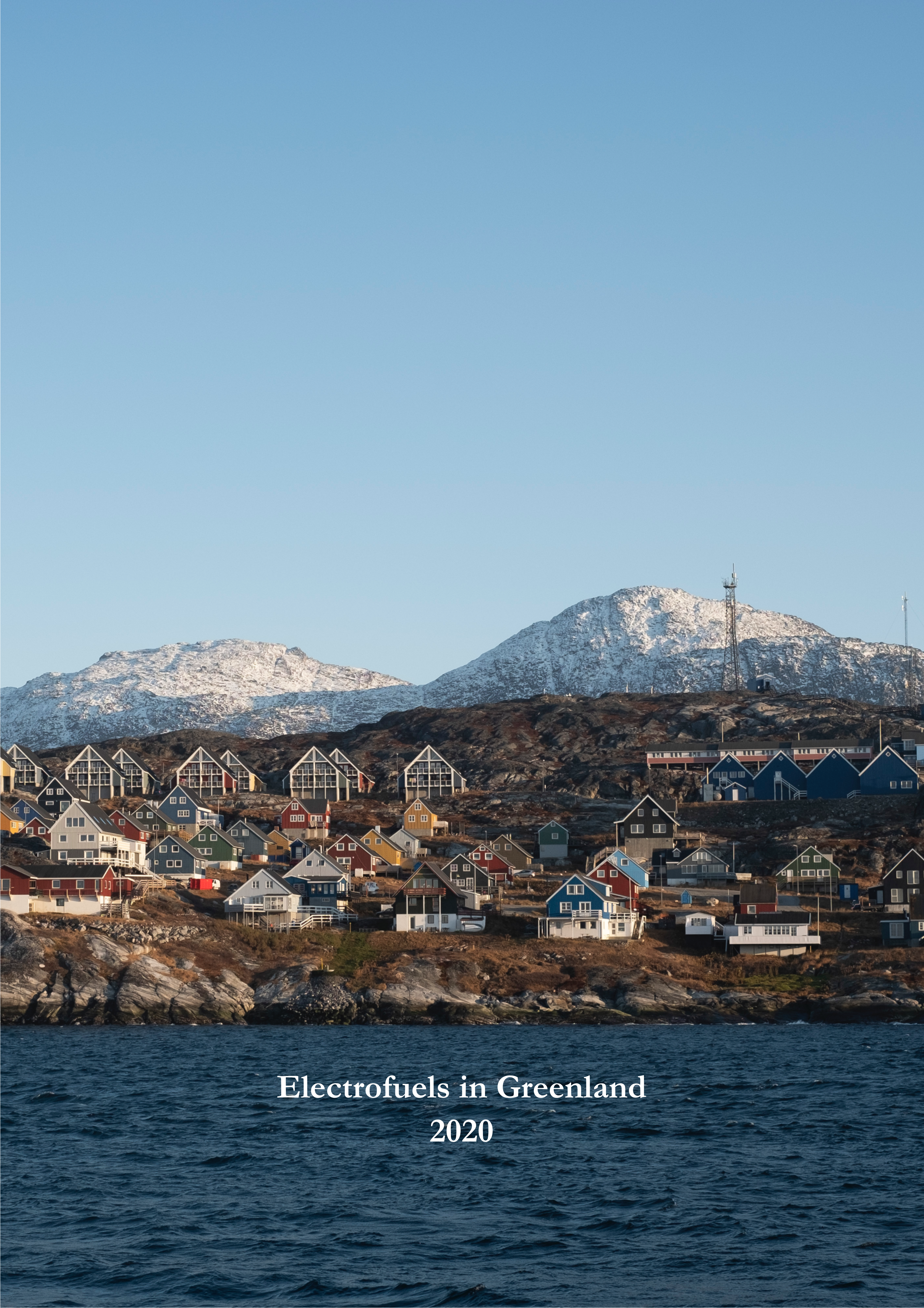

Electrofuels in Greenland

2020

Sustainable Cities
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Title:	**Electrofuels in Greenland**
Semester:	**MSc in Engineering**
Semester theme:	**Master's thesis**
Project period:	**Spring 2020**
ECTS:	**30**
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Synopsis:

The prevailing geographical circumstances in Greenland with long distances between cities and settlements and the cold climate implies that the vast majority of the national energy supply is today covered by fossil fuels.

This master's thesis evaluates whether electrofuels constitute a genuine technological alternatively to the currently used fossil fuels.

The results show that electrofuels could substitute substantial quantities of fossil fuels. However, a gradual replacement of engines and generators is suggested in order to avoid large alteration costs and accommodate future technological and economic progress.

Pages:	98
Appendices:	12
Enclosures:	No

By signing this document, each member of the group confirms participation on equal terms in the process of writing the project. Thus, each member of the group is responsible for the all contents in the project.

Abstract

Due to the prevailing geographical circumstances in Greenland with long distances between cities and settlements and the cold climate, the national energy supply is today predominantly covered by fossil fuels. The Government of Greenland has the objective of becoming supplied by renewable energy sources to the largest extent possible by 2030 and to increase the degree of self-sufficiency. On the basis of the Choice Awareness theory, this master's thesis aims to evaluate whether electrofuels constitute a genuine technological alternatively to the currently used fossil fuels and contribute to strengthen the decision-making process.

The analysis examining the potential of electrofuel production in Greenland has been carried out based on a comprehensive state-of-the-art chapter and analyses designating the most interesting hydropower potentials and available carbon dioxide resources applying the energy-economic model developed in connection to this master's thesis.

The results show that the electrofuel production in all cases would be able to substitute substantial quantities of fossil fuels. Moreover, the electrofuel production could be able to increase the degree of self-sufficiency significantly. The methanol production from Tasersiaq could provide an interesting solution capable of supplying 79% of the total national energy demand with a positive NPV of 260 M€. Alternatively, producing ammonia from domestically captured nitrogen would be able to supply 67% of the demand and showed an NPV of 12.5 M€. In opposition to methanol producing ammonia enables 100% independence of any import of resources. For this reason, it is relevant to consider whether increasing the amount of RES in the energy system or the self-sufficiency degree should be prioritised.

A gradual replacement of engines and generators is suggested in order to avoid large alteration costs and accommodate future technological and economic progress. Such approach would imply only a gradual national improvement of the share of renewable energy and self-sufficiency degree. Therefore, the results from the analysis will first be valid after some years when a transition sufficient enough to accommodate the quantity of electrofuel produced has taken place.

The results of the methanol production form Tasersiaq is most sensitive to variations of CAPEX, discount rate and the CO_2 emission cost which all can turn the project negative in terms of NPV. Other energy technologies and energy savings has not been considered in this study although there might be some interesting potentials.

Preface and motivation

The interest and motivation for this project can be traced back to our first semester of The Master of Science Programme in Sustainable Cities in 2018. Here we were introduced for the first time to the topic concerning PtX in Greenland by Henrik Steffensen from Ramboll who together with others from the company presented a number of different project themes to our programme. Our interest in the project was immediately aroused though it was with some concern of the technical and chemical parts of the topic. This led to a cooperation with Ramboll, which later also resulted in an internship in autumn 2019 and now a collaboration regarding our master's thesis.

We are very grateful for this opportunity and would therefore initially like to thank Henrik Steffensen and Søren Thomsen for making this possible. Søren Thomsen should also receive an enormous thanks for the many sparring and feedback along the way. Also, thanks to the Department of Energy, Strategy and Planning at Ramboll for the opportunity and for providing a desk for this whole period. We would also like to thank Mathis Backen from Ramboll, likewise for sparring as well as for provision of data concerning the energy system in Greenland. Furthermore, thanks to Christian Riber, Tore Hulgaard and Klaus Fafner, all from Ramboll, for dissemination of contacts, data on waste incineration, chemical balances and economic prerequisites.

Moreover, we would like to thank everyone wo has contributed in the course of this master's thesis. Thanks to Klaus Petersen, MAN Energy Solutions, for taking you time to an interview about engines and generators installed in Greenland. Also, thanks to Jens Schiersing Thomsen from Siemens Gamesa on your perspectives concerning an ammonia production in the country. Thanks to Martin Frahm Jensen, Emil Andreas Tjärnehov, Yawar Abbas Naqvi, all from Haldor Topsoe, for the meeting about specific conditions of synthesis processes. Moreover, thanks to Jesper Scramm professor at DTU for sharing your technical knowledge on fuel application. Furthermore, thank you to Tage Lindegaard and Bjarne Lykkegaard from Polaroil for taking you time to an interview about the current fuel infrastructure in Greenland and your perspectives on an application of electrofuels in the country. Thanks to Allan Bertelsen from the Ministry of Industry, Energy, Research, and Labour for your time talking about the political and regulatory framework of the energy sector. Additionally, thanks to Tuperna Maliina Olsen, likewise from the Ministry of Industry, Energy, Research and Labour, for your provision of the latest statistical data. Also, thanks to Kasper Dahl, Asger Dall, Rolf Sloth from the utility company, Nukissiorfiit, for data concerning hydropower resources in Greenland. Also, thanks to Anders N. Andersen for providing free access of the energy system analysis tool, energyPRO. Thanks to Olivia Loftlund for providing the beautiful pictures presented throughout the report.

A very big thanks to Peter and Emma Thomsen's scholarship for the funding, which has allowed us to concentrate fully on our last project of our master's programme.

Lastly, and maybe once and for all, a huge thanks to our supervisor, Iva Ridjan Skov, for your always knowledgeable and profitable feedback as well your encouragement along the way.

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List of abbreviations

AEC	Alkaline electrolyser cell
ARC	Amager Resource Centre
ASU	Air separation unit
BAU	Business as usual
CA	Choice Awareness
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DAC	Direct air capture
DME	Dimethyl ether
DMFC	Direct methanol fuel cell
DTU	Danish Technical University
ESA	Electro-swing adsorption
FT	Fischer-Tropsch
FTS	Fischer-Tropsch synthesis
GHG	Greenhouse gas
H_2	Hydrogen
H_2O	Water
HHV	Higher heating value
HRS	Hydrogen refuelling station
HTFT	High-temperature Fischer-Tropsch
ICE	Internal combustion engine
IPCC	Intergovernmental Panel on Climate change
IRENA	International Renewable Energy Agency
Ista	Isortuarsuup Tasia
Kang	Kangerluarsunnguup Tasersua
LHV	Lower heating value
LPG	Liquified petroleum gas
LTFT	Low temperature Fischer-Tropsch
N_2	Nitrogen
N_2O	Nitrogen Oxide
NGCC	Natural gas combined cycle
NH_3	Ammonia
NPV	Net present value
O_2	Monoxide
OPEX	Operational expenditure
PCC	Post-combustion carbon capture
PEM	Proton exchange membrane
PSA	Pressure swing absorption
PtG	Power-to-Gas
PtL	Power-to-Liquid
PtX	Power-to-X
RES	Renewable energy sources
RTC	Radical technological change
RWGS	Reverse water-gas shift
SCPC	Supercritical pulverised coal
SOA	State-of-the-art
SOEC	Solid oxide electrolysis cell
STP	Standard temperature and pressure
TPES	Total primary energy supply
TRL	Technological readiness level
TSA	Temperature swing adsorption
VSA	Vacuum swing adsorption
WGS	Water-gas shift
WtE	Waste to energy

1. Introduction

Climate change is the defining issue of our time and the emission of greenhouse gases (GHGs) to the atmosphere have significant consequences for the global climate. Many of these gasses occur naturally and are essential for making Earth liveable for humans and millions of other living creatures keeping out some of the sun's warmth by reflecting it back into space. However, driven largely by economic and population growth and with more than a century characterised by industrialisation, deforestation and large-scale agriculture, the quantity of greenhouse gases in the atmosphere has risen to record levels not seen in three million years (United Nations, 2020). Human activity is thus highly responsible for the increased atmospheric GHG concentration and in particular the increased amount of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Carbon dioxide is the most commonly produced greenhouse gas from human activity and represents 76% of the emitted gassed, whereas methane and nitrous oxide accounts for 16% and 6%, respectively. Fossil fuel combustion is the primary source of CO_2 and accounts for 65% of the CO_2 emissions, while forestry and other land use stands for the remaining 11% (IPCC, 2014). The global annual concentration of CO_2 in the atmosphere averaged 407.4 ppm in 2018, which is a major increase compared to pre-industrial levels (1850-1900), which ranged between 180 and 280 ppm (IEA, 2019c).

Some of the observed changes as a result of the increased GHG concentration is that the average temperature level of the atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and the sea level has risen (IPCC, 2019a). The warming from the anthropogenic emissions will cause further changes in the climate system and the risk of severe, pervasive and irreversible impacts for people and ecosystems will be greater. Catastrophic events such as extreme storms, heavy precipitation, fires, draughts and floods are consequently likely to be experiences more frequently due to the warmer climate, especially affecting developing countries and vulnerably communities (IPCC, 2018, 2019b; UNFCCC, 2018).

Two-thirds of global greenhouse gas emissions are derived from energy-related CO_2 emissions and latest figures show that these emissions rose 1.7% to a historic high of 33.1 Gt CO_2 in 2018 driven by higher energy consumption resulting from a robust global economy. While emissions from all fossil fuels increased, the power sector accounted for nearly vast majority of the emissions growth (IEA, 2019c; IRENA, 2019a). Electricity and heat generation is the largest emission driver and accounted for 41% of the total CO_2 emissions in 2017, while industry and transport were both responsible for 24% (IEA, 2019a). In order to reduce the global carbon dioxide emissions and limit the increase of temperature to well below 2 °C above pre-industrial levels and pursue to limit it even further to 1.5 °C as agreed upon by the represented nations of the Paris Agreement (UNFCCC, 2016), alternatives to the current fossil fuel consumption must be comprehensively introduced across all sectors of the energy system. To meet the objective of limiting the global temperature increase to 1.5 °C with no overshoot, the Intergovernmental Panel on Climate Change (IPCC) recommends reductions of the global anthropogenic CO_2 emissions of 45% below 2010 levels by 2030 and net zero emissions by 2050. They find that the world today has less than two decades to make serious cuts in carbon emissions, whereas if we fail we may cross the tipping point into a future of catastrophic climate change (IPCC, 2018). Consequently, the International Renewable Energy Agency (IRENA) argue that the global energy system must undergo a rapid, immediate and sustained change, while the cumulative energy related CO_2 emissions must be 400 Gt lower by 2050 than indicated by the current policies and plans in order to hold the line at 1.5 °C (IRENA, 2019b). This view is complemented by latest Production Gap Report noting that there is a significant gap between the current policy and the performance required to meet the objective. The production gap is currently widest for coal but grows rapidly for both oil and gas (UNEP, 2019).

IRENA claims that renewables and energy efficiency, enhanced through electrification, can achieve more than 90% of the reductions needed in energy-related CO_2 emissions. However, this requires urgent and deep investments in low-carbon technologies and renewables (IRENA, 2019b). However as stated by IPCC, the longer we wait to take action, the more it will cost and the greater the technological, economic, social and institutional challenges we will face (IPCC, 2014). Significant changes in the energy system is thus needed to accommodate the objective of limiting the temperature to 1.5 °C before pre-industrial levels and this entails that the energy system must undergo a far-reaching transition from being largely based on fossil fuels to become based primarily on renewable energy sources (RES).

This study focuses on the energy system of Greenland and aims to contribute to the country's green transition. The objective of the Government of Greenland, Naalakkersuisut, is that the country should be supplied by renewable energy sources to the largest extent possible by 2030 and in the long term be based solely on local renewable energy sources. They furthermore want to carry out a comprehensive modernisation of the energy system and substitute their current use of imported fossil fuels with new energy technology where this has not already happened (Naalakkersuisut, 2017). The geographical circumstances in Greenland however challenges the realisation of a greener energy system.

2. Problem analysis

Greenland is the largest island in the world and with a total area of more than 2,000,000 km^2 the country is about twice the size of Germany and French together or about one fifth the size of Europe. About 80% of the area is covered by inlands ice and with a population of only 56,000, the country is the world's most sparsely populated. The majority of the Greenlandic population of around 60% lives in the five largest cities i.e. Nuuk, Sisimiut, Ilulissat, Aasiaat and Qaqortoq, while the remaining lives in smaller settlements. With 18,000 inhabitants the capital Nuuk contains the largest population in the country (Grønlands Statistik, 2019, 2020a).

Greenland is located in the northern polar region where the artic climate implies that the winters are characterised as long and cold while the summers are mild and short. The cold climate imposes a high energy demand and entails a great importance for security of supply as interruptions may have severe consequences. This also means that the CO_2 emissions per capita is relatively high in Greenland of around nine tonnes compared to a world average of five in 2014 (The World Bank, 2015). The vast majority of these emissions are derived from the energy sector and latest figures from 2015 indicate that the total amount of greenhouse gas emissions from energy consumption was around 524,000 tonnes CO_2 equivalents, which corresponds to 94% of the total emissions in Greenland (Grønlands Statistik, 2016). Gasoil (equivalent to diesel) represents more than two-thirds of the fossil fuel used in Greenland and is the preferred source of energy for the production of electricity and heating in households, institutions as well as in the industry. Likewise, gasoil is also applied in the transport sector (Grønlands Statistik, 2017a). The national utility company, Nukissiorfiit, accounts for around one third of the total energy supply in Greenland, which predominantly obtained from RES (Nukissiorfiit, 2019d). However, the remaining share of the country's consumption is private supply which is the reason why oil boilers and gasoil are still used for heating in many households (Naalakkersuisut, 2017). Before the establishment of the first hydropower plant at Buksefjorden, some 50km outside of Nuuk, in 1993, imported fossil fuels were used exclusively to cover the energy demand in Greenland (Grønlands Statistik, 2019). In the following years, additionally four hydropower plants have been commissioned in Tasiilaq, Qaqortoq/Narsaq, Sisimiut and latest in 2013 in Ilulissat, increasing the total share of energy from hydropower (Nukissiorfiit, 2020b). Figure 1 display the development of the energy supply in Greenland according to the latest statistics. It is evident that imported fossil fuels constituted the entire energy supply in 1990, while a small amount of energy from waste incineration was introduced in 1992.

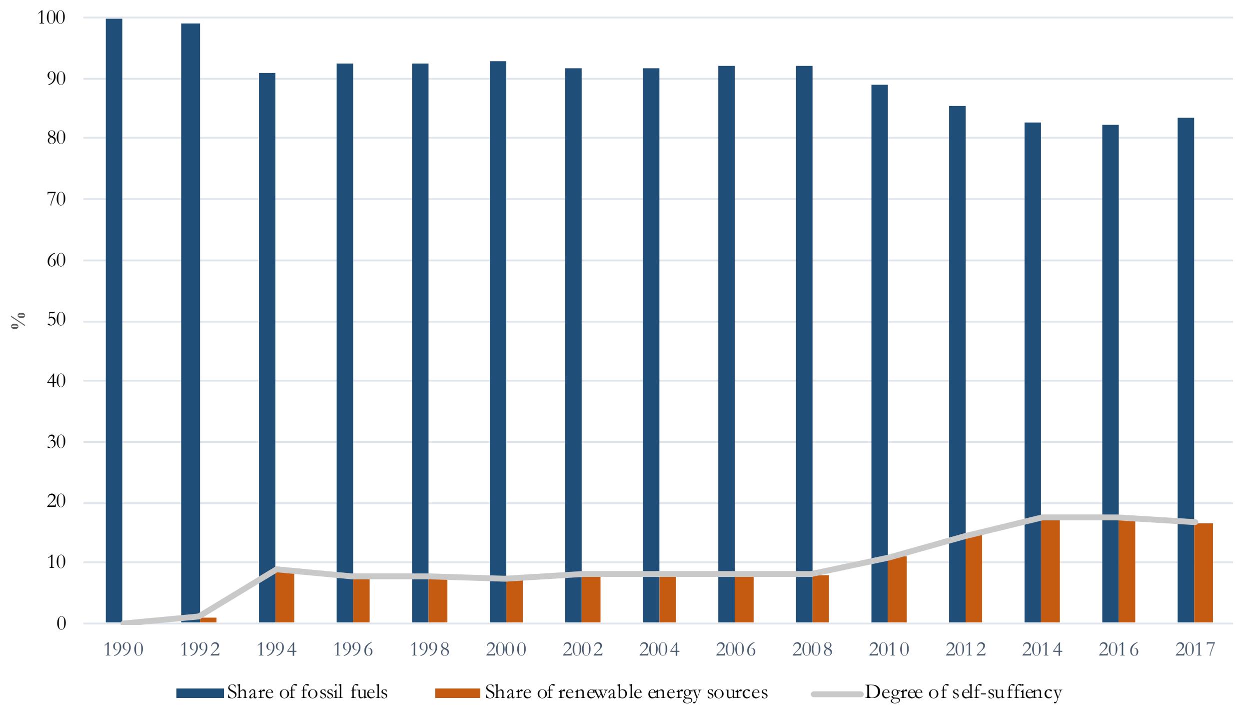

Figure 1: Actual energy consumption in Greenland divided in fossil fuels and renewable energy sources (Department of Business - Energy and Research, 2018; Grønlands Statistik, 2017a).

In 2017, the share of fossil fuels represented 83.5% of the entire energy consumption in Greenland, while the remaining 17% was provided by RES. Hydropower accounted for 15.4% while only a smaller amount of 1.1% came from incineration of waste. The accumulated value of energy from hydropower and waste incineration constitutes the country's degree of self-sufficiency (Grønlands Statistik, 2017b). As shown in the figure, the share of energy from renewables has remained stable since the latest established hydropower plant in 2013 and the country has thus not progressed towards meeting their objective of increasing the share of renewable energy in recent years. According to Naalakkersuisut (2017) the total investment cost for all hydropower plants in Greenland amounts to around 467 M€. The investments in hydropower enables a reduction of imported gasoil by approximately 188,000 tonnes implying an annual saving between 40–54 M€. In Figure 2, the annual savings of gasoil are compared to the total investment cost of hydropower.

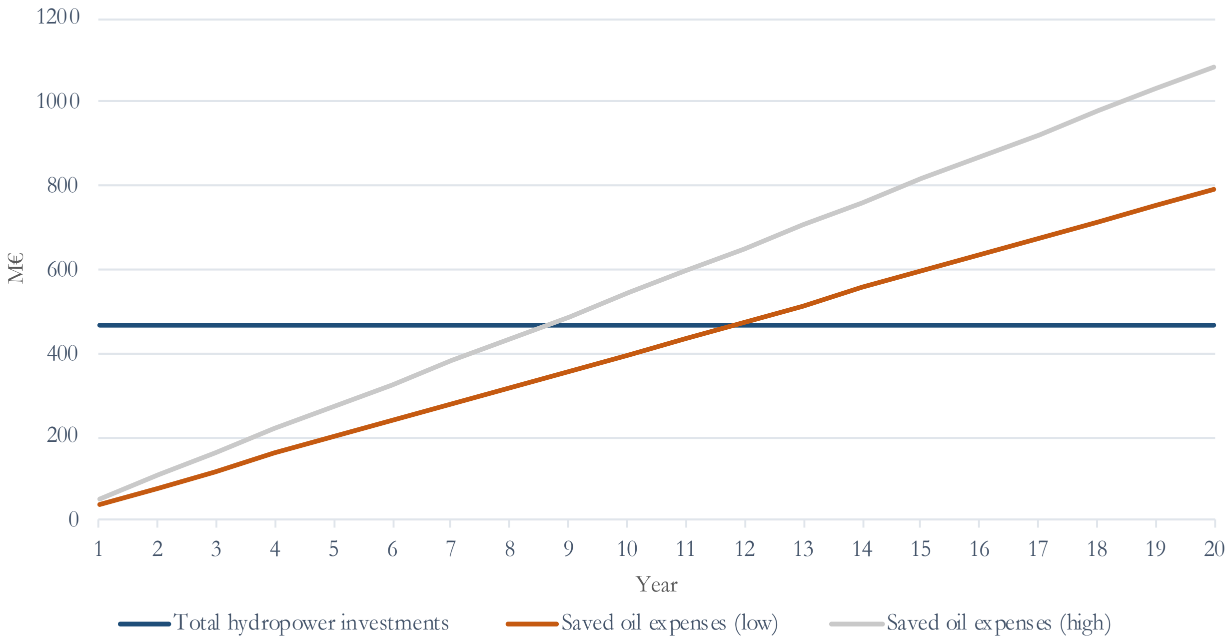

Figure 2: Comparison of the total investments of hydropower and the savings of annual expenses for oil between 1992 and 2017 (Naalakkersuisut, 2017).

It is shown that the investment has been returned after about 9-12 years only taking the oil savings into account. The investments of the five hydropower plants has contributed positively to their objectives of increasing the self-sufficiency and renewable energy supply. Also, according to Naalakkersuisut (2017), the security of supply and environmental aspects has improved as well as economic perspectives, such as reduced operation costs and electricity cost, which are all societal benefits. However, despite the country's huge hydropower potential described in the comprehensive report by Nukissiorfiit (2005) not all potentials would be a societal benefit to carry out. The main decisive parameter is whether utilisation of electricity corresponds to the investment (Naalakkersuisut, 2017). In many cases the total electricity demand does not correspond to the investment cost because every town or settlement has its own island energy system, which is not connected to other towns or settlements.

There are in total 69 isolated energy systems, however Qaqortoq and Narsaq are connected to the same hydropower plant. More than 60 of the energy systems are solely based on fossil fuels. The energy systems of Nuuk and Sisimiut are the only ones covering more than 5,000 inhabitants whereas the majority of around 50 of the stand-alone systems covers less than 500 inhabitants. The prevailing circumstances in Greenland with very long distances between cities and settlements and the harsh climate makes connection and distribution of electricity challenging and extremely costly. According to Naalakkersuisut, the cost of establishing land transmissions lines is estimated to between 0.3 and 0.4 M€ per kilometre without considering the additional costs of overhead line crossing of fjords (Naalakkersuisut, 2017). This makes it difficult to utilise the electricity and thereby increase the share of energy from hydropower in the country. Therefore, studies are being carried out by both the government and by Nukissiorfiit, examining how the energy system can be modernised and how other renewable energy sources and technologies can be introduced. This includes investigations of the potential of e.g. wind energy, heat pumps and photovoltaics.

Energy from wind has earlier been declined as an option due to poor wind power resources and the artic conditions. However, more recent studies prove the technology in artic climate in both Canada and Alaska (Nukissiorfiit, 2019d; WWF, 2017). Studies regarding wind measurements has shown that there are wind power resources in Greenland. It is however stressed that the wind vary a lot on both regional and local scale, which make the optimal location for the mills hard to designate (Berger et al., 2020; Jakobsen, 2016; Radu et al., 2019). In the Nuuk area there has been identified favourable wind conditions at the surrounding islands. However according to EA Energy Analyses (2018) only three wind mills can be located Rypeø which is too small a capacity to meet the increasing energy demand. The infrastructure and connection costs will result in higher electricity costs from wind compared to hydropower. It is stressed that if wind projects should be advantageous it would require much larger areas in order to reduce the cost per kWh (EA Energy Analyses, 2018a). Two small-scale wind mills are being tested in proximity to Sisimiut and more wind measurement are carried out by Nukissiorfiit (Nukissiorfiit, 2019d; Naalakkersuisut, 2017). Wind energy can according to Nukissiorfiit (2019) play a role where hydropower is not accessible or too expensive. Alternatively, photovoltaics is a proven technology in Greenland and Nukissiorfiit (2019) expect it to play an increased role especially in the small settlements. However, there is a major drawback for solar energy in Greenland because the angle of the sunrays varies greatly during the year, especially in the northernmost areas. This means that there will be a high production in the summer period, while there will be almost no production during the winter (Naalakkersuisut, 2017). Moreover, hybrid-utility plant is currently being tested in Igaliku by Nukissiorfiit consisting of a small system photovoltaics, wind energy and batteries. The system requires diesel backup generators when the utility plant supply from solar and wind is not meeting the demand (Nukissiorfiit, 2019d). Biomass resources are not widely available in Greenland and is not considered to play a role in the future energy system (WWF, 2017).

In all cases integrating wind turbines and photovoltaics there will be a need for backup generators and oil boilers due to fluctuations in order to provide electricity and heating at all time (Naalakkersuisut, 2017). A high level of flexibility is required in order to maintain an incessant security of supply and batteries and heat pumps are able to increase the level of flexibility. In terms of heat pumps, the cold outdoor temperatures imply that the coefficient of performance (COP) decline towards one (EA Energy Analyses, 2018a). Also, according to Nukissiorfiit (2019), such system would still require backup generators and oil boilers to meet the demand. The island energy systems are highly dependent on the security of supply, which has only been ensured by storable fossil fuels.

Due to the above described geographical circumstances and the challenges prevailing with long distances between towns and settlements as well as the cold climate and security of supply, this master's thesis project investigate the potential of producing electrofuels in Greenland with the objective of substituting the country's use of gasoil. The technological production pathways Power-to-Liquid (PtL) and Power-to-Gas (PtG), collectively also referred to as Power-to-X (PtX), makes it possible to produce fuels based on CO_2 and hydrogen (H_2) or nitrogen (N_2) (Jadhav, Vaidya, Bhanage, & Joshi, 2014; Schemme, Breuer, Samsun, Peters, & Stolten, 2018). The fuels can be applied in various applications across different sectors. The CO_2 for the production could come from industrial waste streams or be captured from the atmosphere, whereas the hydrogen can be obtained from a water electrolysis technology using renewable energy sources for the process. This could be derived from hydropower in Greenland utilising surplus electricity from new or expanded plants. The nitrogen may be derived from the atmosphere using an air separation unit (ASU) (Morgan, Manwell, & McGowan, 2014; Rouwenhorst, Van der Ham, Mul, & Kersten, 2019). Electrofuels may constitute an interesting option in relation to the given conditions in Greenland as it could be used to supply remote towns and settlements where it is otherwise not geographically or economically feasible to establish hydropower plants or other technologies.

In this master's thesis project, it will be investigated how electrofuel production from hydropower can help Greenland meet their renewable energy target by 2030 and contribute to modernise the energy system. It will be examined to what extend electrofuels can substitute the current use of fossil fuels and how this will affect the country's self-sufficiency degree without compromising the security of supply. A profound feasibility study will furthermore be carried out to examine whether electrofuel production in Greenland constitutes a possible solution for the country to invest in. The aim is to evaluate whether electrofuels is a genuine technological alternative to the currently used gasoil and thus contribute to strengthen the basis for the decision-making process by providing relevant and in-depth information about a potential production in Greenland. Due to plans of establishing two new central waste incineration plants in Nuuk and Sisimiut to handle all waste in the country from 2023, constituting a significant factor to the analysis of this master's thesis, the starting year is set for 2024. The research question of this master's thesis is presented below.

2.1 Research question

How can electrofuel production from hydropower help Greenland meet their renewable energy goal in 2030 and to what extent can it contribute to increase the degree of self-sufficiency?

3. Theory

In the following chapter the theoretical framework of this project is presented, and the application of the theory is explained. The Choice Awareness (CA) theory is formulated by Henrik Lund from Aalborg University in Denmark in the book *"Renewable Energy Systems – A Smart Energy Systems Approach to the Choice and Modelling of 100% Renewable Solutions"*. This book constitutes the literary foundation of this chapter, however supplemented by other articles explaining some concepts and approaches more in-depth.

3.1 Choice Awareness

The Choice Awareness theory is concerning the transition of society towards a 100 percent renewable energy system. The theory emphasises integration of several aspects in order to succeed transitioning a society to be based on RES. These aspects are firstly concerning a technical point of view examining the technical feasibility regarding technology and resources to meet the demands. Secondly, political and social scientific aspects are examined in order to address how such technological changes can be implemented in a society. Choice Awareness addresses the collective decision-making processes at societal level involving many actors representing different interests and level of power to influence the decision-making process. In the theory of Choice Awareness, two theses are embedded along with several key concepts (Lund, 2014). The concepts choice/no choice, radical technological change (RTC), choice perception and choice elimination are applied as defined and described by (Hvelplund & Lund, 1998; Lund, 2014).

The first thesis of Choice Awareness states that when society seeks to implement objectives implying radical technological change, the existing institutions and organisations seeks to create a collective perception that there is 'no choice'. This situation can be obtained by eliminating alternatives leaving no choice but to implement the technologies that will save and constitute existing positions. The second thesis of the Choice Awareness theory argues that the society will benefit from focusing on Choice Awareness and raise the awareness that alternatives do exist, and that it is possible to make a choice. The theoretical framework of Choice Awareness has been briefly described presenting the two theses. In the following it is more thoroughly presented how awareness is raised applying the Choice Awareness.

3.2 Application of Choice Awareness

The application of the Choice Awareness methodology is presented in the following. The methodology is suggested by Lund (2014), however also literature from Hvelplund, Lund and Sukkumnoed (2004) and Hvelplund and Lund (1998) is supplementing.

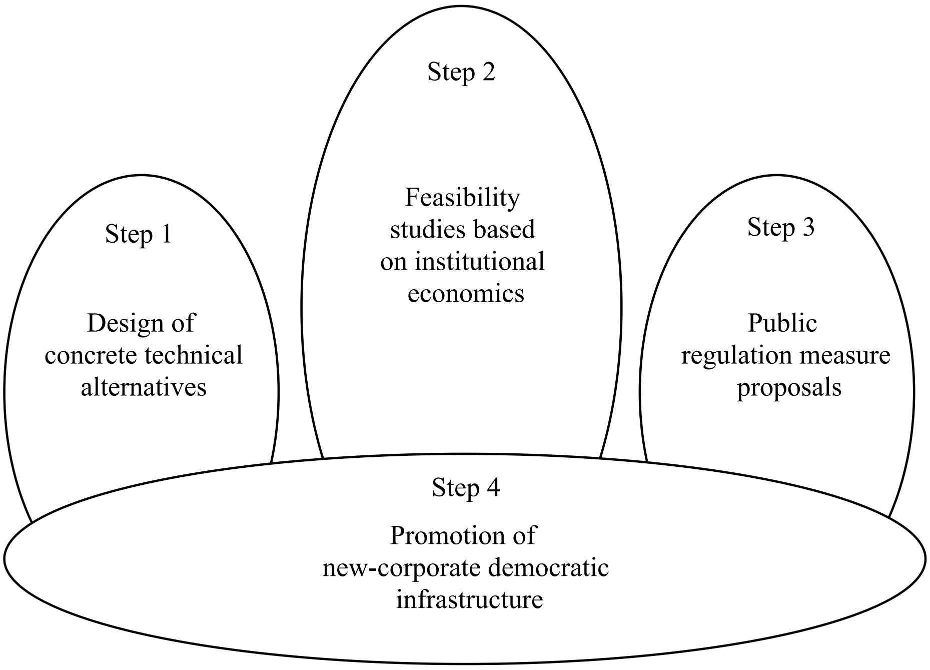

Figure 3: The overall steps applying the Choice Awareness framework. Adopted from Lund (2014).

The methodology of Choice Awareness is structured in accordance to the four steps shown in Figure 3. The application of Choice Awareness follows the steps from the figure and is presented in the following.

The objective of the first step is to create a concrete alternative to the existing technological solutions. This is done by examining different alternatives that are able to be compared. In total 51 alternatives have been examined in this study, which are all compared based on equal parameters. It should be noted that Lund (2014) recommends to include energy savings in the design of alternatives. There might be a potential in Greenland in this regard, however energy savings have not been taken into account in this study.

Feasibility studies should according to Lund (2014) be performed in a such way that it is not in favour of the existing system and should include more analyses and dimensions. A feasibility study in a situation of a radical technological change concerning the environment should follow the guidelines from Lund (2014), which includes a broader scope and focus compared to a conventional cost-benefit analysis. This study is concerning a radical technological change as more than one of the parameters *technique, knowledge, organization, products and profit* are changed. The technique and knowledge are changed as it is a new technology in Greenland. It is a new product that will be produced, and recipients of the profit will change as well. The organisations involved in the total system will change, however some of the current organisations might be able reorganise and together constitute the system required to meet the radical technological change. As illuminated, the alternatives designed entail a radical technological change and therefore the guide, presented in Table 1, is followed.

Table 1: The main steps of the feasibility study (Hvelplund et al., 2004; Lund, 2014).

WWW-analysis
Who will use the feasibility study and for what purpose?
Which relevant political objectives should be included in the study?
Make sure that the study provides relevant information in relation to the actual context.
Which time horizon and time priority should be used?
Diamond-E analysis
What are the organisational goals?
What are the organisational resources?
How is the financial situation? Preliminary financial profile of opportunities and problems.
Analyse development of ownership structure.
Actual calculation of the feasibility study
Have an open political discussion of methodology and parameters.
Analyse the binding of the existing technological system.
Perform a technical sensitivity analysis.
Perform an institutional sensitivity analysis.
Perform a political sensitivity analysis.

In the following, the questions related to both the WWW-analysis and the Diamond-E analysis will be answered. The purpose of the study is to contribute with a technological alternative for the decision-making in relation to the fulfilment of the objective of integrating RES wherever it is possible and that the public energy supply should be based on RES to the widest extend by 2030. Furthermore, there are objectives regarding increased self-sufficiency in Greenland, modernisation of the energy system and economic viability of investment within the energy and water sector, which are also considered in this report. These objectives are all presented by the Ministry of Industry, Energy, Research, and Labour as part of Naalakkersuisut in *"The sectoral plan for energy and water supply"* from 2017 (Naalakkersuisut, 2017).

This report addresses some of the objectives from Naalakkersuisut and it is therefore considered that the findings will be relevant for the government and serve as a technological alternative in the decision-making process. In Table 2, the institutions that are considered to be the main actors concerning decision-making and investment are listed.

Table 2: Main actors in decision-making and field of responsibility.

Actors	Field of responsibility
Naalakkersuisut	National legislative authority
Municipalities	Legislative authority at municipal level
Nukissiorfiit	Utility company

The municipalities where the production could be established are considered to be main actors in the decision-making process and in terms of investment. The relevant municipalities of concern are Qeqqata where Maniitsoq is located, Sermersooq where Nuuk is located and Kujalleq where Qaqortoq is located. Also, Nukissiorfiit the public utility company is considered as main actor. Nukissiorfiit is owned by the government within the Ministry of Industry, Energy, Research, and Labour and supplies water and energy in Greenland.

The identified main actors are all public institutions or publicly owned for whom the interest is to carry out decisions that benefits the society the most. Therefore, a socioeconomic analysis is the most suitable in this context and will be performed in order to address the relevant actors. However, in order to follow the CA research method, a private economic analysis is required to identify the market institutional barriers. It is also stressed by Boardman et al. (2011) that a private economic analysis will increase the robustness of the socioeconomic results. This socio-economic analysis will have a 20 year calculation period which initiates in year 2024, as the two new central waste incineration plants will be operating full-load from the beginning of 2024 (Building Supply, 2019).

The main goals from Naalakkersuisut has been presented which this study is concerning. The other organisation presented in Table 2, pursue the same objectives of increasing the share of RES, self-sufficiency and economic results that benefits the society. The organisational resources are wide knowledge on various levels and within different areas. An important resource is the organisational position of power which enables a proactive approach fulfilling the fundamental objectives. The institutions of concern are financed by the tax system. Their organisational position enables depreciation of investments through taxes. However, these organisations also have a responsibility to act on behalf of the citizens in Greenland. A structure of an ownership is considered to have the aforementioned organisations in the centre. Nukissiorfiit is however also expected to play a more operative role as well as one of expectedly several owners. The steps in the guideline when performing a feasibility study aligns with Choice Awareness and will be performed in the analysis. However, in regard to discussion of methodology and parameters this will partly be carried out in the methodology (see Section 4.4) as well as the discussion chapter.

Step three is concerning public regulation measures. In general, when feasibility studies are performed based on applied neoclassical economics with the 'free market' in the centre, the institutional conditions are not considered to be modifiable through public regulation. The 'real market' is described by Lund (2014) as the market with the institutions and their relation to the private market power, public regulation accessibility of information, infrastructure, business structure etc. Also, there is a high level of private regulation, especially on monopolistic and oligopolistic markets, where there is only one or few suppliers of a specific good. These market conditions are usually the case for energy suppliers. For these reasons following the Choice Awareness methodology, real market conditions should be applied when designing public regulation measures (Hvelplund et al., 2004; Lund, 2014). The regulatory framework in the Greenlandic context concerning the alternatives considered in the analysis will be discussed in Section 7.4.

The fourth step of the Choice Awareness methodology is about promoting a new-corporate democratic infrastructure. This is important to consider and actually perform in order to raise the awareness of alternatives attained through the first three steps when implying a radical technological change. The concept of old-corporative regulation is by Lund (2014) described as a process shaped to favour the existing technologies and organisations, which may not be ideal from a societal point of view. In new-corporate regulations, representatives from new technologies should be part of the decision-making process. The representatives should be representatives of the future societal interests and potential future technologies. This fourth step should contribute to make sure that the 'choice' obtained from the feasibility study is actually available as an alternative in the decision-making process. This step very much aligns with the scientific reflections from Latour (1999) turning matter into form. The matter has through the first three steps been worked and structured into form enabling this fourth step to be offered as a choice in decision-making processes.

4. Methodology

In the following the methods used through this study are presented and it is explained how each of them has been applied in order to help answering the research question.

4.1 Case study

This project focuses on the transition towards renewable energy sources in the specific context of the Greenlandic energy system with the present climatic and geographical challenges, as previously illuminated (Chapter 2), this section will describe how case study is used in this report. The application of case study is based primarily on Bent Flyvbjerg's perception of the method as a qualitative research method.

The term 'case study' originate from the medical and psychological research, where it refers to detailed analysis of an individual case. The method implies that one can acquire proper knowledge of the phenomenon on the basis of an extensive research of a single case. The approach of case study to qualitive analysis implies a systematic way of collecting, organising and analysing data. It is the purpose to gather comprehensive and in-depth information about each case of interest in order to obtain a profound understanding. Therefore, the information of each case must be as complete as possible and should include all the information one has accumulated about the particular case or cases of interest (Flyvbjerg, 1988). The scientific theoretical starting point of case study is the hermeneutic and the phenomenological tradition. Case study thereby intend to examine how the empirical world is experienced and interpreted by the subject. This makes observations, in-depth qualitative interviews, detailed descriptions and qualitative field notes important research methods when performing a case study. A case study is however not exclusively qualitative but can also be quantitative or a combination of both approaches (Flyvbjerg, 1988; Starman, 2013). VanWynsberghe & Khan, (2007) defines case study as a transparadigmatic and transdisciplinary heuristic that involves the careful delineation of the phenomenon. They thereby argue that case study is relevant regardless of one's research paradigm (i.e. critical theory, postpositivism or constructivism) and that case study has no disciplinary orientation and for example can be applied in social science, science, applied science, fine arts and humanities research.

Case study as a qualitative research method can be used in the theory, method and hypothesis development phase as well as in the problem clarification phase due to its holistic and inductive approach and its theses generating possibilities (Flyvbjerg, 1988). However, case study is not only limited to these research activities alone, but is also useful for hypotheses testing and are valuable at all stages of the theory-building process including the testing stage (Flyvbjerg, 2006; VanWynsberghe & Khan, 2007). According to Flyvbjerg 1988, pure induction and pure deduction is not practically possible, but he advocates to pursue an inductive approach when applying a case study in order to let the case 'tell itself' and let issues related to the case evolve from this. He however argues that this should be complemented by a more structural approach involving an understanding of the overlying power structures and external influences, as this knowledge is determining for the examiner's perception of the case study (Flyvbjerg, 1988). Interviews are therefore an indispensable part of the case study and it is important to establish a trusting relationship with the case site early in the process. The purpose is to provide the basis for a profound and holistic data collection in order to be able to describe and analyse the case as a whole, as it is not sufficient to collect data only on the case itself. Thus, an in-depth understanding of a case also requires an understanding of the relationship of the case to its context. In this way, the 'pure' case study is supplemented with a structural analysis (Flyvbjerg, 1988). It is therefore important to this project to establish a contact with the relevant actors in Greenland in order to supplement the quantitative data collected with qualitative data in the form of interviews. The interview method identified to be applicable in this context will be further described in Section 4.2. Moreover, it is important that the case study also involves data on the actual decision-making processes as well as to which extent these processes are open/closed. It is thus essential to distinguish between what has actually happened in the decision-making process and the participant's perception of what happened (Flyvbjerg, 1988). This aligns well with the fundamental premises of the Choice Awareness theory about the awareness of various available choices, as previously described in Chapter 3.

The inductive approach of this report is reflected through the project's focus on the identified challenge to convert the Greenlandic energy system to being supplied by renewable energy sources to the largest extent possible by 2030. Likewise, the focus on the respective island-based energy systems in Greenland, from which empirical observations of the specific energy systems can be translated into a more general context, also implies an inductive approach. This is in contrary to a deductive approach of testing theories and hypothesis about the energy systems. However, the assumption that electrofuels may potentially constitute an important role in the transition to renewable energy in Greenland is an expression of a presumption and thereby a deductive approach. When following an inductive approach, some issues related to the specific case may appear and the examiner must therefore decide the most interesting direction to follow. These may be theoretically grounded but can also be subjectively based on the examiner's own perception (Flyvbjerg, 1988). In order to ensure scientific objectivity, it is therefore important to explain and justify the decision taken along the way. Decision related to the methodological and analytical considerations will therefore be explained in the respective section of this report.

There has been a perception among scientist that one cannot generalise from a single case, why the single-case study does not contribute to a scientific development. According to Flyvbjerg (2006), this is however a misunderstanding and an expression of a conventional wisdom of the case study research. He argues that one can often generalise on the basis of a single case study, and case study therefore may be central to scientific development via generalisation as supplement or alternative to other methods (Flyvbjerg, 2006). Comparing and contrasting cases is thus a way to make tentative generalisations beyond the case itself (VanWynsberghe & Khan, 2007). This study can thereby be perceived as a showcase for other similar projects examining whether electrofuels can constitute an important role in any transition towards more renewable energy in a country. Moreover, it can also contribute with knowledge about the influence of introducing electrofuels into an island-based energy system through the analysis of the different cases. This approach is also referred to as a multiple case study as it consists of several cases. Each case is studied as if it is a singular case and is then compared to the other cased. The knowledge acquired from each case is built on the knowledge obtained from the previous cases (Starman, 2013; VanWynsberghe & Khan, 2007).

As this project examines the feasibility of implementing an electrofuel production into the Greenlandic energy system as a case study, the rationale behind the data collection carried out throughout this project will be illuminated in the following section. This includes a section about the interview method used for acquisition of qualitative data, a section about the literature study applied for the state-of-the-art (SOA) chapter, as well as a section about the energy-economic model developed in connection to this master's thesis in order to carry out the analysis.

4.2 Qualitative interview

Qualitative interview has been applied in this project in order to acquire relevant case-specific knowledge and insight. The purpose of using the method is to obtain a deeper and more comprehensive understanding of the cases we examine. In order to ensure the best possible interaction between the informant and us as interviewers and to enable flexibility in the interview for the purpose of enlighten other essential aspects of the case, we have used the partially structured interview approach. This section therefore describes this type of interview to which the underlying theory is based on the book *Interview* by Kvale & Brinkmann (2015).

As also stated in the methodology of case study (see Section 4.1), in-depth qualitative interviews are essential in order to obtain a profound understanding about the case of interest. The partially structured interview type creates an exploratory approach to the informants with the purpose of using the informant's own rhetoric to further the interview in the correct context. A partially structured interview requires an interview guide with prepared questions or keynotes that can direct the interview through the specific topics sought to be answered, while leaving a room for the informant to influence the direction and open up the possibility of new knowledge and insight (Kvale & Brinkmann, 2015). In this project the partially structured interview is used to achieve a more accurate and thorough understanding of both the possibilities and potential barriers in relation to introducing an electrofuel production into the specific circumstances of Greenland. It can be important that the questions invite the informant to speak openly and on their own terms as this can contribute to a wider insight about the case. Thus, questions which does not necessarily lead to a certain answer can benefit the interview as it may lead to new knowledge since the informant will be more reflective when answering (Kvale & Brinkmann, 2015). It is moreover stressed by Kvale and Brinkmann (2015), that the informant should have plenty of time before asking a new question in order to allow the informant to disseminate the whole answer.

When conduction a partially structured interview it is important that the interviewer is well-prepared and has familiarised themselves with the substance. This will legitimise why the informant spend time on the interview and create a better symmetry between the informant and the interviewer. It is moreover important to determine which points and topics that are relevant to the report prior to the interview in order to sharpen the focus (Kvale & Brinkmann, 2015). Considerably emphasis has therefore been placed in the performance of a detailed interview guide to make sure that it was covering all topics of interest. The interview guide can be found in Appx. 11.6. In Table 3 an overview of all informants contributing to the carrying out of this project is listed.

Table 3: List of informants and their informative contribution.

Informant	Organisation/ company	Type of interview	Date	Outcome
Klaus Petersen	MAN Energy Solution	Teams interview	19.03.2020	Overview of types of engines and generators in GL
Jens Schiersing Thomsen	Siemens Gamesa	Teams meeting	05.04.2020	Perspectives on ammonia production in GL
Martin Frahm Jensen, Emil Andreas Tjärnehov, Yawar Abbas Naqvi	Haldor Topsoe	Teams meeting	07.04.2020	Background knowledge on synthesis, temperature and pressure
Jesper Scramm	Danish Technological University (DTU)	Skype interview	14.05.2020	Technical knowledge on fuel application in GL
Tage Lindegaard, Bjarne Lykkegaard	Polaroil	Telephone interview	14.05.2020	Current fuel infrastructure and application of electrofuels in GL
Allan Bertelsen	Naalakkersuisut	Telephone interview	27.05.2020	Political and regulatory framework of the energy sector

The interview with Klaus Petersen from MAN ES was predominantly considering engines and power generators in Greenland in relation to applicability of various electrofuels. He supplied us with a reference list of all delivered units to Greenland since 1936 that has been used to identify a suitable electrofuel. The meeting with Jens Schiersing Thomsen was carried together with a number of employees in Ramboll. The outcome of this meeting was mostly concerning state of application of ammonia in various engines and perspective on this topic. The meeting with Haldor Topsoe was likewise carried out with employees in Ramboll and provided us with technical and in-depth information on the synthesis process. The interview with Jesper Scramm from DTU was carried out to identify the most suitable electrofuel in the context of Greenland and to gather knowledge about the modification requirements in relation to various fuels. Tage Lindegaard and Bjarne Lykkegaard from Polaroil explained how the current fuel infrastructure in Greenland works and the importance of the fuels being able to handle the cold climate. Lastly, an interview with Allan Bertelsen from the Ministry of Industry, Energy, Research and Labour has been conducted in order to understand the prevailing political and regulatory framework of the energy sector.

4.3 Literature study

Literature study has been widely used in various parts of this project and constitute an important role as this project build on to already existing knowledge and known technologies in order to apply it in the specific context of Greenland. A profound and carefully carried out literature study increases the validity and reliability of the statements produced. The process towards the production of a statement or a conclusion including what has contributed along the way is important. This is emphasised by Bruno Latour (1999), who argues that knowledge and literature are a 'chain of elements', which is infinite from the past to the future. Knowledge is thereby linked together and builds upon existing knowledge. An essential property of this chain is that it must remain reversible, meaning that the succession of the stages must be traceable in both directions: *"If the chain is interrupted at any point, it ceases to transport truth – ceases, that is, to produce, to construct, to trace, and to conduct it"* (Latour, 1999, p. 69). In order to keep the chain of elements traceable, references have been used thoroughly in this report. Likewise, the method applied as well as the decisions taken along the way is explained to make the conclusion and statements of this report replicable.

A profound literature study has been carried out in order to identify the state-of-the-art regarding the different technologies involved in the production of electrofuels. The literature used to describe the respective technologies are preferably published within the last three years to ensure that the content is up to date. Some articles may however be older as they provide more explanatory and in-depth information about certain technologies included. Peer-reviewed articles from ScienceDirect are primarily used to ensure the credibility of the articles. Also, articles from other databases such as ResearchGate and the Aalborg University Library has been supplementary used. The SOA chapter describes the fundamental concept of the various technologies involved in each stage the electrofuel production chain, including their key properties, performances and costs. The chapter functions as a comprehensive and detailed basis for the further analysis of whether and how an electrofuel production can constitute a role in the transition towards more renewable energy sources in the energy system of Greenland. Also, the economic evaluations will be anchored in these parameters.

Furthermore, an extensive literature study has been carried out in order to obtain concrete information about the different island-based energy systems of interest as well as for the acquisition of statistical data regarding the energy and fuel consumption in Greenland. For this purpose, data from the government, utility company and the national statistical provider has been utilised. Since the handling of the national energy statistics in Greenland has recently passed from Statistics Greenland to the Ministry of Industry, Energy, Research and Labour, we have asked the ministry for insight into the latest data from 2017, which we have fortunately been granted. This data has been applied in the thesis. We have furthermore been provided with data from the national utility company, Nukissiorfiit, about the current energy systems in Greenland. These data give us an in-depth understanding of the energy systems and makes it possible to analyse and develop concrete solutions on how to implement an electrofuel production through energyPRO. The table below provides an overview of the contributors to the provision of data throughout the carrying out of this thesis.

Table 4: Overview of contributors to the provision of data.

Informants	Institution/company	Type of contact	Outcome
Tuperna Maliina Olsen	Ministry of Industry, Energy, Research and Labour	Email	Statistical data of national energy consumption
Kasper Dahl	Nukissiorfiit	Email	Technical data of energy systems
Asger Dall	Nukissiorfiit	Email	Data concerning hydropower potentials
Rolf Sloth	Nukissiorfiit	Email	Data concerning hydropower potentials
Mathis Backen	Rambøll (experience from Nukissiorfiit)	Email/meetings	Provision of energy data

4.4 Energy-economic model

To be able to answer the research question a technoeconomic model including both energy system analysis and economic analysis has been (see Appx. 11.1). In order to ensure the lowest possible degree of uncertainty, the energy system analysis tool, energyPRO has been integrated to the model as well, as shown in Figure 4.

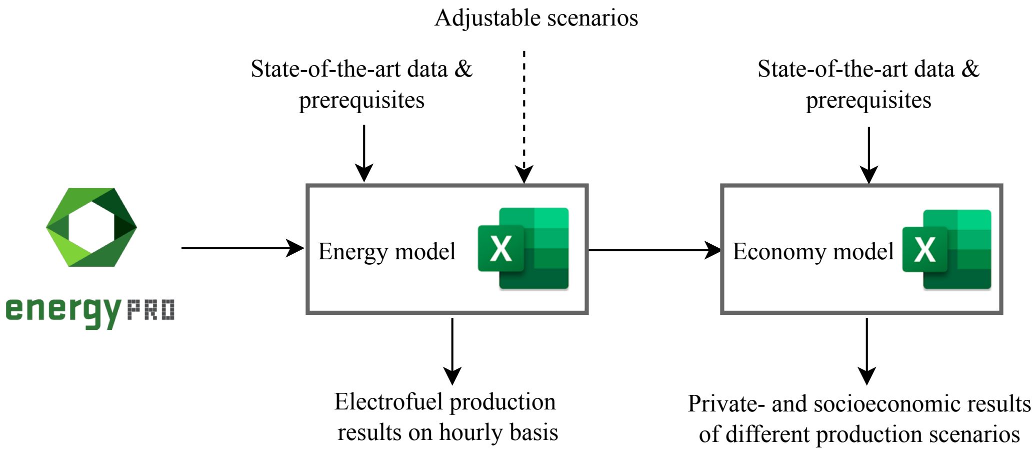

Figure 4: The technoeconomic model for analysing different alternatives of electrofuel production.

The tool energyPRO, is developed in Denmark by EMD International A/S to perform detailed technical and financial analysis of energy projects (EMD International, 2019). It is an optimisation tool that enables optimisation of both operation and investment in energy systems generated by both thermal and electrical aspects (Sameti & Haghighat, 2017). The tool is highlighted by Ferrari et al. (2019) for its user-friendliness covering urban/district scale at an hourly basis. The use of energyPRO enables to distribute heat and power demands throughout the year to an hourly basis by importing data from the weather stations in proximity to areas of the analysis. The distributed demand curves from energyPRO has been exported to the energy model in an excel spreadsheet.

The energy model is built up by technical data of the technologies included in the analysis. This is all presented in tables throughout the state-of-the-art chapter (see Chapter 5) or presented in the analysis. The model enables by drop-down menus to adjust the main prerequisites, such as location, hydropower options, electrolysis, fuel synthesis etc. This generates a long list of outputs and results, which are used to describe different alternative electrofuel productions. The same results are used in the economic model to monetary quantify the chosen alternative.

The economy model is also built up by the most recent data identified in Chapter 5. Projections from the Danish Energy Agency has been applied concerning CO_2 equivalent emission cost (Danish Energy Agency, 2019b). As their projections ends in 2040, linear regressions have been applied to extend the projection period by three year in order to cover the entire calculation period of the analysis. Local fuel prices and taxes is applied as well as the marginal cost of producing electricity from hydropower (Skattestyrelsen, 2010; Uldum, 2019). In the economy model both socioeconomic and private economic results are available. The socioeconomic model is based on the book by Boardman et al. (2011) *"Cost-benefit analysis – Concepts and Practice"* along with the guide from the Danish Energy Agency performing socioeconomic analysis (Danish Energy Agency, 2018b).

Table 5: Key figures for economic analysis (Danish Energy Agency, 2019b; Finansdepartementet, 2015; Finansministeret, 2019).

Parameter	Unit	Value
Calculation period	year	20
Project initiation	year	2024
Discount rate	%	4
Tax distortion factor	%	15
Net tax factor	%	0
Cost of emitting CO_2 equivalents	€/t	37[a]

Notes: [a] The projections of the CO_2 emission costs increases along the calculation period starting at around 37 €.

In Table 5, the key figures applied in the economic model is presented which are based on local key figures in Greenland with the exception of the cost of emitting CO_2 equivalents. These costs are not applied in local guidelines for socioeconomic analysis. However, as the importance is stressed by both Boardman et al. (2011) and the Danish Energy Agency (2018), these costs will be applied in the socioeconomic analysis but left out in the private economic analysis. The private economic or business economic analysis differentiates from the socioeconomic analysis by excluding tax distortion factor, net tax factor and CO_2 emission costs. Taxes are included in opposition to the socioeconomic analysis (Danish Energy Agency, 2018b).

The economic model uses the results from the energy model in regard to quantities and capacities in order to calculate the costs and revenues from the different alternatives. The economic outputs of the model are the net present value (NPV) indicating the economic consequences of investing in an alternative and the marginal cost of the electrofuel produced is available as output from the model.

5. State-of-the-art

As stressed in the introduction of this report (see Chapter 1), it is crucial to reduce the amount of anthropogenic carbon dioxide emissions that derives from the energy sector in order to combat climate change. To accommodate this, a radical and far-reaching conversion of today's energy system is needed. Consequently, many reports and studies has proposed an energy system based on a hydrogen economy (Ball & Weeda, 2015; Blanco, Nijs, Ruf, & Faaij, 2018; CCC, 2018; IEA, 2019d; IRENA, 2019a). Due to its high energy content of 120 MJ/kg (see properties in Appx. 10.1), hydrogen can play an essential role in a clean energy future as it represents a promising option to decarbonise a range of sectors as it is a versatile energy carrier that can be transformed into various fuels. Hydrogen can thus be used to meet different energy demands both in the transport sector, e.g. through fuel cell vehicles, and in other sectors across the energy system (IRENA, 2019a; Varone & Ferrari, 2015). It can enable renewable energy to provide an even greater contributor to the transition, as it allows to store surplus electricity from intermittent renewable energy sources for long periods of time (Ball & Weeda, 2015; Guilera, Morante, & Andreu, 2018; IEA, 2019d; Schemme, Samsun, Peters, & Stolten, 2017).

There are however some practical issues associated to the use of hydrogen as an energy carrier due to its very low volumetric energy density, which imposes high requirements for storage facilities. Since hydrogen is one of the lightest and smallest elements it can diffuse into some materials, such as iron and steel, and increase their risk of failure. Hydrogen is also more likely to escape through sealings and connectors compared to larger molecules, such as natural gas (IEA, 2019d). Moreover, many technical and safety concerns are related to the transportation and storage as hydrogen is a highly explosive gas and requires extremely high pressures or low temperatures (Al-Zareer, Dincer, & Rosen, 2019; CCC, 2018; Institute for Sustainable Process Technology, 2017; Varone & Ferrari, 2015). This means that an introduction of hydrogen implies some changes in the energy infrastructure, including modifications of the pipeline systems, compressors and gaskets. It can however, at low shares in volume of 10-20%, be blended into natural gas without any significant technical challenges (IRENA, 2019a). To overcome the low volumetric energy characteristic of hydrogen, it may either be compressed or embedded in other energy carriers. Hydrogen can thus be used in its pure form or combined with other molecules to produce synthetic hydrogen-based fuels with a higher volumetric energy density.

This opportunity enables another attractive approach to accommodate the green transition in the energy sector, as PtX technologies, encompassing both PtL and PtG, makes it possible to convert electricity into liquid or gaseous fuels based on hydrogen and carbon dioxide or nitrogen. PtL refers to the production of a liquid chemical fuel such as methanol, dimethyl ether (DME) or Fischer-Tropsch (FT) diesel, while PtG involves gaseous energy carriers such as hydrogen, methane or ammonia (IEA, 2019d; Nielsen & Skov, 2018). The higher volumetric density is an advantage of the liquid fuels, whereas the gas products has their main advantage in the already existing gas infrastructure (Guilera et al., 2018). In order for the lifecycle of these fuels to be genuinely carbon-neutral, the CO_2 must be captured from the ambient air, while the hydrogen must be produced from RES (CCC, 2018; Dinca, Slavu, Cormoş, & Badea, 2018; Jiang et al., 2020). Noncarbon-based electrofuels such as ammonia that uses nitrogen instead of carbon can provide a carbon-neutral fuel as long as the energy used for the process is based on renewables. These fuels are most commonly referred to as electrofuels or e-fuels and can likewise constitute an essential role in the decarbonisation of various sectors as they offer a convenient storage option for intermittent renewable energy from all sources (IEA, 2019d; Jadhav et al., 2014; Schemme et al., 2018). The PtX technologies are, according to Schemme *et al.* (2019), inevitable in order to meet the objective of a greenhouse gas neutral energy supply in the future. A simplified flow diagram of the electrofuel production is presented in Figure 5.

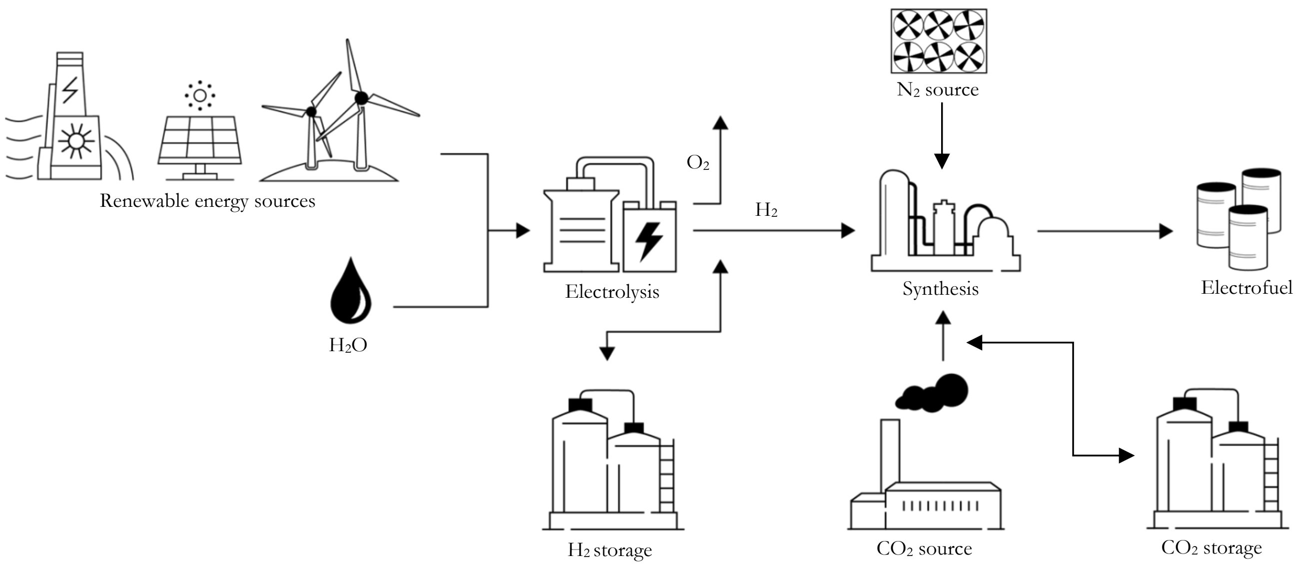

Figure 5: Simplified diagram of electrofuel production process.

As shown in the figure, electricity from renewable energy sources are used to split water (H_2O) into H_2 and oxygen (O_2) in the electrolysis technology. The hydrogen is then synthesised with carbon dioxide either captured from an industrial waste steam or the atmosphere or nitrogen captured by an air separation unit to produce a gaseous of liquid electrofuel. In the following sections, the respective technologies involved in each stage of the electrofuel production chain will be described. Data concerning the various technologies will function as a basis for the further analysis and specific values and figures will be applied for the carrying out of calculations and estimates of an electrofuel production in Greenland (see also Appx. 11.1 for calculations and prerequisites). The following sections are concerning the technologies presented in the table below.

Table 6: List of technologies included in the SOA chapter.

Electrolysis	Carbon capture	Nitrogen capture	Fuel synthesis
AEC	Oxyfuel-combustion carbon capture	Cryogenic distillation	Methanol
PEM	Post combustion carbon capture	Pressure swing adsorption	DME
SOEC	Carbon dioxide transport	Membrane	Fischer-Tropsch diesel
	Carbon dioxide storage		Ammonia

Note: Section concerning direct air capture (DAC) and hydrogen storage can be found in Appx. 10.2.

The descriptions will include the fundamental concepts of each technology, their key parameters and the costs associated with the specific technology. Technoeconomic parameters for each of the technologies included in the SOA chapter will be summarised in datasheets at the end of the respective section. The technologies included are those considered relevant in a Greenlandic context. Therefore, in view of the existing energy system infrastructure in Greenland where large amounts of imported gasoil are presently distributed to various islands-based energy systems, liquid electrofuels are considered to be the most suitable to supply cities and settlements. This is mainly due to the possibility of transporting the liquid fuels for long distances without any major changes to the current infrastructure. Applying gaseous fuels would in contrary imply huge infrastructural investments establishing long pipes or particularly high pressure or temperature making the transportation extremely costly, as previously explained. Methane is consequently not considered relevant and will not be treated in the following. The gaseous fuel ammonia will however be included in the fuel synthesis section due to its properties allowing it to be applied in larger stationary applications for power generation or in the shipping sector under strict safety conditions (IRENA, 2019a).

The different technologies are also considered based on their respective development stage as this is highly relevant due to the analysis period of this master's thesis. This is therefore applied using the technology readiness level (TRL), which ranks the maturity of a technology on a scale from one to nine in accordance to the definitions given in Table 7.

Table 7: Definitions of TRL levels (European Commission, 2017).

TRL	Definitions
1	Basic principles observed
2	Technology concept formulated
3	Experimental proof of concept
4	Technology validated in lab
5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
7	System prototype demonstration in operational environment
8	System complete and qualified
9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

5.1 Electrolysis

Hydrogen can be produced from various sources but almost the entire hydrogen production today comes from natural gas and coal, as previously mentioned. This is currently the least costly solution, but it is not sustainable. Water electrolysis offers a sustainable solution and is a mature and well-established technology that has been known for more than a century even at industrial scale (Atsonios, Panopoulos, & Kakaras, 2016; Brauns & Turek, 2020; Leonzio, 2018; Iva Ridjan Skov & Mathiesen, 2017). Water electrolysis can play a central role in the deployment of zero-carbon hydrogen production (IRENA, 2019a), and is an electrochemical process that uses electricity to split water into hydrogen and oxygen. Further explanations and chemical reaction can be found in Appx. 10.2.1.

There exist three main electrolyser technologies today. The most mature technologies today are alkaline electrolysis cell (AEC) and proton exchange membrane (PEM), which both operates at relatively low temperatures. The high temperature solid oxide electrolysis cell (SOEC) provides another promising option and is on the brink of commercialisation (Brauns & Turek, 2020; Brynolf, Taljegard, Grahn, & Hansson, 2018; Buttler & Spliethoff, 2018; DEA, 2019; Götz et al., 2016; Kopp et al., 2017; Lange et al., 2018; I R Skov, Nielsen, Nørholm, & Vestergaard, 2019). Main technical and economic characteristics of the three electrolysis technologies are summarised in Table 8, while key operational parameters including advantages/disadvantages as well as a section concerning hydrogen storage can be found in Appx. 10.3 and Appx. 10.2.2, respectively. The following will illuminate the three electrolysis technologies, AEC, PEM and SOEC.

5.1.1 Alkaline electrolysis

Alkaline is the most mature and commercially available electrolysis technology and has been used since the 1920s, particularly for hydrogen production in the fertiliser and chlorine industries (Buttler & Spliethoff, 2018; David, Ocampo-Martínez, & Sánchez-Peña, 2019; Götz et al., 2016; IEA, 2019d). Due to the availability of 100 MW system capacities, the TRL of alkaline electrolyser is nine (Schnuelle et al., 2019). A front-runner project among several hydrogen initiatives are planned to be established in Delfzijl, the Netherlands, involving a 20 MW alkaline electrolyser (Paige, 2020). However, as the market develops, a large share of the new electrolysis projects now opts for PEM technology (IEA, 2019e).

The alkaline electrolysis uses an aqueous electrolyte solution, typically consisting of KOH/NaOH, and operates at temperatures between 60 and 80 °C under either atmospheric or pressurised conditions (1-30 bar) (Buttler & Spliethoff, 2018; Shiva Kumar & Himabindu, 2019). The alkaline electrolysis technology has an efficiency in the range of 63-70% (Brynolf et al., 2018; Götz et al., 2016; IEA, 2019d). An advantage of operating under pressurised conditions is that less energy is required for the production of compressed hydrogen for decentralised use or storage at refuelling stations. This however reduces the process efficiency and the purity of the hydrogen produced (Brynolf et al., 2018; Götz et al., 2016). Alkaline is characterised by relatively low capital costs in comparison to both PEM and SOEC electrolysers due the avoidance of precious materials.

5.1.2 Polymer exchange membrane electrolysis

The PEM electrolyser were first introduced in the 1960s by General Electric to overcome some of the operational drawbacks of alkaline electrolysis (IEA, 2019d; Shiva Kumar & Himabindu, 2019). The technology is less widely deployed compared to alkaline and has a TRL of eight due to projects in multi MW scale e.g. Energiepark in Mainz of 6 MW (Schnuelle et al., 2019). PEM however seems to make a significant entry into the market with an increase of new electrolysis installations over the last decade. Most of these projects are located in Europe, although projects have also been initiated or announced in Australia, China and the Americas. The average unit size has increased from 0.1 MW in 2000-09 to 1 MW in 2015-19, indicating a shift from small pilot and demonstration projects to commercial-scale projects. Moreover, several projects with electrolyser sizes of 10 MW or above are now under development (e.g. a 10 MW plant by Shell in Germany and a 20 MW plant by Hydrogenics in Canada), while projects with electrolysis sizes of 100 MW or larger are currently being discussed (Hydrogenics, 2019; IEA, 2019d; IRENA, 2019a; Refhyne, 2018).

In contrast to AEC, this electrolysis uses a solid polymer membrane, typically Nafion, as an electrolyte solution, thus avoiding the recovery and recycling of the KOH electrolyte solution necessary with the alkaline electrolysers (Brynolf et al., 2018; Rouwenhorst et al., 2019; Schmidt et al., 2017; Shiva Kumar & Himabindu, 2019). PEM typically operates at temperatures in the range of 50-80 °C and pressures of 30-60 bar allowing it to produce highly compressed hydrogen. The conversion efficiency of PEM is in the range of 56-60%. The electrolyser offer a flexible operation and the load flexibility can go from zero to 160% of design capacity, making it possible to overload the electrolyser for a period of time (IEA, 2019d; Schmidt et al., 2017). However, due to its membrane materials, the expensive electrode catalysts (typically consisting of platinum or iridium) and the shorter lifetime, the overall costs of PEM electrolyser are considerably higher compared to alkaline electrolysers (Brynolf et al., 2018; IEA, 2019d).

5.1.3 Solid oxide electrolysis cell

The high temperature SOEC is the least developed electrolysis technology and was introduced by Donitz and Erdle in the 1980s (Shiva Kumar & Himabindu, 2019). The technology is not yet commercialised, although the German company Sunfire is already offering systems of 150 kW, while individual companies, such as Halder Topsoe and Toshiba, are aiming to bring it to market (Anghilante, Colomar, Brisse, & Marrony, 2018; BioPress, 2017; I R Skov et al., 2019; Sunfire, 2017). As only kilowatt size plants are now available, SOEC has a TRL of five-six (Schnuelle et al., 2019). The technology may however enter the market in the near future and the first commercial-scale use of the high temperature SOEC is set for Neste's biofuel refinery in Rotterdam, the Netherlands. The MULTIPLHY project will use a 2.6 MW SOEC electrolyser built by Sunfire and be able to produce 60 kg of hydrogen per hour (Collins, 2020).

The electrolyser is comprised of a dense electrolyte layer consisting of ZrO_2 doped with Y_2O_2 allowing it to operate at high temperatures (Brynolf et al., 2018; Götz et al., 2016). Thus, the typical operations temperature of SOECs is in the range of 650-1000 °C, enabling high electrical efficiencies between 74 and 81%, and at atmospheric pressure (IEA, 2019d). The possibility of using heat as a supplement to electricity in the energy supply thus increasing the efficiency, makes SOEC particularly interesting in cases where a high temperature heat source is available. Waste heat from a synthesis process producing electrofuels could therefore advantageously be recovered to produce steam for further SOEC electrolysis (Buttler & Spliethoff, 2018). Unlike AEC and PEM, it is possible to operate SOEC electrolysers in reverse mode as a fuel cell, converting hydrogen back into electricity, or in co-electrolysis mode, where carbon dioxide and steam are converted into syngas (gas mixture consisting of carbon monoxide and hydrogen) for subsequent conversion to a synthetic fuel (DEA, 2019; Schmidt et al., 2017; I R Skov et al., 2019). One key challenge of SOEC electrolysers is however the degradation of materials that results from the high operation temperatures (IEA, 2019d). The costs of SOEC electrolysis are still uncertain but due to its high electrical efficiency and its use of non-noble materials, it may become a cheap and competitive technology (Lange et al., 2018).

Table 8: Costs and performances of electrolyser technologies, averages across studies, ranges are in parenthesis (Brynolf et al., 2018; Buttler & Spliethoff, 2018; IEA, 2019d; Schmidt et al., 2017).

	AEC		PEM		SOEC	
	Today	2030	Today	2030	Today	2030
Efficiency ($\%_{LHV}$)	66 (63-70)	68 (65-71)	58 (56-60)	65 (63-68)	77 (74-81)	80 (77-84)
System size (MW)[a]	1.1-5.3	4.9-8.6	0.10-1.2	2.1-90	<0.2	0.5-50
System life span (years)	25 (20-30)	30	20 (10-30)	30	-	10-20
Stack life span (1000 hours)	75 (60-90)	95 (90-100)	60 (30-90)	75 (60-90)	20 (10-30)	50 (40-60)
CAPEX (€/kW_e)[b]	875 (450-1,300)	575 (350-800)	1,375 (1,100-1,650)	1000 (600-1,400)	3,875 (2,600-5,150)	1,675 (750-2,600)
OPEX (% of capital costs/year)	2.5 (2-3)	2.5 (2-3)	4 (3-5)	3.5 (2-5)	3	2.5 (2-3)
Stack replacement costs	50% of CAPEX		60% of CAPEX		Included in OPEX	

Notes: [a] Refers to maximal stack size. Several stacks can be combined to meet larger MW outputs (Bertuccioli et al., 2014). [b] CAPEX ranges represent different system sizes and uncertainties for future estimates.

5.2 Carbon capture

In this section carbon capture technologies will be described addressing the current state of the technologies including a detailed presentation of the technical and economical parameters of the most mature technology. It should be noted that direct air capture is also a potential future option, but due to its lower state of maturity, this technology is not relevant for this thesis and is just briefly illuminated in Appx. 10.2.5.

Through the literature research it is clear that most applications of carbon capture have so far been fossil-based CO_2 sources rather than carbon obtained from the atmosphere, waste or biomass. Therefore, the technoeconomic data sheet is concerning fossil-based carbon capture applications. However, it should be noted that the first large-scale carbon capture application on a waste incineration plant was commissioned in Duiven, Netherlands, in 2019 utilising the carbon dioxide in a greenhouse (Braal, 2019). Also, it has been announced that Amager Resource Centre (ARC) in Copenhagen will introduce carbon capture at their waste incineration plant (Amager Ressourcecenter, 2020). There are different strategies capturing carbon dioxide which depends on the given context and purpose. The main strategies are listed in Table 9.

Table 9: Advantages and disadvantage of existing carbon capture strategies (Bui et al., 2018; Liu, 2020; Mikulčić et al., 2019; Song, Liu, Deng, Li, & Kitamura, 2019; Symes & van Ogtrop, 2019).

Carbon capture strategy	Advantages	Disadvantages
Pre-combustion	High CO_2 concentration (~45 vol%) and pressure Commercially applied in some industrial sectors	Challenging operating conditions (15-20 bar and 190-210 °C) High efficiency-drop and energy penalty due to the ASU Unfavourable to be retrofitted
Oxyfuel-combustion	Very high CO_2 concentration (80-98 vol%) Low capital cost of boiler and other equipment	High efficiency-drop and energy penalty due to the ASU
Post-combustion	Straightforward to be retrofitted The most mature of the strategies	Dilute CO_2 concentrations (5-15 vol%) at near atmospheric pressure Energy penalty due to solvent/sorbent regeneration
Direct air capture	High CO_2 capture potential Minimum CO_2 neutral Flexible placement	Adverse thermodynamic conditions High costs Low CO_2 concentration ~0.040 vol%[a]

Note: Chemical looping processes are not considered. [a] The CO_2 concentration is from 2017.

Oxyfuel-combustion is a method to generate CO_2-rich flue gas by removing the nitrogen from the air, which is led to the combustor (Ortiz, Valverde, Chacartegui, Romeo, & Perez-Maqueda, 2018; Toftegaard, Brix, Jensen, Glarborg, & Jensen, 2010). The removal of nitrogen improves the combustion of the fuel, as the high level of oxygen increases the temperature in the combustor. This process increases the level of CO_2 in the flue gas (Song et al., 2019). Oxyfuel-combustion requires an air separation unit, which implies a parasitic power load reducing the total efficiency of the plant (Mikulčić et al., 2019).

The strategy post-combustion carbon capture (PCC) is the simplest and most well-known method today for capturing CO_2 (Hussin & Aroua, 2020). By this strategy, the CO_2 is captured from a flue gas from which the concentration of CO_2 is dilute of 5-15% compared to the pre-combustion and oxyfuel-combustion strategies (Song et al., 2019). Within post-combustion carbon capture there are different technologies which has proven sufficiency such as absorption, adsorption, membrane and cryogenic carbon capture (Hussin & Aroua, 2020; R. Zhao et al., 2019).

Absorption is a well-established and commercial technology for post-combustion carbon capture (Liu, 2020). Chemical absorption using amines has been applied for decades for capturing CO_2 from natural gas. In 2014, the first commercial-scale carbon capture unit was applied on a coal-fired power plant. It was applied on the 110 MW coal-fired power plant Boundary Dam located in Estevan in Canada and captures 8.4 $MtCO_2$ per year (Bui et al., 2018). Therefore, absorption using amines has a TRL at nine (Mikulčić et al., 2019).

Monoethanolamine is a well-known solvent recognised for its high reactivity and great absorption capacity and therefore represents a low cost solvent (Hussin & Aroua, 2020). In Figure 6, the absorption carbon capture process is shown using MEA absorbents.

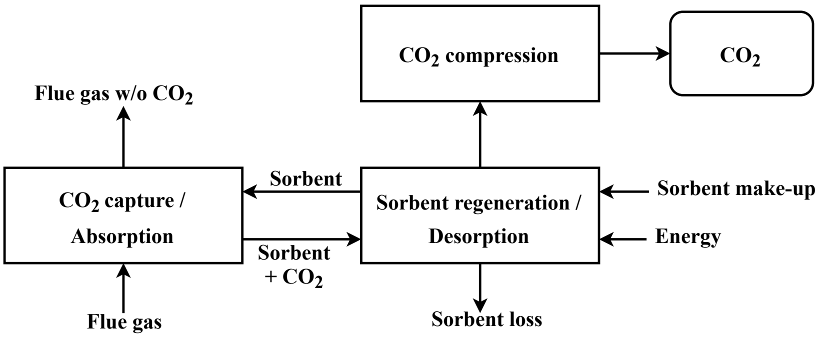

Figure 6: Absorption and desorption process. Adapted from Utgard (2007); Song et al. (2019).

The flue gas is led into the absorber where high level of CO_2 capture can be achieved due to the strong covalent bindings. According to Bui *et al.* (2020), the CO_2 capture rate increases to between 89-97% when the flow rate of the flue gas is reduced using MEA. However, there are some limitations that decreases the total plant efficiency, which should be solved in order to improve the technology (Araújo & de Medeiros, 2017; Hussin & Aroua, 2020). The main challenges of the absorption process are high energy consumption, the energy penalty related to the regeneration process and the solvent degradation (Hussin & Aroua, 2020).

The other post-combustion technologies adsorption, membrane and cryogenic carbon capture are all at a TRL between six and nine (Ben-Mansour et al., 2016; Hussin & Aroua, 2020; Kárászová et al., 2020; Leung, Caramanna, & Maroto-Valer, 2014; Mikulčić et al., 2019; Song et al., 2019; Toftegaard et al., 2010; Voskian & Hatton, 2019; H. Zhang, Wang, Van herle, Maréchal, & Desideri, 2020). These technologies are presented more in depth in Appx. 10.2.3. Direct air capture is a technology capturing carbon dioxide from the ambient air which has a TRL of seven (Mikulčić et al., 2019). DAC is also presented detailly in Appx. 10.2.5 based on the articles from (Azarabadi

& Lackner, 2019; Evans, 2017; Fasihi, Efimova, & Breyer, 2019; Mikulčić et al., 2019; Sanz-Pérez, Murdock, Didas, & Jones, 2016).

Table 10: Costs and performance of MEA absorption applied at different plants (Mikulčić et al., 2019; Rubin, Davison, & Herzog, 2015).

	SCPC[a]	NGCC	Oxyfuel
Maturity (TRL)	9	9	7
Plant performance measures			
SCPC reference plant net power output (MW)	587	549	684
Emission rate w/o capture (tCO2/MWh)	0.762	0.37	0.83
Emission rate w/ capture (tCO2/MWh)	0.112	0.05	0.08
Plant efficiency w/o capture, HHV (%)	42	50	39
Plant efficiency w/ capture, HHV (%)	32	43	32
Plant cost measures			
CAPEX w/o capture (M€/MW)	1.86	0.81	2.36
CAPEX w/ capture (M€/MW)	3.03	1.42	4.49

Notes: [a] SCPC means supercritical pulverised coal.

5.2.1 Carbon dioxide transport

Transporting liquified gases by ship has been practised for around 80 years. Ship transport of hydrocarbon gases has evolved since then and become a worldwide industry (Nilsson et al., 2011). Commercial CO_2 transportation by ship is at a TRL of nine (Bui et al., 2018).

The CO_2 is transported in supercritical or dense liquid phase (see Appx. 10.4 for CO_2 phase diagram) to ensure reliability and cost-efficiency (Bui et al., 2018; Mazzoldi, Hill, & Colls, 2008). The investment costs related to CO_2 transport by ship are high but the transport operation itself only marginally increases along with distance, while the costs of CO_2 pipelines are proportional to the distance. Thereby, in short and medium distances pipelines are more cost-effective, whereas ship transport make sense at long distances (Crotogino, Prelicz, & Rudolph, 2013; Danish Energy Agency, 2018a; Mazzoldi et al., 2008). Due to the long transportation distances for alternative carbon dioxide sources, the transport by ship is considered to be the only relevant technology. In Table 11 are the specific costs of CO_2 transportation by ship presented. The CO_2 transportation will benefit from future refinement in terms of standardisation, increased size and number of transport vessels. This will reduce the cost of CO_2 transportation compared to the figures in the data sheet (European Commission, 2019).

Table 11: Costs and performance of CO_2 transportation by ship (Bui et al., 2018; Christensen et al., 2011; Nilsson et al., 2011).

	180 km	500 km	750 km	1,500 km
Maturity (TRL)	9	9	9	9
Ship size (m^3)	22,000	29,300	36,600	2*25,700
CAPEX, cap. 2.5 Mtpa (€/tkm)	306.9	125.8	93.1	57.1
OPEX, cap. 2.5 Mtpa (€/tkm)	49.1	19.0	13.3	8.4
CAPEX, cap. 20 Mtpa (€/tkm)	178.3	75.6	57.9	37.4
OPEX cap. 20 Mtpa (€/tkm)	39.9	15.6	11.1	6.8

Note: The costs of liquefaction are included (Nilsson et al., 2011).

5.2.2 Carbon dioxide storage

For utilising carbon dioxide, temporary storages may be needed in regard to logistics and productions. Storing carbon dioxide in a temporary pressure vessel cylindrical and spherical vessel are opportunities. Spherical pressure vessel has a lower surface compared to cylindrical pressure vessel storing the same volume. However, it is more difficult to manufacture and require large space to establish (Seo, Lee, Kim, Huh, & Chang, 2017a). The CO_2 is handled identically to CO_2 for transportation in the supercritical or dense liquid phase (see Appx. 10.4) (Bui et al., 2018; Mazzoldi et al., 2008). Therefore, the carbon dioxide is pressurised and cooled down in order to ensure the liquid phase (Seo, Lee, Kim, Huh, & Chang, 2017b). The financial data in the table below is assumed to be equal to the costs presented by Ikäheimo, Kiviluoma, Weiss, & Holttinen (2018) for ammonia storage.

Table 12: Tank CO_2 storage where the financial costs are assumed to be equal to ammonia storage (Bui et al., 2018; Ikäheimo et al., 2018; Seo et al., 2017b).

Maturity (TRL)	9[a]
Technical lifetime (years)	20
CAPEX (€/t)	900
OPEX (% of CAPEX)	2

Note: The technical data is concerning ship-based temporary CO_2 storage tanks. [a] As ship transportation of CO_2 is at TRL nine, CO_2 tank storage is considered to be at TRL nine as well.

5.3 Nitrogen capture

An air separation unit is used to separate the content of air which consists of around 79% nitrogen, 20% oxygen and 1% argon (Aziz, Oda, Morihara, & Kashiwagi, 2017; Ebrahimi & Ziabasharhagh, 2017; Habib, Nemitallah, Afaneh, & Mezghani, 2017). The most well-known ASUs are cryogenic distillation, membrane separation and pressure swing adsorption, that are all mentioned in former sections (Frattini et al., 2016; Habib et al., 2017). Cryogenic distillation enables great scalability and purity levels of 99.9% of both oxygen and nitrogen but has a high power requirement and capital costs (Frattini et al., 2016; Juangsa & Aziz, 2019). The pressure swing absorption (PSA) adsorb the oxygen and enables to determine the desired purity of the nitrogen. The PSA is operated at ambient temperatures in a pressure of ten bar. Membrane air separation cannot reach high purity levels when the flowrate is increased. Cryogenic onsite generation performs better purity depending on flowrate compared to PSA, for instance 100% purity with a flowrate of 10,000 Nm^3/h. However cryogenic separation is also more costly (Frattini et al., 2016).

The properties of nitrogen (see Appx. 10.5 for nitrogen properties) produced through the air separation units can be used as feedstock in Haber-Bosch synthesis (Aziz, Putranto, Biddinika, & Wijayanta, 2017; Frattini et al., 2016). According to Rouwenhorst *et al.* (2019), membrane is preferred at a capacity below 1 MW, PSA is preferred at capacities between 1-100 MW, while cryogenic is preferred at a capacity above 100 MW. The air separation technologies are more thoroughly described in Appx. 10.2.3.

Table 13: Technoeconomic parameters of different air separation technologies (Ikäheimo et al., 2018; Kim, Seo, & Chang, 2016; Rouwenhorst et al., 2019; H. Zhang et al., 2020).

	Cryogenic distillation	Pressure swing adsorption	Membrane
Maturity (TRL)	9	8-9	8-9
Purity (%)	99.9	99.8	95
Energy consumption (kWh/kg_{N2})	0.11	0.22-0.31	0.22-0.63
CAPEX (€$M/ton_{N2}/h$)	1.45	-	-
OPEX (% of CAPEX)	2	-	-

Note: Cryogenic distillation co-produces a pure oxygen product (98% oxygen).

5.4 Fuel synthesis processes

A wide range of different energy carriers for both stationary and mobile applications can be created in a fuel synthesis process combining carbon dioxide and hydrogen. Synthesis processes for the production of methane, methanol, Fischer-Tropsch diesel and ammonia are all routinely used (Billig et al., 2019; Brynolf et al., 2018; IEA, 2019d). However, also new innovative energy carriers may be produced from these inputs in the near future. The synthesis process for the production of methanol, DME, Fischer-Tropsch diesel and ammonia are presented in the following, as these fuels are considered to be the most appropriate in relation to the current energy infrastructure in Greenland. Further explanations and chemical reactions of the various synthesis processes can be found in Appx. 10.2.6. The synthesis process including reaction conditions and costs as well as applications for each of the respective fuels included in this section are summarised in Table 14, while fuel properties can be seen in Appx. 10.1.

5.4.1 Methanol synthesis

Methanol is conventionally produced from syngas derived from natural gas or coal (Bargiacchi, Antonelli, & Desideri, 2019; IRENA, 2019a), but the production process of green methanol is already well-established today and several companies, such as Haldor Topsoe, Lurgi and Mitsubishi, offers commercial solutions (Jadhav et al., 2014). George Olah Renewable Methanol plant in Iceland is the largest commercial production of green methanol with a production capacity of 4,000 tonnes per year. The plant is operated by the company Carbon Recycling International and reacts CO_2 from an integrated capture system with H_2 from water electrolysis using renewable electricity from a geothermal power plant (CRI, 2019; DEA, 2019). The direct hydrogenation of CO_2 synthesis for methanol production has a TRL of nine (Schemme et al., 2020).

Methanol can be used as a convenient energy carrier for hydrogen storage and is considered one of the most valuable chemical compounds due to its flexible properties enabling it to be used both as a fuel and in the chemical industry (Brynolf et al., 2018; da Silva, Pimentel, Monteiro, & Mota, 2016; Dalena et al., 2018; Schemme et al., 2018). It is in fact one of the most promising building blocks for obtaining more complex chemical structures and may act as the base substance for the production of various fuels, such as acetic acid, dimethyl ether or polyoxy dimethyl ether. Methanol is considered a promising clean-burning fuel due to its high octane number allowing it to be used as an additive to gasoline or substitute for petrol in Otto engines (Dalena et al., 2018; Decker, Schorn, Samsun, Peters, & Stolten, 2019; Leonzio, 2018; Ridjan, Mathiesen, Connolly, & Duić, 2013; Schemme et al., 2020). With minor modifications of the existing combustion engine up to 85% methanol can be mixed with conventional gasoline. This is also referred to as M85. However, only 3 vol% is allowed by the Fuel Quality Directive adopted in 2009 (European Parliament, 2009; Skøtt, 2019). Direct methanol fuel cells (DMFC) is another attractive application of methanol (Dalena et al., 2018). MAN ES has produced a two stroke dual-fuel engine for the Swedish ferry Stena Line which is running on methanol but has oil as backup (Scramm, 2020). Such engines are however produced on an immature commercial level. It has gained much more interest the recent years and according to Petersen (2020), MAN ES is starting up a research project concerning methanol engine this year.

Methanol is however a highly toxic substance if ingested in larger quantities and can lead to blindness, metabolic acidosis or even death. The safety restriction are thus similar to that of petrol (I. Skov, 2015). Methanol is moreover highly flammable and corrosive and storage provisions is subject to substantially the same as those used for gasoline storage. However, tanks must be grounded to avoid hazards associated with static discharge, while extra precaution is made for leak detection (Methanol Institute, 2017).

The synthesis of methanol is typically carried out at temperatures between 250 and 300 °C and a pressure of 50-100 bar (Bargiacchi et al., 2019; Bozzano & Manenti, 2016; da Silva et al., 2016; DEA, 2019; Jadhav et al., 2014; Schemme et al., 2018). The reaction is exothermic and favoured by low temperatures, while high temperatures reduces the efficiency. An efficiency of 79% can be achieved for the direct hydrogenation of CO_2 together with a methanol selectivity rate of more than 99.8% (Bozzano & Manenti, 2016; Brynolf et al., 2018). The direct methanol synthesis from CO_2 can be seen in Figure 7 below.

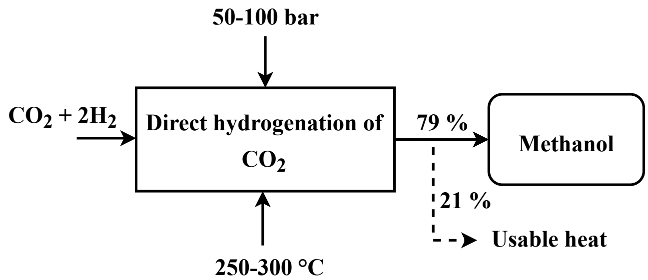

Figure 7: Methanol production from direct hydrogenation of CO_2.

The excess heat from the reaction may e.g. be utilised in high temperature electrolysis in order to optimise the overall efficiency of the production process (German Environment Agency, 2016). Due to the development of effective reactors and catalyst materials, the direct methanol synthesis from CO_2 has become technically competitive with the industrial methanol production from syngas (Bargiacchi et al., 2019; Leonzio, 2018).

5.4.2 DME synthesis

Dimethyl ether is an organic compound, which is mainly used as aerosol propellant as well as for the production of dimethyl sulphate and acetic acid that are both widely applied. DME is an interesting fuel and companies, such as Haldor Topsoe, Total and Mitsubishi, are dedicated to promote it as the new fuel that can substitute both liquified petroleum gas (LPG) and diesel (Michailos, McCord, Sick, Stokes, & Styring, 2019). There are two distinct production routes for the synthesis of DME. The TRL of the indirect production of DME from methanol is nine, while the direct production route is four (Schemme et al., 2018). Due to the low TRL of the direct production route, this process is taken further into consideration. However, this route may contain a promising potential in the future.

Due to its high cetane number of 55-60, dimethyl ether can provide a green alternative to conventional diesel as it is virtually free from both sulphur and aromatics while it emits less CO, NO_x, SO_x and particles at burning (Azizi, Rezaeimanesh, Tohidian, & Rahimpour, 2014; da Silva et al., 2016; Michailos et al., 2019; I. Skov, 2015). It is a highly flammable gas at ambient conditions that forms liquid phase when pressurised above only five bars and it is therefore commonly handled and stored as a liquid. DME is moreover nontoxic and noncorrosive and can also be used as a replacement for propane in LPG for residential cooking or industry, as a fuel in gas turbine power generators due to its high cetane number or as a transportation fuel in diesel or petrol engines. Some moderate engine modifications are though necessary to convert a diesel engine to burn DME (Azizi et al., 2014; Prabowo, Yan, Syamsiro, Setyobudi, & Biddinika, 2017; I. Skov, 2015). Volvo have demonstrated that their trucks are able run on DME with only minor modifications of the engine (Voss, Katerinopoulou, Montesano, & Sehested, 2019).

DME is known to be a clean and valuable fuel due to following reasons: It can safely be stored and handled as it does not form explosive peroxides in contrast to other homologous ethers. Its combustion products, such as carbon monoxide and unburned hydrocarbon emissions are less than those of natural gas, as DME contains about 35% oxygen and only has C-H and C-O bonds but no C-C bonds. Owing to its high cetane number, DME is considered an excellent alternative to the currently used transportation fuel with no emissions of particulate matter and toxic gases such as NO_x at burning. It has similar vapor pressure to that of LPG and can hence be used in the existing infrastructure for storage and transportation. Lastly, DME is not a greenhouse gas and is degradable in the atmosphere (Azizi et al., 2014; Bakhtyari & Rahimpour, 2018; Michailos et al., 2019; Prabowo et al., 2017).

The indirect production process is preferably carried out at lower temperatures as it is mildly exothermic, while this also reduces the formation of by-products, such as ethylene, carbon monoxide, hydrogen and coke (Azizi et al., 2014; Michailos et al., 2019). This synthesis process is typically carried at temperatures of 250-400 °C and 2-20 bar, while the pass-per methanol conversion is between 70 and 85% before recycling. The unreacted methanol is recycled to achieve a selectivity above 99% (Michailos et al., 2019; Pontzen, Liebner, Gronemann, Rothaemel, & Ahlers, 2011). A conversion efficiency for the dehydration of methanol to DME of 85% can be reached (Akarmazyan, Panagiotopoulou, Kambolis, Papadopoulou, & Kondarides, 2014), giving an overall efficiency of 67% for the entire process in accordance to Figure 8. However, the conversion losses and the costs associated to this this process is compensated by the higher energy contain of dimethyl ether compared to methanol (Schemme et al., 2020).

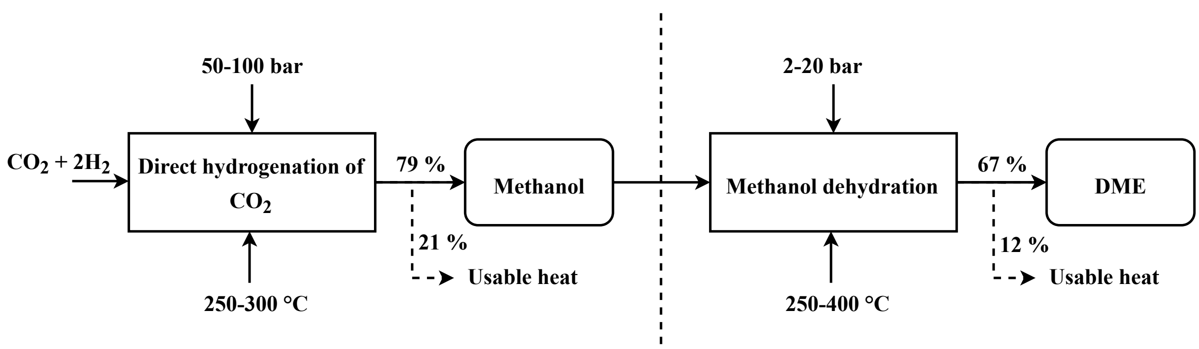

Figure 8: Production of DME from methanol dehydration.

The excess heat from the dehydration of methanol is between 300 and 350 °C and can be recovered to supply endothermic reactions elsewhere in the production process (Ateka et al., 2017; Bakhtyari, Parhoudeh, & Rahimpour, 2016; Bakhtyari & Rahimpour, 2018).

5.4.3 Fischer-Tropsch synthesis

The Fischer-Tropsch synthesis (FTS) was initially developed by Franz Fischer and Hans Tropsch in Germany in 1920s for producing hydrocarbon products from gasification of coal (Mißbach et al., 2018; Schulz, 1999). The synthesis process has recently gained increasingly interest as it enables a sustainable production of liquid synthetic fuels. In 2014 the German company Sunfire inaugurated a demonstration plant in Dresden for the production of diesel through the FTS. The plant uses a high temperature SOEC electrolyser that utilised the excess heat from the synthesis process in order to optimise the overall production efficiency (German Environment Agency, 2016). The Fischer-Tropsch synthesis process has a TRL of six (Schemme et al., 2020).

The Fischer-Tropsch synthesis is a hydrogenation of carbon monoxide and can be used to produce different higher hydrocarbon (C_{5+}), which mostly consist of alkanes and alkenes, i.e. single or double C-C bonds. The produced mixture is also referred to as syncrude and can be further refined into various transportation fuels such as gasoline and diesel, which largely consists of a complex mixture of higher hydrocarbons (Becker, Braun, Penev, & Melaina, 2012; Decker et al., 2019; IEA, 2019d; Schemme et al., 2017). The carbon number (C_n) and the properties of the fuel produced in the FTS are largely determined by the synthesis temperature.

The Fischer-Tropsch synthesis typically operates at a pressure of 10-60 bar and can be distinguished in High-temperature Fischer-Tropsch (HTFT), operating at temperatures between 310 and 340 °C, and Low-temperature Fischer-Tropsch (LTFT) with a temperature ranging from 210-260 °C. The fuel produced from HTFT mainly consists of aromatics and olefins, whereas the LTFT fuel is mostly comprised of paraffins. Due to the high octane number of aromatics, HTFT is more appropriate for the production of gasoline fuel, while LTFT is most suitable for diesel fuel production because of the high cetane number of the paraffinic compounds (Dry, 2001; Gill, Tsolakis, Dearn, & Rodríguez-Fernández, 2011). The fuel products from FTS is suitable for use in heavy transport and diesel engines as well as in power generators without any engine modifications needed (Gill et al., 2011). According to Scramm (2020), the FT diesel are able to be utilised without any modifications of the existing infrastructure. However, the fuel injection might have to be adjusted but he stresses that it is simple and easy to do. The FT fuels are interesting in terms of environmental consideration as they have proven lower emission levels when applied in internal combustion engines compared to both gasoline and diesel. This is because the FT fuels do not contain any sulphur and have a very low concentration of aromatics and nitrogen (Ail & Dasappa, 2016; Todic, Nowicki, Nikacevic, & Bukur, 2016).

The chain growth and the specific mixture of hydrocarbons are determined by various operating conditions, such as the catalyst, temperature and pressure of the synthesis process (Ail & Dasappa, 2016; Becker et al., 2012; Brynolf et al., 2018; Schemme et al., 2017). The overall efficiency of the synthesis of syngas towards higher hydrocarbons typically ranges from 60-90% (Becker et al., 2012; Brynolf et al., 2018; Rane, Borg, Yang, Rytter, & Holmen, 2010). This however includes all FT products, such as waxes and by-products, and the selectivity of a LTFT synthesis for the production of diesel is thus considerably lower of around 26% (Sage et al., 2017). The product stream of the FT synthesis is therefore subsequently separated and refined to obtain a consistent fuel product (Schnuelle et al., 2019). Due to the low selectivity the FTS is an economically intensive process. However, the FT syncrude can be further refined into various high value chemicals like olefins (ethylene and propylene). This represents a valuable solution to increase the economic profitability at an industrial scale (Wu, Feng, & Li, 2018). The synthesis process of LTFT is presented in Figure 9.

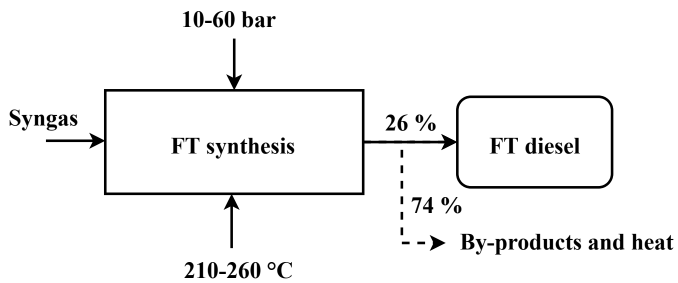

Figure 9: Low-temperature Fischer-Tropsch synthesis.

The excess heat from the synthesis can be utilised elsewhere in the process in order to optimise the overall efficiency of the process e.g. for CO_2 sequestration or in a high temperature electrolysis (Schemme et al., 2020)

5.4.4 Ammonia

Ammonia (NH_3) is a global commodity and around 175 Mt is produced annually, making it the second most produced synthetic chemical product (IRENA, 2019a). The ammonia production process was originally developed by Fritz Haber and Carl Bosch in the 1910s in Germany and has since been referred to as the Haber-Bosch synthesis (Bartels, 2008; H. Zhang et al., 2020). The process has been used for more than a century for industrial production of ammonia and has a TRL of nine (Rouwenhorst et al., 2019).

Ammonia is typically used as a feedstock for further processing into solid or gaseous nitrogen fertilisers, such as urea, ammonium nitrate and ammonium phosphate. It is moreover used for large scale refrigeration and air-conditioning for buildings and industrial processes as well as for explosives (IEA, 2019d; IRENA, 2019a; H. Zhang et al., 2020). Ammonia has a high octane rate of 130 and an energy content of 18.6 MJ/kg, which is much higher than that of compressed hydrogen and roughly half that of oil products, making it, in principle, an excellent energy storage compound for on-board power generation, e.g. in internal combustion engines (ICE) or fuel cells (Al-

Zareer et al., 2019; Bargiacchi et al., 2019; Ikäheimo et al., 2018; IRENA, 2019a; Yapicioglu & Dincer, 2019; H. Zhang et al., 2020). Ammonia is the only carbon-free electrofuel and only emits nitrogen and water vapour at combustion unlike other electrofuels (IEA, 2019d; IRENA, 2019a; Morgan et al., 2014).

Ammonia can easily be stored as a liquid by cooling below -33 °C at atmospheric pressure or pressurised to ten bar at room temperature (CCC, 2018; IEA, 2019d; Ikäheimo et al., 2018; Kobayashi, Hayakawa, Somarathne, & Okafor, 2019). Advantageously, transmission and storage of ammonia is already at a mature stage and ammonia is routinely distributed in large quantities by truck, ship and pipeline and thus has an existent international supply chain in its favour (Al-Zareer et al., 2019; IEA, 2019d; IRENA, 2019a; Lan, Irvine, & Tao, 2012). On the downside, ammonia is corrosive and has significant toxicity concerns for both humans as well as for aquatic life if leakages occur in water sources. Exposure to very high concentrations of gaseous ammonia can cause lung damage or even death (CCC, 2018; IRENA, 2019a). Consequently, the use of ammonia should be restricted to professionally trained operators, both in terms of stationary storage solutions and for the applications in the transportation sector (IEA, 2019d; Makepeace et al., 2019). However, according to Thomsen (2020) it is due the experiences from other sector, such as agriculture and refrigerant, possible to handle ammonia safely.

The Haber-Bosch synthesis process is the most commonly used production route, covering more than 90% of the current ammonia production (Bargiacchi et al., 2019). The synthesis is carried out with a temperature of 300-500 °C and a pressure between 200 and 350 bar, as visualised in Figure 10.

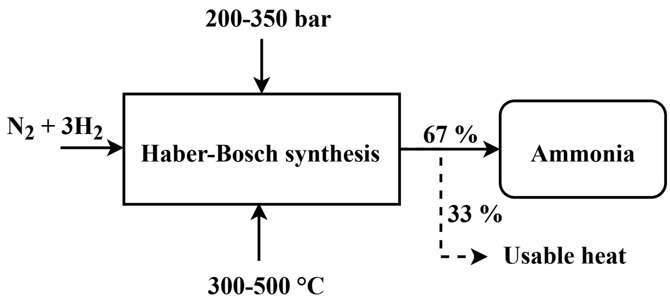

Figure 10: Ammonia production through Haber-Bosch synthesis.

The purified nitrogen for the reaction is normally derived from the air using an air separation unit, typically either cryogenic distillation, pressure swing adsorption or membrane separation is applied, as previously described (see Section 5.2) (Morgan et al., 2014; Rouwenhorst et al., 2019), while water electrolysis can be utilised for the acquisition of hydrogen, as previously illuminated.

Table 14: Synthesis processes including relevant reaction conditions and costs as well applications (Jim Andersson & Lundgren, 2014; Brynolf et al., 2018; Gill et al., 2011; Ikäheimo et al., 2018; Institute for Sustainable Process Technology, 2017; Jarvis & Samsatli, 2018; Rouwenhorst et al., 2019; Schemme et al., 2020, 2018).

	Methanol	DME	Fischer-Tropsch diesel	Ammonia
Synthesis	Direct hydrogenation	Methanol dehydration	Fischer-Tropsch synthesis	Haber-Bosch synthesis
TRL	9	9	6	9
Reaction temperature (°C)	250-300	250-400	210-340	300-500
Reaction pressure (bar)	50-100	2-20	10-60	200-350
Efficiency (%)	79	65	26	67
Catalyst	$Cu/ZnO/Al_2O_3$	$Cu/ZnO/Al_2O_3/\gamma\text{-}Al_2O_3$	Co or Fe	Fe or Ru
Selectivity (%)	99.8	>99	~85	>98
Ratio H_2/CO_2	2:1	-	2:1	-
Ratio H_2/N_2	-	-	-	3
ΔH (kJ/mol)	-90.5	-23.5	-158.5	-92
CAPEX (M€/MW)[a]	0.875	0.875	1.161	0.870
OPEX fixed (% of CAPEX)	4	4	4	2
Applications	• Fuel additive in gasoline (up to 3 vol%) • Substitute for petrol in Otto engines • Direct methanol fuel cells	• Alternative fuel in diesel or petrol engines • Replacement for propane in LPG • Gas turbine power generators	• Transportation fuel in heavy transport and diesel engines • Power generators	• On-board power generation in ICE or fuel cells • Promising fuel for stationary applications

	• Feedstock for e.g. DME and formaldehyde • Solvent • Automotive refrigerant	• Feedstock for e.g. olefins and dimethyl sulphate • Propellent in aerosol products	• Further refined into high value chemicals	• Feedstock for fertilisers e.g. urea and ammonium nitrate • Large scale refrigerant and air-conditioning

Notes: [a] The CAPEX values for the different synthesis are calculated by power regression. This is done in order to scale the investment costs from the three €/kWh ranges presented by Brynolf et al. (2018).

5.4.5 Alteration of fuel storages

In Aalborg in Denmark the first refuelling station has been established modifying a conventional gasoline refuelling station (OK - HAMAG A/S - Serenergy, 2017). In order to store DME as a liquid, five bar pressure is required which implies more modifications (Lindegaard & Lykkegaard, 2020). According to Scramm (2020), Fischer-Tropsch diesel is able fit the current gasoil infrastructure in Greenland. Therefore, it is assumed that no alteration is needed for FT diesel in order to be stored in existing gasoil storages. Ammonia in large quantities is stored refrigerated at -33 °C in double-walled cylindrical storage tanks (Ikäheimo et al., 2018). Due to these requirements for storing ammonia it is assumed that new storage tanks are required. In general, it is stressed by Lindegaard and Lykkegaard (2020) that it is important that fuels do not absorb water both when stored and applied as it can pose a threat of clogging.

Table 15: Alteration of fuel storages for different electrofuels financial data for ammonia storage represents investing in a new storage (Ikäheimo et al., 2018; Lindegaard & Lykkegaard, 2020; OK - HAMAG A/S - Serenergy, 2017; Scramm, 2020).

	Methanol	DME	Fischer-Tropsch diesel	Ammonia[a]
Technical lifetime (years)	20	20	20	20
CAPEX (€/t)	6.8	8.0	0	900
OPEX (% of CAPEX)	2	2	-	2

Notes: [a] The costs for ammonia represents a new storage in opposition of the other fuels which are assumed to altered.

6. Analysis

In this chapter, a detailed description of the current energy system in Greenland is initially presented in order to provide an overview of how the country's energy system works and is supplied today. This is followed by a section, which based on Greenland's large hydropower resources, examines and identifies the most relevant hydropower potentials that could be utilised in relation to an electrofuel production. As also carbon dioxide constitutes an input for a carbon-based electrofuel production, a section designating the largest and most prospective sources for the recovery of CO_2 will be illuminated. The latter two section provides the basis for the analysis examining how an electrofuel production can help Greenland meet their renewable energy goal in 2030. This analysis will on the basis of the three parameters; fuel quantity, self-sufficiency degree and NPV, identify the most promising locations and potentials for an electrofuel production in Greenland.

6.1 National energy system

In this section the energy systems in Greenland is presented showing the overall energy consumption and the composition of the energy production units. Nukissiorfiit is the public utility company in Greenland owned by the Department of Business, Energy and Research. Nukissiorfiit is obligated to supply 17 towns and 53 settlements with electricity, heat and water. In 2017, Nukissiorfiit supplied approximately 34% of the total energy demand in Greenland. According to Nukissiorfiit (2018), 71.5% of the energy delivered in 2018 was supplied by hydropower and waste energy. However, the energy consumed, which is not supplied by Nukissiorfiit, is solely based on fossil fuels. In Figure 11 the overall primary energy supply (TPES) of Greenland is presented.

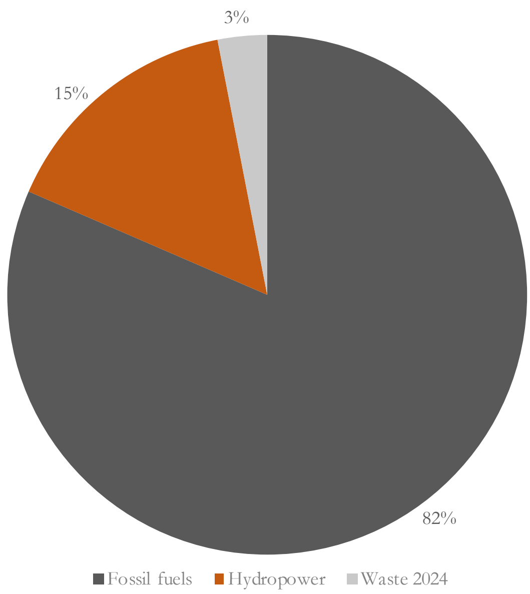

Figure 11: National total primary energy supply in Greenland with the central waste to energy plants (Department of Business - Energy and Research, 2018).

The three percent of energy from waste is the collective output from the two central waste incineration plants that are planned to be operating by 2023 (Building Supply, 2019). These two incineration plants increase the energy delivered from waste by two percent in the TPES, which is relevant to present as the calculation period of this thesis initiates in 2024. It is the recent established municipally owned waste company ESANI A/S that are responsible for establishing and operating the new waste incineration plants (Building Supply, 2019). The 15% share of hydropower is supplied from the five hydropower plants supplying Qaqortoq/Narsaq, Sisimiut, Ilulissat, Nuuk and Tasiilaq today (these can be seen on the map in Figure 14). The fossil share is the accumulated part of fossil fuels from every sector in Greenland. In Figure 12, the energy consumption is divided by sector.

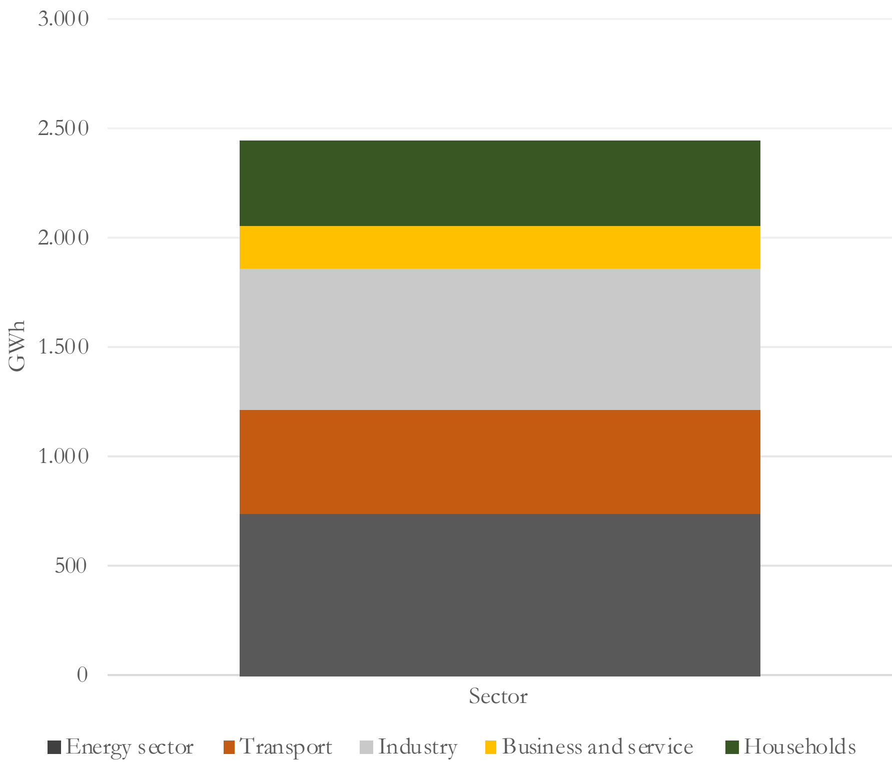

Figure 12: Energy consumption by sector in 2017 (Department of Business - Energy and Research, 2018).

In the transport sector aviation accounts for the largest share of energy consumption followed by maritime transport. Road transport is less consumptive as towns and settlements are not connected by a road system. The fishing industry accounted for 77% of the industry sector in 2017. In the households, 91% of the consumption is for heating, while nine percent is for light and power. The total fossil share of TPES from Figure 11 is divided by type of fuel (see Figure 13 below).

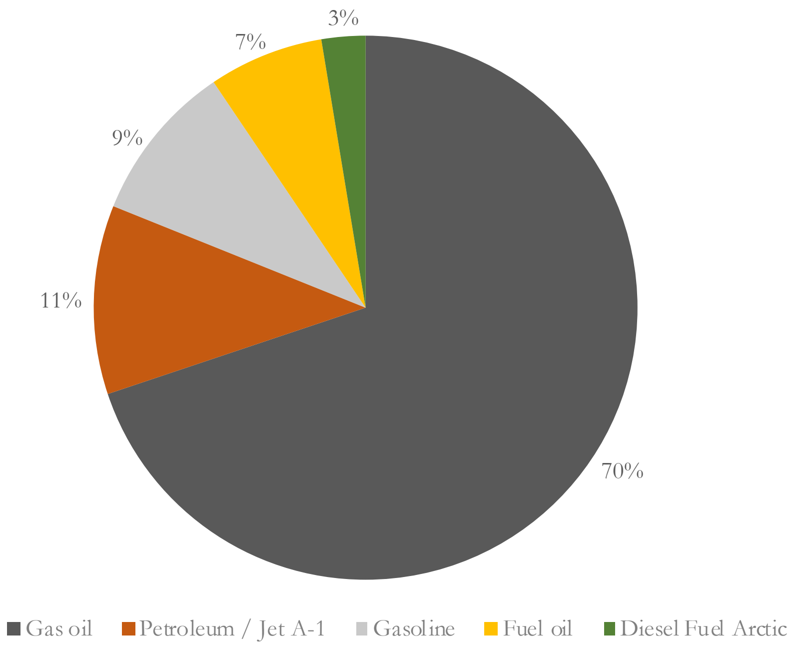

Figure 13: Total fossil fuel consumption in Greenland divided in type of fuel (Department of Business - Energy and Research, 2018).[1]

It is evident that gasoil accounts for the most significant part. Note that also LPG, aviation gasoline and lubricating oil is consumed however it counts for less than one percent accumulated. Polaroil is the company responsible for the distribution of fuel products in Greenland ensuring the fuel demand is met all year around. The imports of fuels takes place five times a year in the period of April to December and is delivered to oil loading terminals in Kangerluarsoruseq, Nuuk, Kangerlussuaq and Sisimiut (Polaroil, 2020). The fuel is delivered from the Swedish refinery Preem in Gothenburg by the company German Tanker Shipping. The tank vessels have each a capacity of 45,000 m^3 fuel. Polaroil manage the distribution to the towns in Greenland whereas the company Pilersuisoq manage the distribution for the settlements (Polaroil, 2020). In Figure 14, a map of all island energy systems is presented, distinguished in hydropower and solely fossil fuel-based energy systems. Also, the interesting hydropower potentials applied in the further analysis are marked. These are treated in-depth in Section 6.2.

[1] In the statistics in Greenland the term fuel oil is covering IFO-30, IFO-180 and HFO-380 (Department of Business - Energy and Research, 2018).

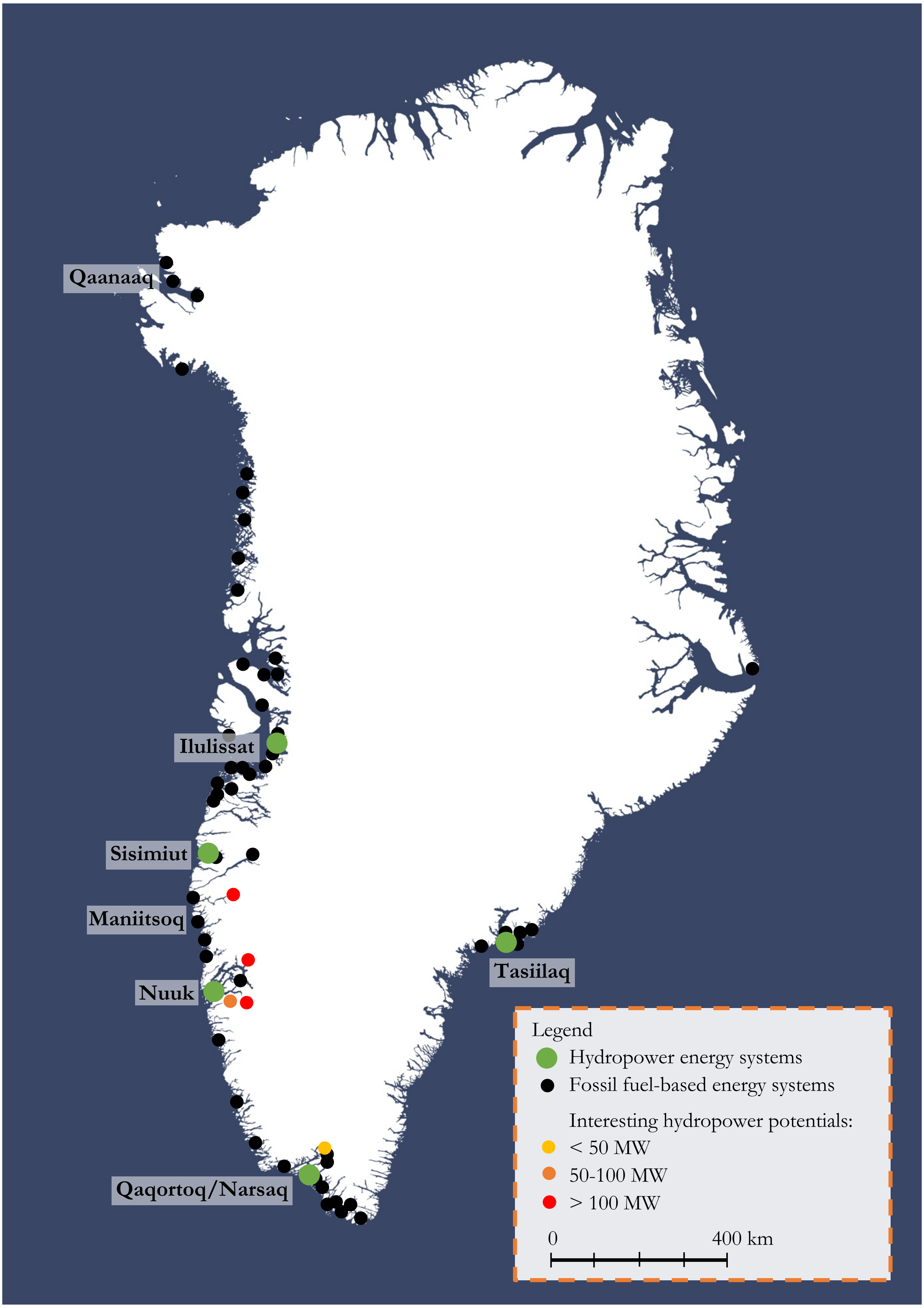

Figure 14: Map of energy systems and interesting hydropower potentials in Greenland.

In order to explain how the energy systems are build up and operated, the different systems are categorised into two groups. Five of the systems are supplied by hydropower of which two are supplied by waste energy as well. The remaining systems are solely based on fossil fuels. It is acknowledged that both photovoltaic and wind power are being demonstrated, however only at small scale. The systems only based on fossil fuel are described as one group. The five other systems are briefly described individually due to the higher level of complexity.

Electricity in all of the systems is produced by either hydropower or oil-based products. However, the heat production is more complex and is thus briefly explained to provide a better understanding of the energy systems. The district heating grids can supply heat from waste incineration plants, excess heat from power production and heat from both electric boilers and oil boilers. In systems with hydropower, it is possible to be supplied by electrical heat, either fixed or interruptible. Fixed electrical heat operates with either electrical radiators or small electric boilers, located in the households. Interruptible electrical heat is produced by central electric boilers when there is enough hydropower available. When the electricity available from the hydropower plant is not sufficient, oil boilers will be started. This interruptible heat enables more flexibility for the operator and is therefore the most inexpensive type of heat (Nukissiorfiit, 2019a, 2020c). Heat is also produced by individual oil boilers and most of the energy systems in Greenland are solely based on heat from individual oil boilers as Nukissiorfiit is only supplying heat 16 places (Nukissiorfiit, 2020c).

6.1.1 Fossil fuel-based systems

Today, several towns and settlements have smaller waste incineration plants where the generated heat is or could be supplied to the households. However, when the new incineration plants are operating by 2023, the waste will be collected and shipped to the two central plants. Although there might be hydropower potentials in proximity to some of settlements, which are today solely supplied by fossil fuels, they are not feasible to realise if most of the electricity cannot be utilised (Naalakkersuisut, 2017). This is one of the main challenges and reasons why the vast majority of the energy systems in Greenland are run on fossil fuels today. These energy systems consist of CHP diesel engines supplying both electricity and heat, oil boilers only producing heat and generators only for electricity. In these systems there is backup capacity in case any failure occurs. A diagram representing fossil fuel-based energy systems can be seen on the figure below.

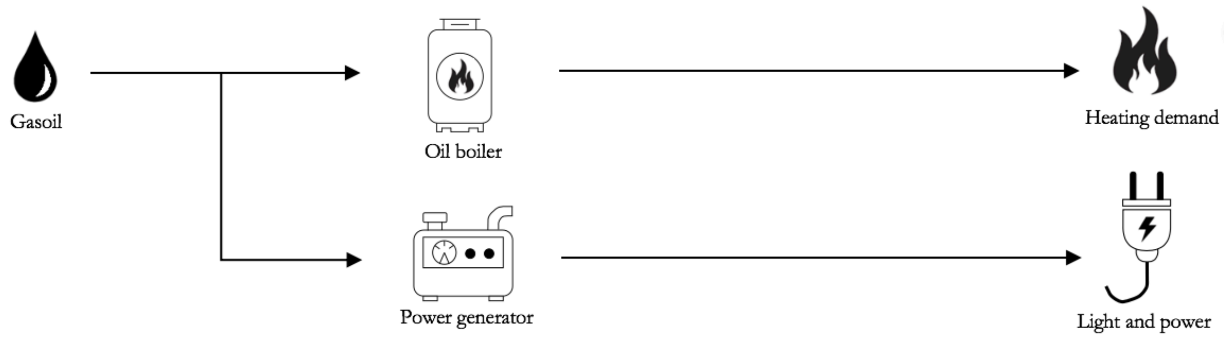

Figure 15: Diagram of fossil fuel-based energy systems.

6.1.2 Cities not solely based on fossil fuels

Qaqortoq/Narsaq, Sisimiut, Ilulissat, Nuuk and Tasiilaq are the only cities today that are not exclusively supplied by fossil fuels. A representation of these cities energy system is presented in the diagram below of which only Nuuk and Sisimiut will have a waste incineration plant by 2023.

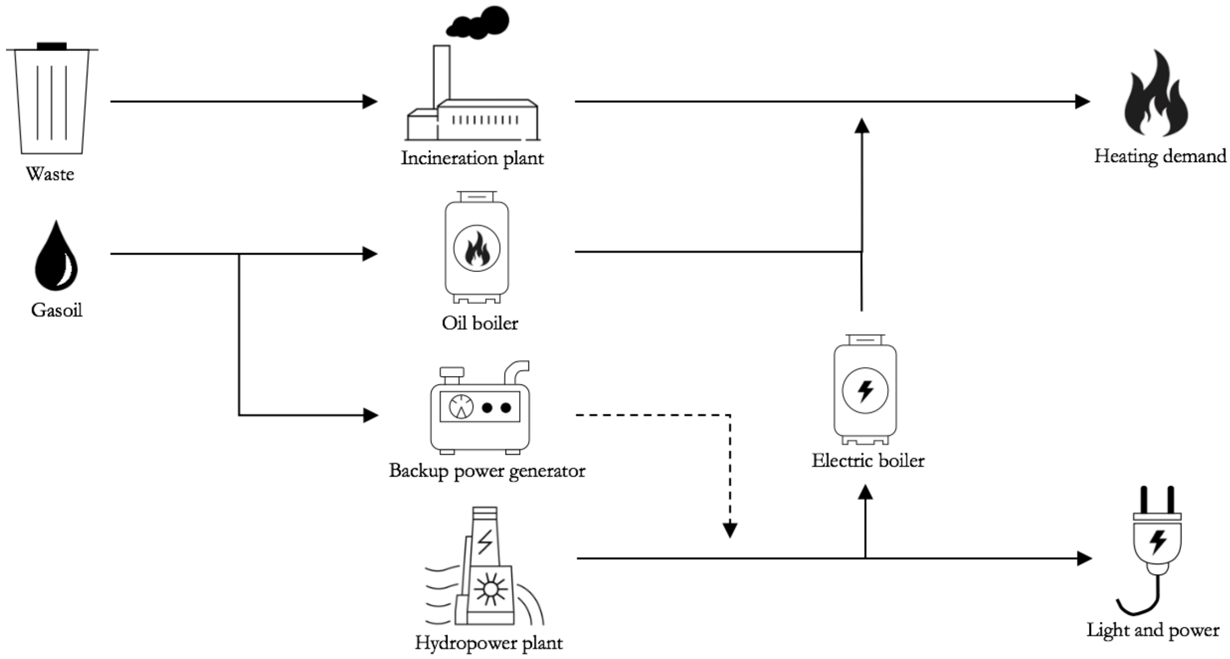

Figure 16: Diagram of energy systems not solely based on fossil fuels.

Qaqortoq is located in the southernmost part of Greenland being hometown for 3,012 inhabitants. Qaqortoq is supplied by 7.6 MW hydropower. However, this hydropower plant is not only supplying Qaqortoq but also Narsaq and is the only energy system in Greenland that are interconnected. This interconnection is however only transmitting electricity (Naalakkersuisut, 2017). In Narsaq some of the electricity is converted to heat through electric boilers (see Appx. 11.2). The hydropower capacity is sufficient to cover the electricity demand in Qaqortoq but is not sufficient to cover the heat demand. Therefore, all of the heat is based on fossil fuels.

Sisimiut is the second largest town in Greenland with 5,509 inhabitants located approximately between Ilulissat and Nuuk (see map on Figure 14). Sisimiut is one of the locations where the new incineration plants will be established. The incineration plant should be running one year before the plant in Nuuk. The plant in Sisimiut will receive waste by ship from towns and settlements more north from Sisimiut. This means that there will be a constant heat production of 4.25 MW all the year around. Sisimiut is supplied by 15 MW hydropower covering most of the electricity demand and part of the heating demand through 1.2 MW electric boilers.

The town Ilulissat is located in the Disko bay, a great bay on the Greenlandic west coast. Ilulissat is by its 4,554 inhabitants the third largest town in Greenland after Nuuk and Sisimiut (Appx. 11.2). Today, there is a waste incineration plant operating however it is expected to be shut down when the two central incinerations plants are running. The hydropower plant in Ilulissat is the most recently established (2013) with a capacity of 22.5 MW. The hydropower capacity exceeds the conventional electricity demand, therefore electric boilers have been introduced in order to utilise some of the surplus electricity for heat production (EA Energy Analyses, 2018b).

Nuuk is the capital of Greenland with around 18,000 inhabitants and thus also has the largest energy system. The population in Greenland is expected to decrease but Nuuk has experienced population growth over past ten years. Therefore, the population is expected to increase even further, which means that the energy demand will increase as well. The second central waste incineration plant should be established in 2023 and be operating at full load from 2024 (Building Supply, 2019). The waste to energy (WtE) plant is likewise dimensioned to constantly produce 4.25 MW heat all around the year. Nuuk is today supplied by 45 MW electricity from the hydropower plant located in Buksefjorden. It is the biggest hydropower capacity in Greenland, but it is not enough. The sustainable threshold of the water withdrawal from the Kangerluarsunnguup Tasersua (Kang) reservoir of 230 GWh/a has been exceeded since 2010, i.e. that if this overconsumption continues, at some point there will be no more water for the turbines (Nukissiorfiit, 2019b, 2019c). The overconsumption can be seen in Figure 17.

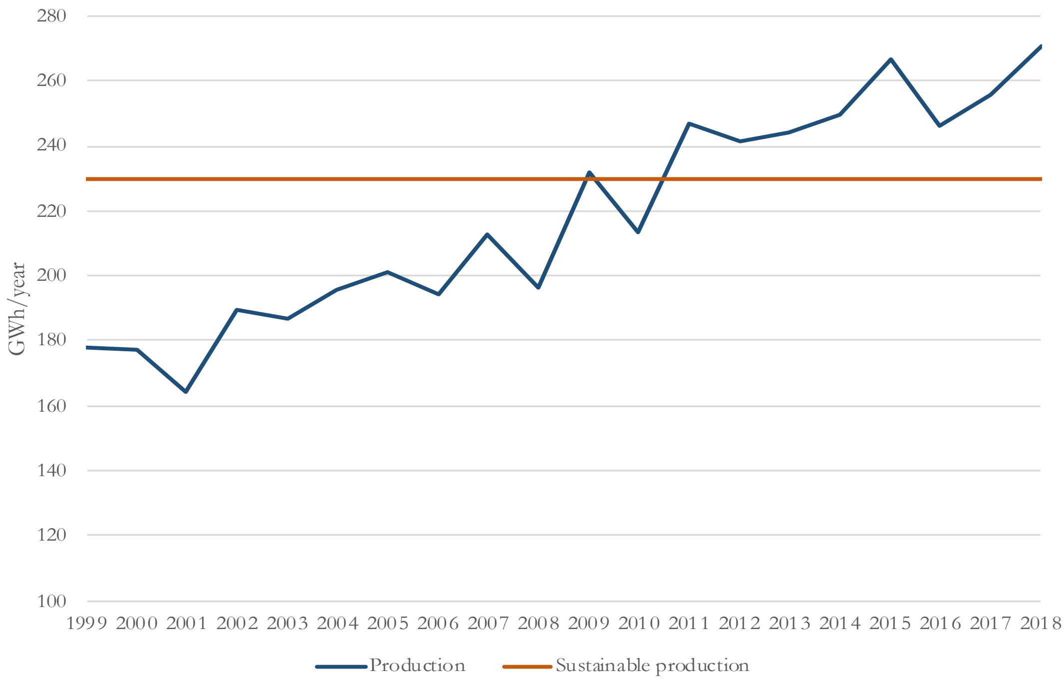

Figure 17: Sustainable and actual withdrawal from Kang reservoir supplying Nuuk with hydropower (EA Energy Analyses, 2018a; Nukissiorfiit, 2019b).

Tasiilaq is located on the east coast with 2,063 inhabitants. It is the simplest energy system of those with hydropower. There are two diesel engines producing electricity with a total output of 1.6 MW. The hydropower of 1.2 MW covers most of the electricity demand. There is no electrical heat and no heat from waste incineration and the heating demand is thus met by gasoil. The data from Nukissiorfiit does not mention any central oil boilers and it is therefore assumed that all heating is supplied by individual oil boilers.

6.2 Hydropower potentials

An examination of Greenland's hydropower resources has been carried out in order to designate the most relevant potentials in relation to an electrofuel production. This has been done based on the extensive report *"Greenland's hydropower resources - An overview"* (2005) as well as the more recent report *"Hydropower plants in West Greenland – Update of size potential and estimates for 5 urban plants"* (2019) both published by Nukissiorfiit. The latter contains an update of the hydrological basis for the potential of five hydropower plants. Collectively, these reports provide an overall overview of all localised hydropower resources since 1974 and identifies the most promising plant potentials. An updated hydropower map by Nukissiorfiit (2020) is moreover utilised in order to ensure that the data applied in this section is fully up-to-date. The data on the plant potentials constitutes the foundation for choosing the most advantageous and optimal hydropower potential in relation to an electrofuel production.

A list of all identified hydropower potentials in Greenland relevant to an electrofuel production can be found in Appx. 10.7. It is a prerequisite that the concrete hydropower resource contains a significant capacity and the potential is therefore assessed on the basis of the amount of electricity available annually. Hence, if a hydropower resource is located in proximity to a city, it is required that the production potential to a significant degree exceeds the current energy demand for electricity and heating, as there would otherwise not be any surplus electricity available for the production of electrofuels. The list therefore only contains those hydropower resources that possesses a substantial production capacity potential.

6.2.1 Most interesting hydropower resources

With reference to the hydropower potentials listed in Appx. 10.7, the most interesting hydropower resources in relation to an electrofuel production will be selected based on the technoeconomic parameters listed below:

- Proximity to city
- Energy potential
- Economy
- Planning stage

Proximity to a city is an advantage as it enables synergies between the hydropower plant, the electrofuel production and other energy demands in the city. It is likewise assumed that a hydropower plant and an electrofuel production located close to a larger city is an advantage in terms of the acquisition of labour as well as the necessary skills and knowledge. The energy potential is an expression of the annual sustainable threshold of the water withdrawal in relation to retaining the long-term availability of water in the reservoir and is determining for the possible capacity of the hydropower plant. This is estimated based on the annual run-off, the reservoir capacity and the fall height (calculations can be found in Appx. 11.2). The economy covers the total costs associated with the establishment of the hydropower plant including buildings, construction work, electrical mechanics and transmission line. Lastly, the planning stage is important as it indicates to what extent the hydropower resource has been examined and when a utilisation can be expected to be realised. The planning stage from I to VII is estimated based on the descriptions listed in Nukissiorfiit (2005), where the lowest planning stage (I) indicates that the hydropower resource has only been localised, while the highest planning stage (VII) means that a hydropower plant is in operation. It should be noted that it is not always possible to determine the exact planning stage according to Nukissiorfiit (2005). Therefore, these are only used indicatively.

Based on the technoeconomic parameters described above, Table 16 presents the most interesting hydropower potentials in relation to an electrofuel production on the basis of all hydropower resources identified to be relevant. These potentials are also marked on the map at Figure 14.

Table 16: Most interesting hydropower resources (Nukissiorfiit, 2005, 2019c, 2019b, 2020a).

	Qaqortoq/ Narsaq	Nuuk extension options			Nuuk	Maniitsoq
Plant	Johan Dahl Land	Option 2	Option 3	Option 4[a]	Imarsuup Isua	Tasersiaq
Planning stage[b]	IV	V	V	V	IV	V
Plant capacity (MW)	40	100	135	190	154	300-439
Energy potential (GWh/a)	290	762	1,207	1,207	1,278	2,699-3,756
Maximum production potential (GWh/a)	290	762	830	1,207	1,278	2,568-3,756
Proximity to city (km)	(Nar) 56 (Qaq) ~65[c]	56.5	87	87	~130[c]	~150[c]
CAPEX (M€)	100[d]	226	287	353	374[d]	400-583[d]
CAPEX (M€/GWh)	0.35	0.30	0.35	0.29	0.29	0.16

Notes: [a] Prerequisite: option two have been established earlier with a new transmission line. [b] The planning stage from I to VII is estimated based on the descriptions listed in Nukissiorfiit (2005). [c] Distances are estimated based on the maps from Nukissiorfiit (2019c). [d] Prices are estimated based on investment costs of comparable capacities by identifying the cost per GWh.

With reference to Appx. 10.7, the hydropower potential available approximately 80 km from Paamiut is not considered relevant due its low planning stage of I. Likewise, the resources Tasersuuq Isua near Nuuk and Nussuaq between Ilulissat and Uummannaq are also disregarded due to their low planning stage of II, i.e. that only theoretical calculation has been carried out. Another hydropower potential, which is disregarded from further examination is the hydropower resource 31 km from Qasigiannguit. This potential is located in proximity to the city and has a planning stage of V, but should also be used to supply Aasiaat, which is located 114 km away. This resource is thus not considered to be located proximate to the city. Moreover, the total electricity demand for the two cities is estimated to about 20 GWh /a (see Appx. 11.2), which leaves less than 74 GWh/a of surplus electricity in order to retain a sustainable production from the hydropower resource. Therefore, this potential is also not considered relevant in the context of an electrofuel production.

In contrast to these discarded options, an interesting opportunity in terms of both proximity to city as well as energy potential is Qaqortoq/Narsaq. This is due to the fact that the electricity demand in Qaqortoq/Narsaq is already supplied from an existing hydropower plant and an establishment of a new hydropower plant can thus be utilised for an electrofuel production. Moreover, the hydropower extension options for Nuuk between 56.5 and 87 km away are also interesting to consider as they also contain great energy potentials. A realisation of one of these extension options are currently being discussed due to the fact that the energy consumption exceeds the current sustainable production from Kang, as previously illuminated (also see Figure 17). Also, an option one is considered however this option only involves a tunnel leading water from the lake Isortuarsuup Tasia (Ista) to Kang increasing the annual run-off and thereby the sustainable energy potential. These options are visualised in the figure below in order to provide a better overview followed by a further explanation to increase the understanding

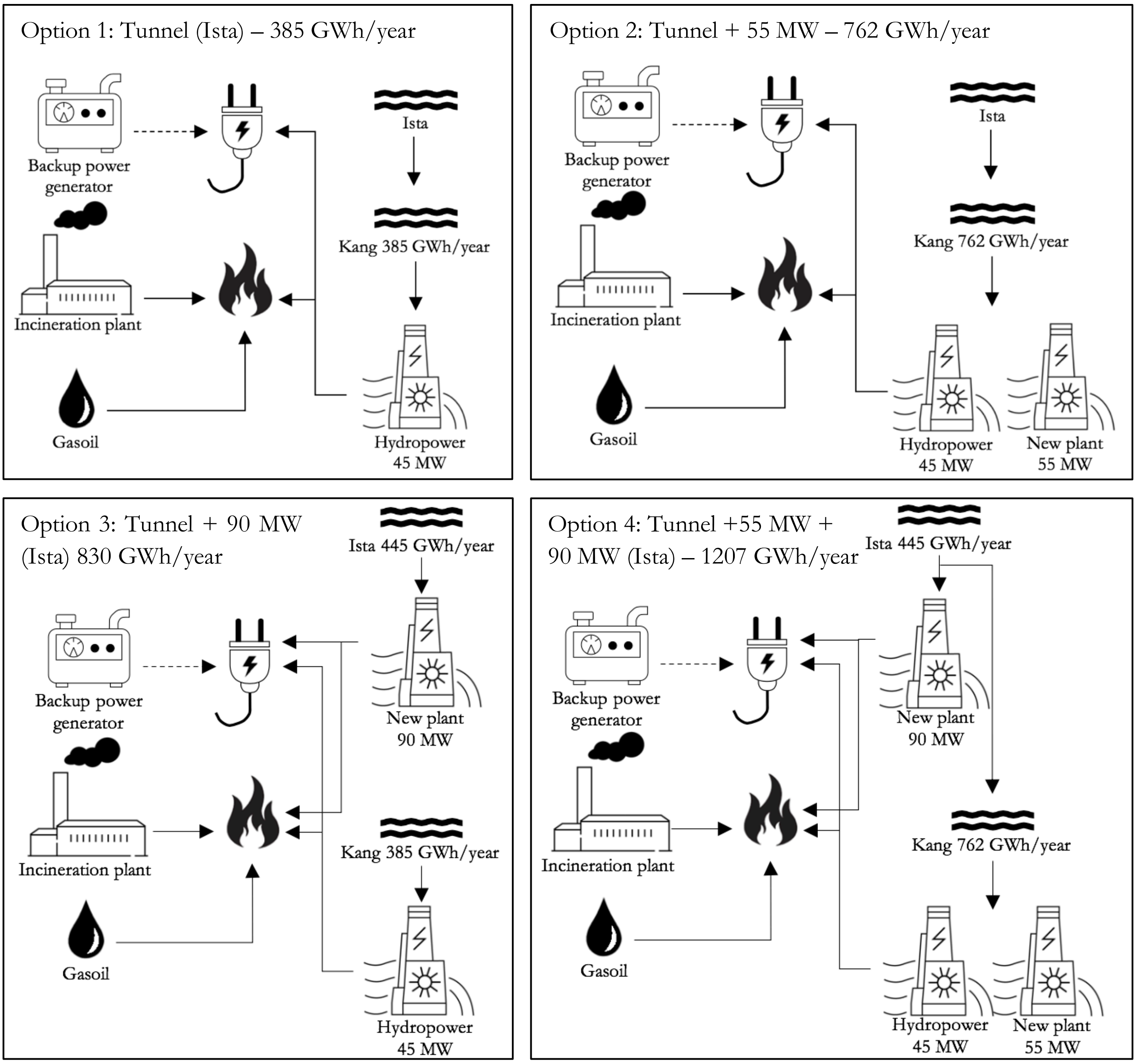

Figure 18: Various hydropower extension options in Nuuk inspire by Backen (2019).

Option one involves a tunnel from the higher elevated Ista reservoir that will transfer water to Kang and increase the catchment area and thus the amount of water available which will raise the annual sustainable water withdrawal from the reservoir. This would increase the sustainable energy potential in the reservoir to 762 GWh/year. However, the production is limited by the capacity of the existing hydropower plant of 45 MW, which will only be able to produce around 385 GWh per year with 8,560 annual operation hours set as a prerequisite for calculating the hydropower production potential. The reason for the number of operation hours is explained later in Section 6.4. In option two a new hydropower turbine with a capacity of 55 MW will be established in proximity to the existing together with the tunnel from Ista. This option makes possible to exploit the increased energy potential of Kang, which will at the same time be the limiting factor ensuring a maximum sustainable production of 762 GWh/a. The third option also contains a tunnel leading water from Ista to Kang but includes a hydropower turbine of 90 MW between the two reservoirs. In this way, the maximum sustainable energy potential in the water flowing from Ista to Kang can be utilised and increase the annual production to 830 GWh/year. Option four is an extension of option two and also includes a hydropower plant between Ista and Kang with a capacity of 90 MW. This option makes possible to utilise the entire energy potential of both Ista and Kang reservoirs of 1,207 GWh/a.

Moreover, the two hydropower resources Imarsuup Isua, Nuuk, and Tasersiaq, Maniitsoq, are due to their enormous energy potentials interesting to explore despite their location of 130 and 150 km from Nuuk and Maniitsoq, respectively. Tasersiaq is the longest lake in Greenland and its surface lies approximately 682 metres above sea level. The lake's most important water source is melted ice from glaciers at its eastern and southern end (Business Greenland - Government of Greenland, 2020). Based on the specified values of the reservoir capacity, annual run-off and fall height, the hydropower resource has an annual energy potential of 2,699 GWh/a (see Appx. 11.2). However, according to Nukissiorfiit (2005) another catchment area can potentially be utilised to increase the water supply, which allegedly will increase the energy potential by an additional of 670 GWh/h. It has moreover been suggested to establish the power station with expiration towards Eternity Fjord. This would increase the fall height from 620 to 709 metres (Business Greenland - Government of Greenland, 2020). Overall, this will increase the energy potential to 3,756 GWh/a (see Appx. 11.2) and enable an energy capacity for Tasersiaq of around 439 MW of continuous power. This potential may however be even higher and according to the Government of Greenland it is expected that Tasersiaq can deliver an energy capacity of 475-500 MW (Business Greenland - Government of Greenland, 2020). This makes Tasersiaq by far the largest hydropower resource in Greenland and thus constitutes an interesting opportunity. The American company Alcoa has previously been interested in utilising the large hydropower resource in Tasersiaq for an aluminium production (Sermitsiaq AG, 2018).

6.3 Carbon dioxide resources

As mentioned, in 2024 the two new central waste incineration plants will be operating in Nuuk and Sisimiut both with a capacity of around 2.5 tonne waste per hour (Building Supply, 2019). Both plants are expected to receive around 17,000 tonnes of waste annually, which each containing 17,183 tonnes of CO_2 when taking into account both the fossil and the biogenic share of carbon dioxide (see calculation in Appx. 11.1). The two incineration plants are considered to be the largest point sources of carbon dioxide. In regard to industry, there might be some point source emissions of CO_2 for instance in relation to the fishing industry. However, these emissions are only smaller quantities compared to the waste incineration plants. Alternatively, applying direct air capture could constitute immense carbon dioxide resources as CO_2 from the atmosphere is captured. However, as described in Appx. 10.2.5, the technology is still immature and very costly. Therefore, the technology of direct air capture is not examined further regarding capturing of carbon dioxide throughout the analysis.

Another carbon dioxide resource considered is import from other countries where CO_2 is captured from industry and waste incineration plants. It is however important to stress that dependence on import do not align with the objective of increasing the self-sufficiency in Greenland (Naalakkersuisut, 2017). At the new Danish waste incineration in Copenhagen, Amager Resource Centre, it is decided to establish carbon capture which should be operating from between 2022 and 2023. It will be a pilot project enabling to capture 25 tCO_2 per day. If the pilot project turns out to be successful, a full scale carbon capture can be operating from the end of 2025 capturing 500 kt per year (Wittrup, 2020). In Table 17, the assumed cost of CO_2-import is presented.

Table 17: Assumed cost CO_2-import from ARC.

Expected cost per tCO_2 captured at ARC (€/tCO_2)	13.3

At ARC they imagine storing the carbon dioxide underground or supply it for electrofuel production. They expect the cost per ton CO_2 to be around 13€ if establishing full scale carbon capture (Wittrup, 2020). In the further analysis it is assumed that it is could possible to buy the CO_2 for around 13.3€ per tonne from a similar carbon capture facility.

6.4 Electrofuel analysis

In the following analysis, the potential for electrofuel production in Greenland is examined. The analysis is carried out based on the interesting hydropower resources identified previously in the analysis (see Table 16 for hydropower resources) as well as the largest point-discharge sources of carbon dioxide identified. The calculations have been conducted using the energy-economic model presented in Section 4.4. Technoeconomic parameters of the respective technologies are applied on the basis of the SOA chapter (see Chapter 5).

In the table below, some general prerequisites and assumptions for the further analysis are listed while site specific assumptions are presented under each of the respective section.

Table 18: Assumptions and prerequisites.

Share of conversion to electric heating (%)	100
Annual operation hours of hydropower (h/year)	8,560
Annual operation hours of PtX systems (h/year)	7,800
Starting year of analysis (year)	2024
Total years of analysis (years)	20
Fuel storage required (% of total fuel produced)	30
CO_2 storage required when imported (% of imported CO_2)	50

It is a general prerequisite that the energy systems in the cities examined are supplied by heat from waste incineration and the electrofuel production which is only possible in Nuuk and Qaqortoq. The remaining heating demand is converted to be based solely on electricity from hydropower, which entails that the heating is supplied by electric boilers. This enables to examine the potential of utilising the surplus electricity from the various hydropower options for electrofuel production. It is moreover assumed that the possible annual operation of the hydropower plant is limited to 8,560 hours as maintenance and overhauls of the plant are usually between 100-200 hours a year. Hydropower production potentials are thus distributed based upon this operation time. The annual operation of the PtX system is conservatively expected to be running 7,800 hours per year. As the waste incineration in Nuuk is set to be fully operational by 2024, this year is set as the starting year of the analysis, which is determined to run for 20 years. It is assumed that a fuel storage capacity of 30% of the fuel produced is required in order to store the fuel during the winter period where impassable seaways makes it impossible to distribute the fuel (Lindegaard & Lykkegaard, 2020). Lastly, a storage capacity capable of storing 50% of the required CO_2 annually is assumed to be required in order to accommodate the import, which can be expected twice a year according to Lindegaard & Lykkegaard (2020). Since security of supply is essential in the country, all analysis has been made to maintain this. Distribution of both electricity and heating demand has been carried out using energyPRO. The economic key figures used for carrying out the economic evaluations in a Greenlandic context are presented in Table 5 (Section 4.4).

All various alternatives of electrofuel productions are analysed through the energy-economic model and gives relevant outputs in order to compare and identify the most interesting alternatives. All the different variables constitute in total 51 alternatives. The variables are presented in Table 19 showing the hydropower options and fuels synthesis causing the majority of the variables. Due to prevailing assumptions, the variables do not apply to all compositions e.g. it is assumed that the captured CO_2 from the waste incineration only is feasible to utilise in the production alternatives located in Nuuk.

Table 19: Different variables included in technoeconomic analysis of electrofuel production.

Variables	Amount
Hydropower plants	6
Electrofuel synthesis	4
Carbon capture yes/no	2
Import of CO_2 yes/no	2

The alternatives examined in the analysis are not equally interesting to elaborate on considering the objectives from Naalakkersuisut (2017) which this report builds upon. Therefore, an elimination of alternatives has been carried out in order to identify the most interesting alternatives. Throughout the elimination process the objective is to identify the best alternative connected to every of the three cities close to the identified hydropower potentials. In Figure 19, the elimination is depicted showing the criteria that are based on the objectives from Naalakkersuisut

(2017). The alternatives examined receives a score of the three criteria indicating the performance compared to the other alternatives.

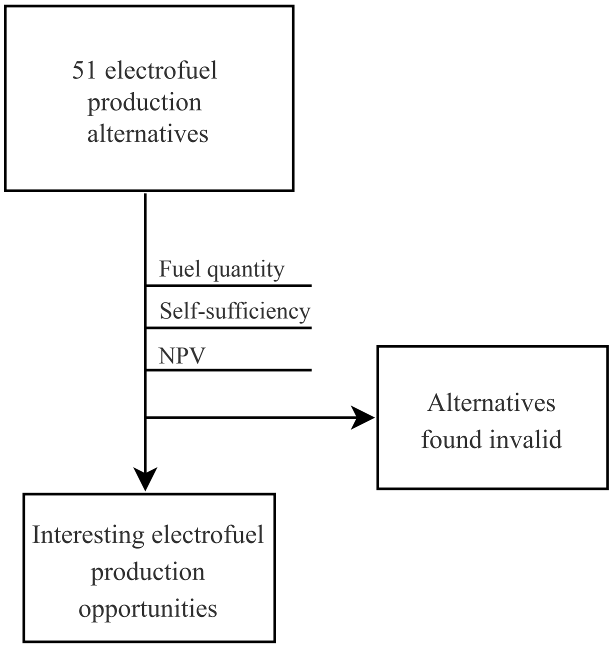

Figure 19: Analysis criteria for identifying the most promising electrofuel alternative.

The three criteria are weighted equally and therefore the performance is decided by highest fuel quantity produced in MWh, increase of self-sufficiency and net present values. The increase of self-sufficiency is depending on whether CO_2 is imported for the production. In such alternatives the ratio of imported CO_2 and fuel produced are calculated and the share of imported CO_2 is subtracted. The production of Fischer-Tropsch diesel requires the highest import of CO_2 whereas methanol requires a little less compared to DME. All calculations and results from the 51 alternatives and selection can be found or replicated in the energy-economic model (see Appx. 11.1). In the following the best alternatives from each of the three cities will be presented.

6.4.1 Qaqortoq/Narsaq

Qaqortoq and Narsaq are today already supplied by electricity from the hydropower plant at Qorlortorsuaq and while some of the electricity is converted to heat in Narsaq, Qaqortoq's heating demand is covered solely by fossil fuels. Therefore, an additional hydropower plant at Johan Dahl Land with a maximum production potential of 290 GWh/a should be utilised to cover the remaining demand for both heating and electricity in the two cities, as stressed in the previous section (Table 18). According to Statistics Greenland (2020b), these cities have been experienced a decline in population of approximately 1% a year during the last ten years. If this development continues, the cities will have a total population of about 3,500 by the end of the analysis period in 2043. Since there is no CO_2 point discharge source of significance in the two cities, it assumed that the carbon dioxide for the production of carbon-based electrofuels is imported exclusively, whereas nitrogen for the production of ammonia is captured by an air separation unit locally. In the examined scenario, the electrofuel production is assumed to be located in proximity to Qaqortoq and excess heat from the PtX process is therefore utilised for heating in the city.

6.4.1.1 Johan Dahl Land

The figure below displays the total energy demand in year zero of the analysis period (2024) that should be supplied by electricity from the new hydropower plant with a suggested capacity of 40 MW. This demand accumulates to a total of around 72 GWh, whereas the cities remaining energy demand of 33.5 GWh will be supplied from the existing hydropower plant. The figure also shows the surplus energy from a full utilisation of the new hydropower plant. The energy surplus from the reservoir is distributed throughout the year in order for the hydropower plant to utilise all potential energy of almost 218 GWh yearly.

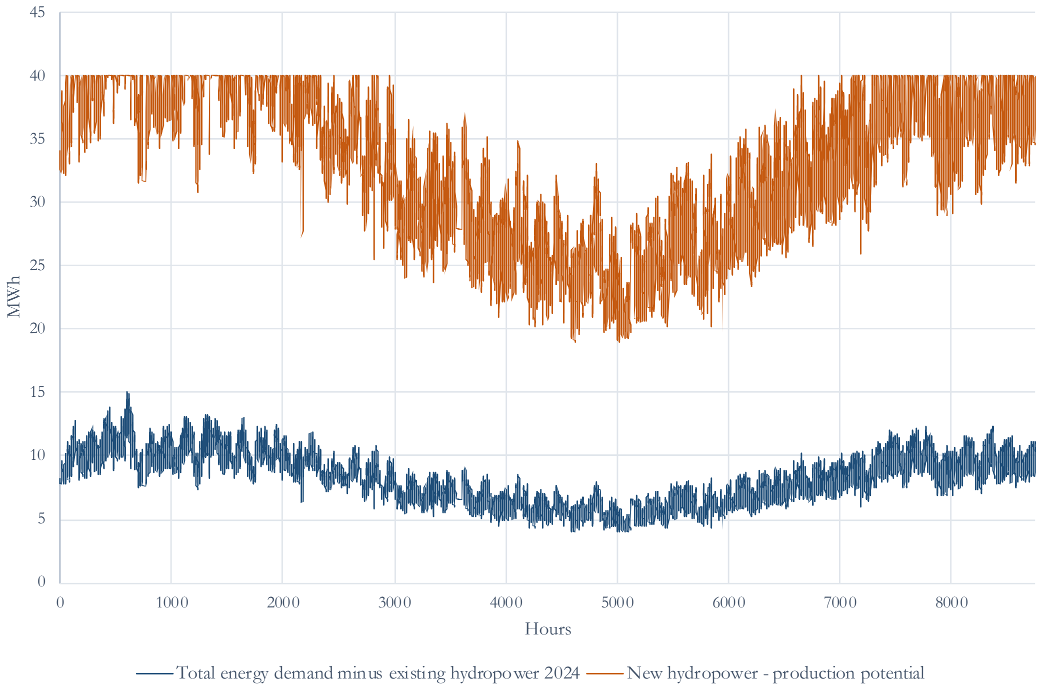

Figure 20: Energy demand of Qaqortoq and Narsaq to be covered by the hydropower plant and new hydropower production potential.

Due to the decline in population, the energy demand will decrease continuously throughout the 20-year analysis period causing the energy surplus to raise. This means that 17.5 GWh could additionally be utilised in the final year of the analysis. The development of available surplus electricity is visualised by the duration curves in Figure 21 below.

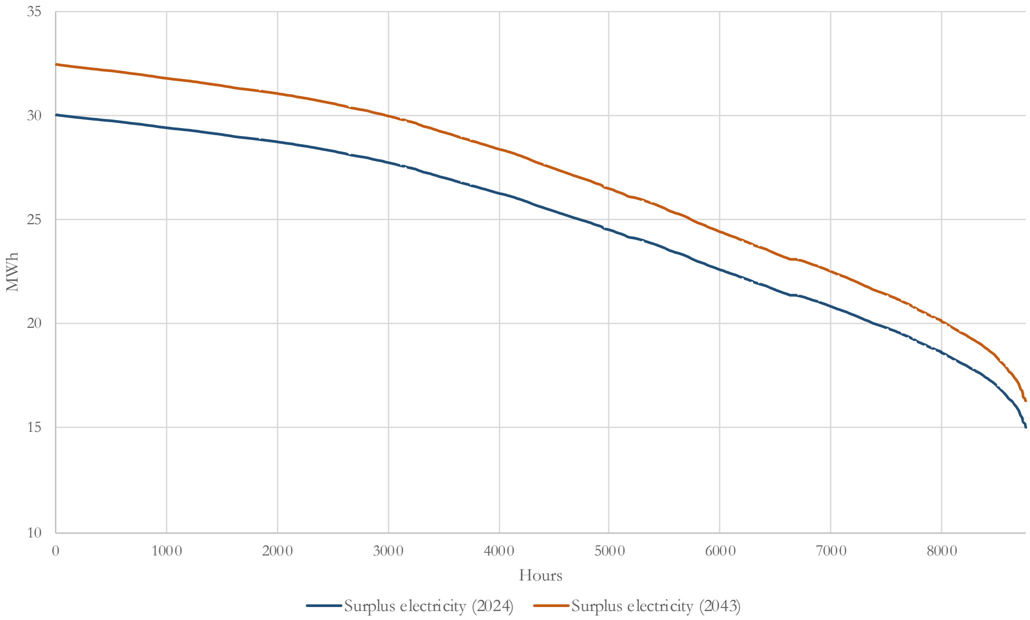

Figure 21: Surplus electricity increase from year zero to year 20 of the analysis period due to population degrowth.

Despite the increasing energy potential, it is assumed that the energy demand from the cities will not decrease throughout the calculation period and therefore, the PtX production capacities are dimensioned based on the surplus electricity of year 2024. This means that a stable electrofuel production can take place providing a constant fuel output every year. The remaining energy surplus in the reservoir however allows to upgrade the facilities gradually. The quantities of the various electrofuel productions are displayed in Figure 22 below.

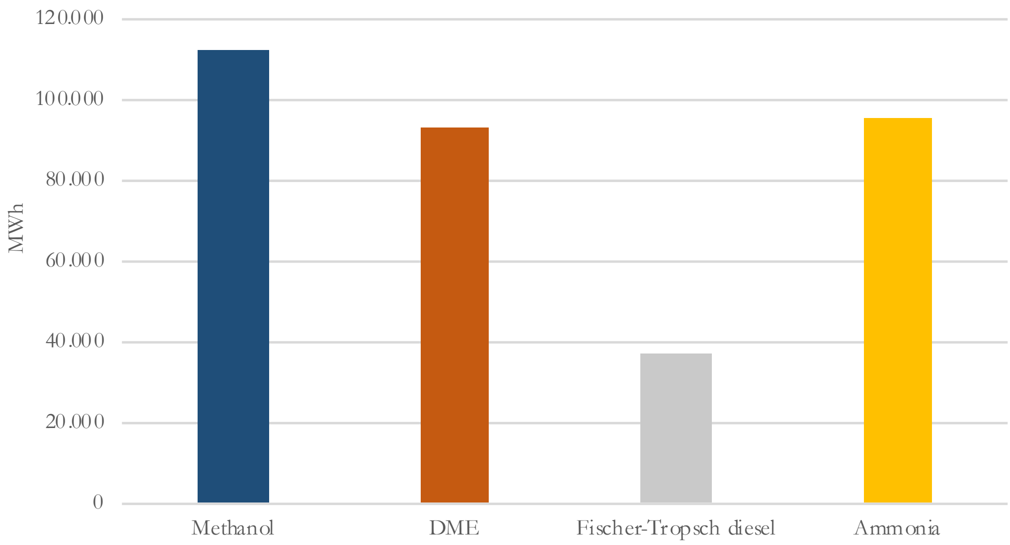

Figure 22: Carbon-based fuel productions based on imported CO_2 and ammonia based on captured N_2 from ambient air.

As clearly indicated by the figure, it is possible to produce more MWh methanol compared to the other electrofuels. This is mainly due to the higher efficiency of the methanol synthesis and because electricity is the limiting resource in this scenario. The table below presents the total amount of electrofuel possible to produce annually as well as the imported carbon dioxide or nitrogen required for the various productions. Also, the share of produced fuel estimated to contribute to increase the self-sufficiency, as explained at the beginning of this analysis section, is presented together with the socioeconomic NPV identified using the energy-economic model.

Table 20: Performances of the best alternatives connected to Qaqortoq/Narsaq, in regard to fuel quantity, self-sufficiency and NPV.

Electrofuel	GWh/year	CO_2/year (kt)	N_2/year (kt)	Self-sufficiency share (GWh/year)	NPV (M€)
Methanol	112.5	27.9	0	84.6	-11.8
DME	93.0	22.1	0	70.8	-24.6
Fischer-Tropsch diesel	37.3	11.9	0	25.5	-64.9
Ammonia	95.5	0	30.4	95.5	-15.9

It was found based on the three criteria of fuel quantity, degree of self-sufficiency and NPV that methanol is the best electrofuel to produce in Qaqortoq despite the negative NPV of -11.8. The flow diagram below displays the methanol production from Johan Dahl Land including respective capacities of units and excess heat available to supply the heating demand in Qaqortoq, which however only amounts to 22 GWh in year zero of the analysis. All flow diagrams have been extracted from the energy-economic model (Appx. 11.1).

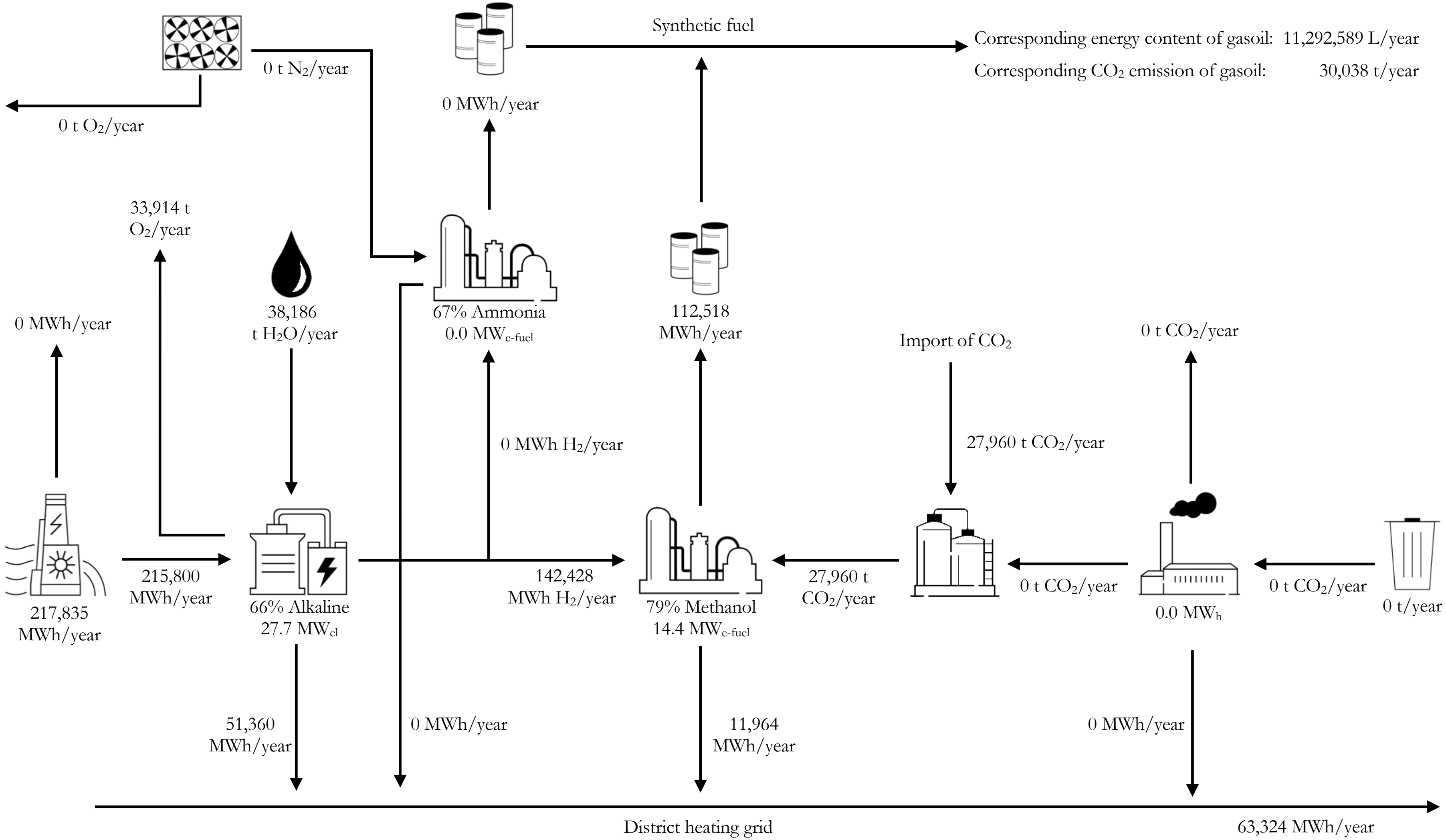

Figure 23: Flow diagram of PtX system from Johan Dahl Land producing methanol.

It can be inferred from the flow diagram that the process enables to substitute substantial amount of gasoil. The different costs and revenues constituting the total NPV for the methanol production is presented by the waterfall chart below.

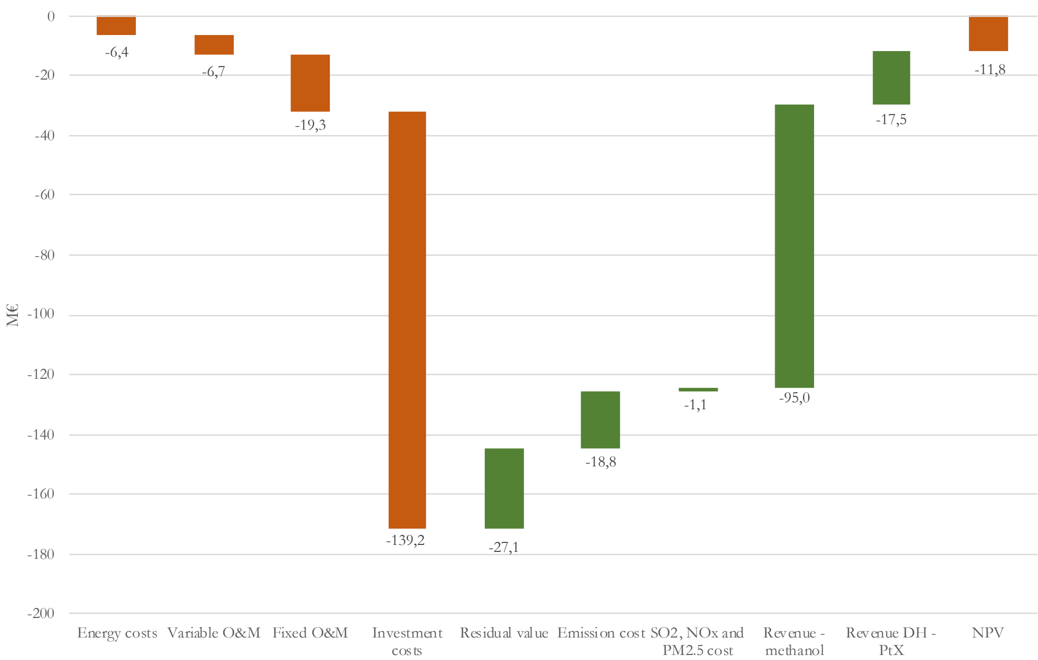

Figure 24: Waterfall chart of costs and revenues for methanol production in Qaqortoq/Narsaq.

The tax distortion factor is included in CAPEX and OPEX. It is evident that the investment costs make up the vast majority of the total costs. Therefore, a cost-breakdown chart visualising the different investments for the methanol production is shown in Figure 25.

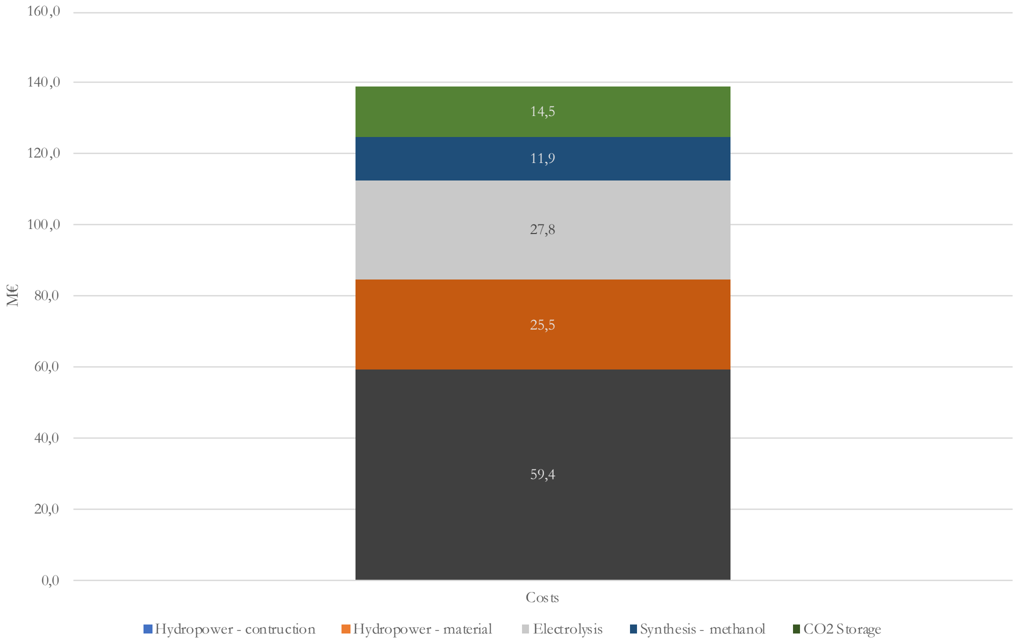

Figure 25: Cost-breakdown chart of different investments for methanol production in Qaqortoq/Narsaq.

The hydropower investments dominate the total investment accounting for more than half. The PtX system is assumed to have a flexible synthesis, which enables to follow the hydrogen production and thereby there are no need for hydrogen storage. The long-term marginal cost of producing methanol in this scenario was found to 78 €/MWh as visualised below.

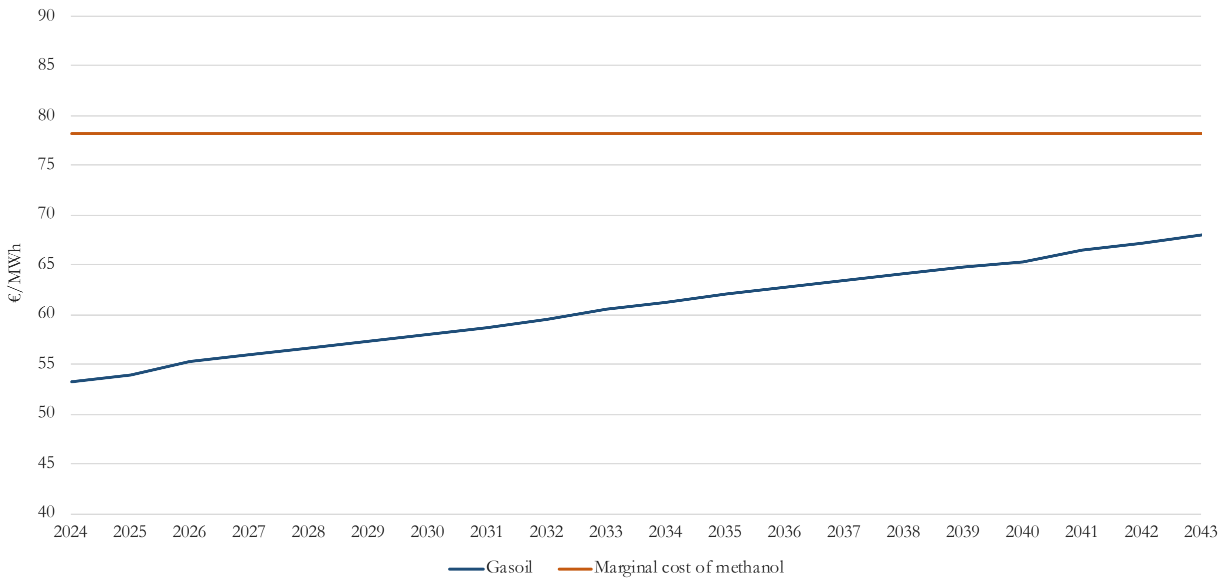

Figure 26: Long-term marginal cost of methanol production from Johan Dahl Land.

The marginal cost of methanol represents the cost of producing one MWh assuming the costs are distributed equally throughout the calculation period. It is the total costs of the calculation period subtracted emissions costs and residual value. The increasing cost of the gasoil is based on the projections from Danish Energy Agency, (2019).

6.4.2 Nuuk

As previously described, Nuuk already has a hydropower plant operating at Buksefjorden, around 60 km from the city supplying the city with electricity. However, its current annual production exceeds the sustainable water withdrawal rate of 230 GWh/year from the Kang reservoir. In addition, the population in Nuuk is expected to increase by around 1.5% annually during the next 20 years based on developments over the past ten years. This means that Nuuk will accommodate a population of around 25,500 at the end the analysis period in 2043 (Grønlands Statistik, 2020b). As a result of the exceeded production limit and the expected increase in population, it is currently being planned to extend the existing hydropower plant and different opportunities are therefore being discussed, as previously described in Section 6.2.1 (also see Figure 18).

As it is an assumption that the current energy system in Nuuk is supplied by heat from the PtX process and the waste incineration while the remaining demand is covered by electricity from an extension of the hydropower plant, the total energy demand in Nuuk accumulates to 343 GWh annually by 2024 (see Appx. 11.1). Another prerequisite for estimating the electrofuel production potential in Nuuk derives from the new central waste incineration plan that will be operating at full loads from 2024. This is going to be the city's largest CO_2 point discharge source and could thus possibly constitute a significant role in the production of a carbon-based electrofuel. The incineration plant will be an important part of the following calculation to examine the potential of utilising this CO_2 point source for producing a carbon-based fuel in Nuuk. Hence, key parameters of the waste incineration plant are listed in the table below. Other prerequisites and assumptions can be found in Appx. 11.1.

Table 21: Key parameters of waste incineration in Nuuk (Danish Energy Agency, 2019b; Rambøll, 2019; Song et al., 2019).

Annual amount of waste incinerated (t/year)	17,000
Lower heating value of waste (MJ/kg)	10,6
Capacity (t/h)	2.5
Heat efficiency, LHV (%)	85
Capturing efficiency of CO_2 (%)	85
Amount of CO_2 per tonne of waste (t)	1.01

Applicable to option one, two, three and four the excess heat from the whole PtX process is utilised for heating in Nuuk as the production is placed near the city. It is assumed that 70% and 40% of the excess heat from the electrolysis and the synthesis process, respectively, can be utilised for district heating. This displaces some of the total energy demand delivered from hydropower. However, in relation to the Imarsuup Isua hydropower resource, the excess heat from the PtX process is in contrary not considered to be utilised in the district heating grid in Nuuk due the long distance from the reservoir to the city. Moreover, the CO_2 for the electrofuel production is for this scenario only available from import. For all scenarios, the surplus electricity is used to cover all energy needs related to the electrofuel production process, such as for the electrolysis, synthesis and carbon capture unit. These various options and the prerequisites explained above are the basis for the further analysis, where calculations of the electrofuel production potential in Nuuk will be performed.

6.4.2.1 Ista and Kang

By converting the energy system in Nuuk to be supplied by electricity, the annual surplus of electricity from the various hydropower options are estimated. In Table 22 below, the total electricity surpluses for the different options are presented for year zero (2024) of the analysis. These values are used in the analysis to calculate the electrofuel production potential. Due to the population growth, these surpluses are expected to decline throughout the analysis period.

Table 22: Surplus electricity for electrofuel production for various hydropower extension options in 2024.

Options and capacities	Production potential (GWh)	Surplus electricity for electrofuel production (GWh)
Option 1: Tunnel (Ista)	385.2	47.2
Option 2: Tunnel + 55 MW	762	424
Option 3: Tunnel + 90 MW (Ista)	830.2	492.2
Option 4: Tunnel + 55 MW + 90 MW (Ista)	1,207	869

The possible production distribution of the various hydropower options, in relation to the different plant capacities suggested, is presented in Figure 27 below. The blue graph represents the total current energy consumption in Nuuk whereas the area between this graph and the options constitute the difference between demand and production potential. The energy consumption is distributed throughout the year based on the outdoor temperature and the electricity consumption for power using energyPRO. The business as usual (BAU) graph shows the current annual production potential from Kang of 230 GWh. This potential is distributed based on the actual production from the hydropower plant today, which significantly exceed the sustainable withdrawal rate from the reservoir. It can be seen for option one that the energy consumption in Nuuk exceeds the production potential limited by the hydropower capacity of 45 MW during the cold winter period, while there will be a surplus of untapped energy in the warmer summer period. This means that the energy demand cannot be met solely by electricity although, overall, there is an annual surplus of 47 GWh remaining in the reservoir. In contrast, it is clear to see that in option two, three and four there will be a large surplus energy during all periods of the year in relation to the energy demand in Nuuk. Due to the respective capacities of the hydropower plants in each option, the given energy surplus is distributed to other periods of the year, i.e. mainly in the summer, in order to exploit all the energy in the reservoirs.

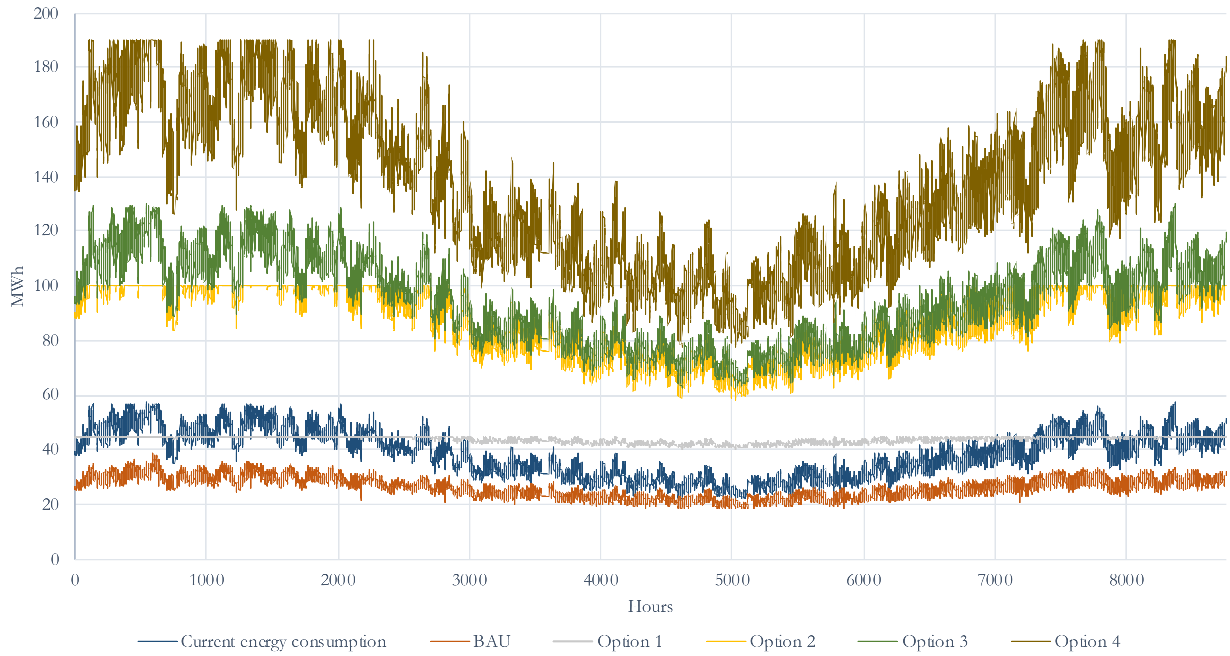

Figure 27: Energy consumption in Nuuk and production potential of various hydropower extension options.

The figure thereby displays the surplus electricity from the various hydropower extension options in Nuuk for every hour during the year that can be utilised for an electrofuel production. This means that the BAU does not leave any room for an electrofuel production, while option one only enables a production during the warmer periods of the year for the initial year of the analysis.

The projected population growth in Nuuk will lead to an increased energy demand in the city and thus reduce the annual energy surplus for the various options. This is taken into account in Figure 28 showing the difference in surplus in year zero and year 20 for the various options. The duration curves display both the highest as well as the lowest energy potential from the respective hydropower option in a given hour of the year. It is evident from the duration curve of option one that it will not be able to supply the expected increased energy demand caused by the increased population by 2043 and in total this deficit accumulates to more than 85 GWh annually. This option is thus not able to provide any long-term surplus electricity and has therefore not be taken further into consideration in regard to an electrofuel production in Nuuk. Meanwhile, the remaining three options will still be able to deliver a surplus every hour of the year despite the increased energy demand.

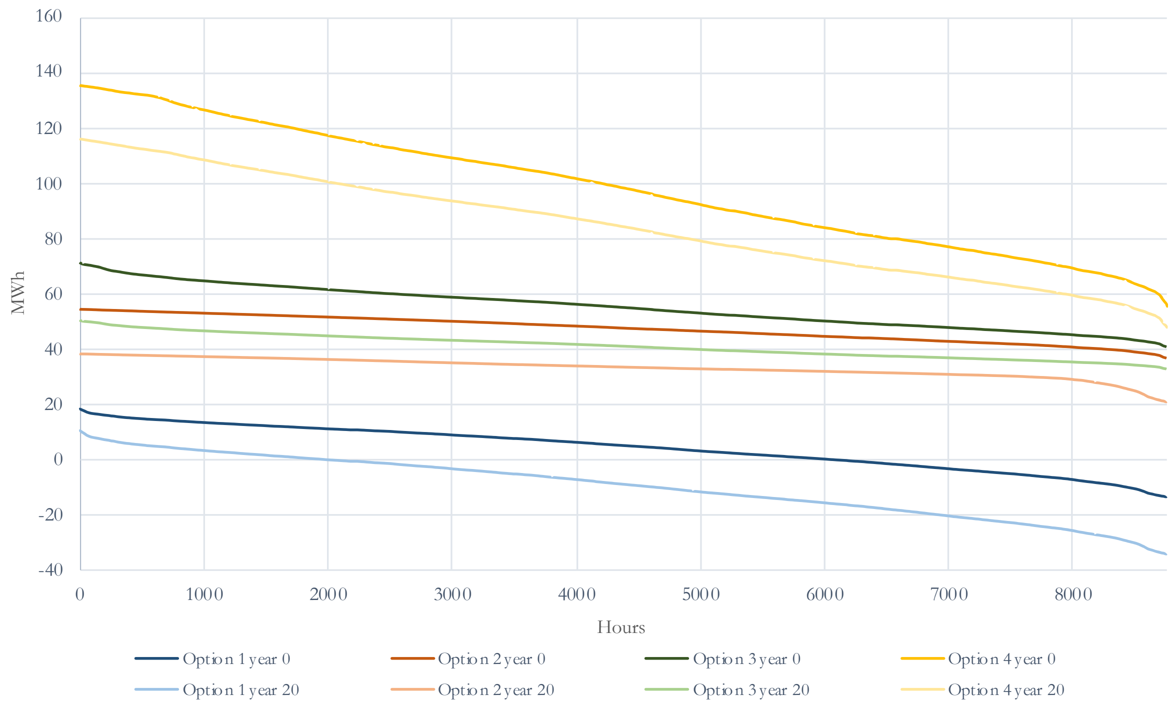

Figure 28: Duration curves for the various hydropower options in year zero and year 20 showing energy surplus with expected population growth in Nuuk.

The electrofuel productions potential of various fuels has been examined based only on CO_2 from the waste incineration plant in Nuuk. These alternatives were not interesting considering the three objectives concerning fuel quantity, self-sufficiency and positive NVP due to the large quantities of unutilised electricity. Therefore, also alternatives assuming an import of CO_2 balanced to meet this unutilised electricity was carried out. Although these alternatives performed better regarding the quantity of fuel produced, these alternatives were likewise out of interest in regard to fulfilment of the governmental objectives.

6.4.2.2 Imarsuup Isua

Imarsuup Isua is due to its huge hydropower potential interesting in relation to an electrofuel production in Greenland. The reservoir is located 130 km from Nuuk and is therefore considered in this context not to be close to the city. This implies, as mentioned earlier, that the excess heat from the PtX process is considered not to be usable for heating in Nuuk. The long distance also means that CO_2 import is required and therefore this scenario only examines the electrofuel production potential with the amount of carbon dioxide needed to exploit the surplus energy from the reservoir. In contrary to the previous section examining the various hydropower extension options from Kang and Ista, this scenario is an interesting alternative in accordance to the three parameters of interest.

The electricity produced from the hydropower plant is similarly to the previous section primarily used to supply Nuuk with its remaining energy demand. This is the energy demand which cannot be met by the existing hydropower plant at Buksefjorden, which is limited to its sustainable production potential of 230 GWh. This means that around 108 GWh from the new hydropower plant is delivered to supply Nuuk, while the remaining 1,170 GWh (see Table 16) can thus be used for an electrofuel production. In the figure below, the most promising electrofuel production opportunities for Imarsuup Isua are presented. These were found to be methanol and ammonia produced separately. The productions are shown along with the best options for Kang and Ista, which were identified not to constitute an interesting alternative, to allow comparison.

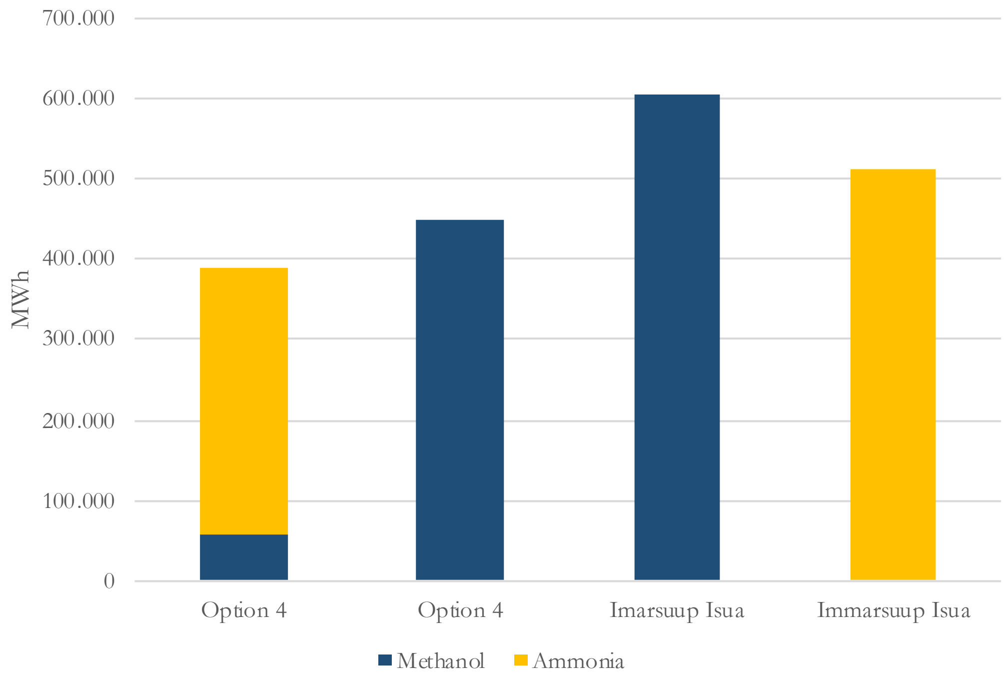

Figure 29: The fuel production of the four best alternatives showing coproduction of methanol and ammonia and methanol individual in option four and methanol and ammonia individually in Imarsuup Isua.

It is evident from Figure 29 that the co-production of methanol and ammonia in option four have the lowest total energy output. Producing methanol with imported carbon dioxide enables the highest energy output in Imarsuup Isua whereas producing ammonia has a lower energy output of more than 90 GWh.

Table 23: Performances of the best alternatives connected to Nuuk, in regard to fuel quantity, self-sufficiency and NPV.

Hydropower option	Electrofuel	GWh/year	CO_2 import/year (kt)	N_2/year (kt)	Self-sufficiency share (GWh/year)	NPV (M€)
Option 4	Methanol/Ammonia	389	0	105	374	-97.6
Option 4	Methanol	449	112	0	337	-69.6
Imarsuup Isua	Methanol	604	150	0	454	-27.5

Imarsuup Isua	Ammonia	513	0	163	513	-86.2

The higher energy output for methanol compared with producing ammonia, makes the production of methanol from Imarsuup Isua identified as the best alternative in connection with the energy system of Nuuk. In Table 23 it is shown that the ammonia production has a better performance in terms of self-sufficiency. Below, the PtX process can be seen utilising the surplus energy from Imarsuup Isua for the production. Due to the long distance between the reservoir and Nuuk, the excess heat from the process is not considered to be able to utilise contrary to the previous scenario of Qaqortoq/Narsaq.

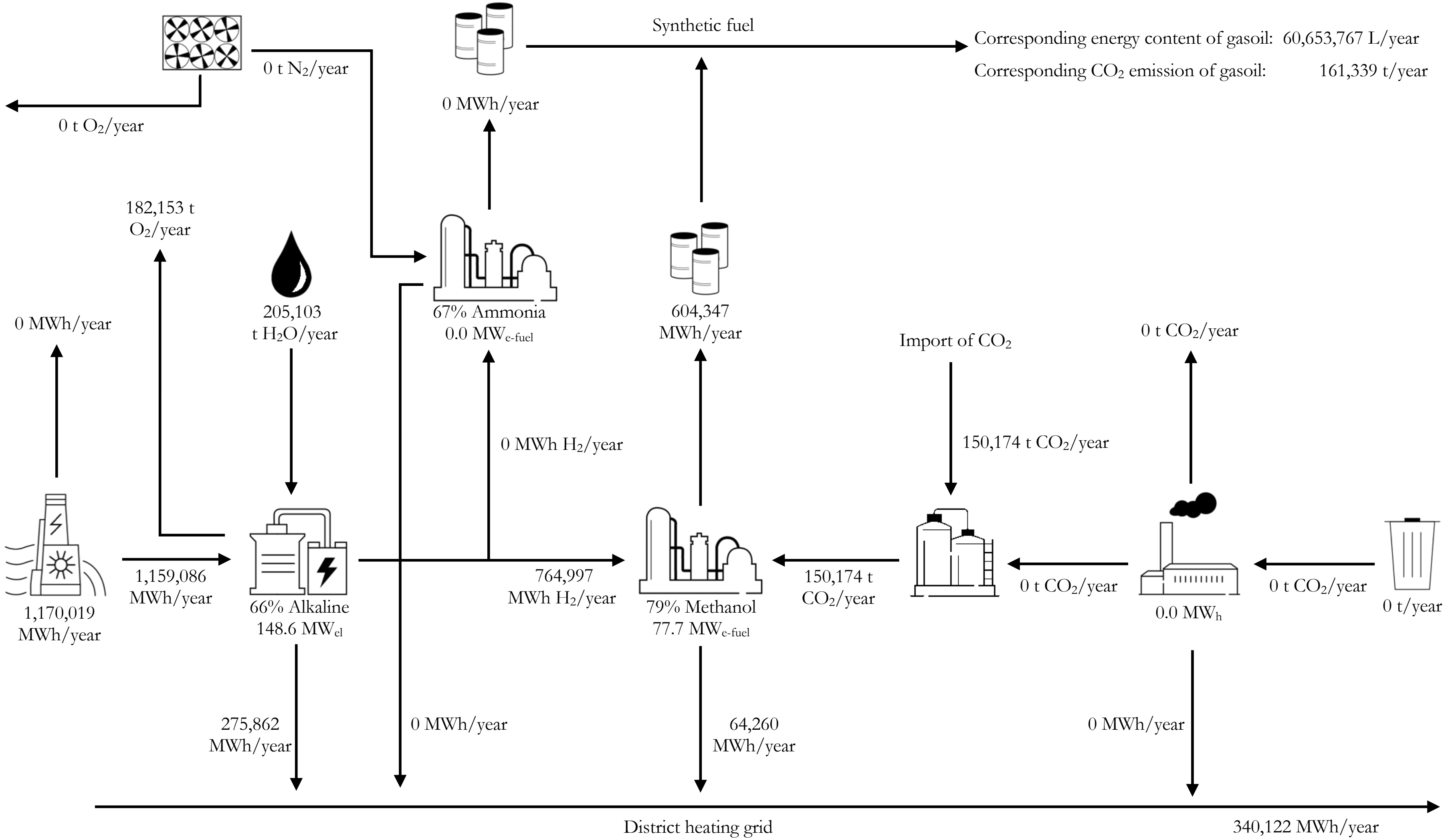

Figure 30: Flow diagram of PtX system from Imarsuup Isua producing methanol.

The production makes possible to substitute a huge amount of fossil fuels from the country's energy consumption, while also significant amount of pure oxygen is released from the electrolyser. This could potentially have been used to optimise the combustion process in the waste incineration plant in Nuuk if this had been located closer by. In Figure 31, a waterfall diagram is presented showing the costs and revenues of the NPV for methanol production based on hydropower from Imarsuup Isua.

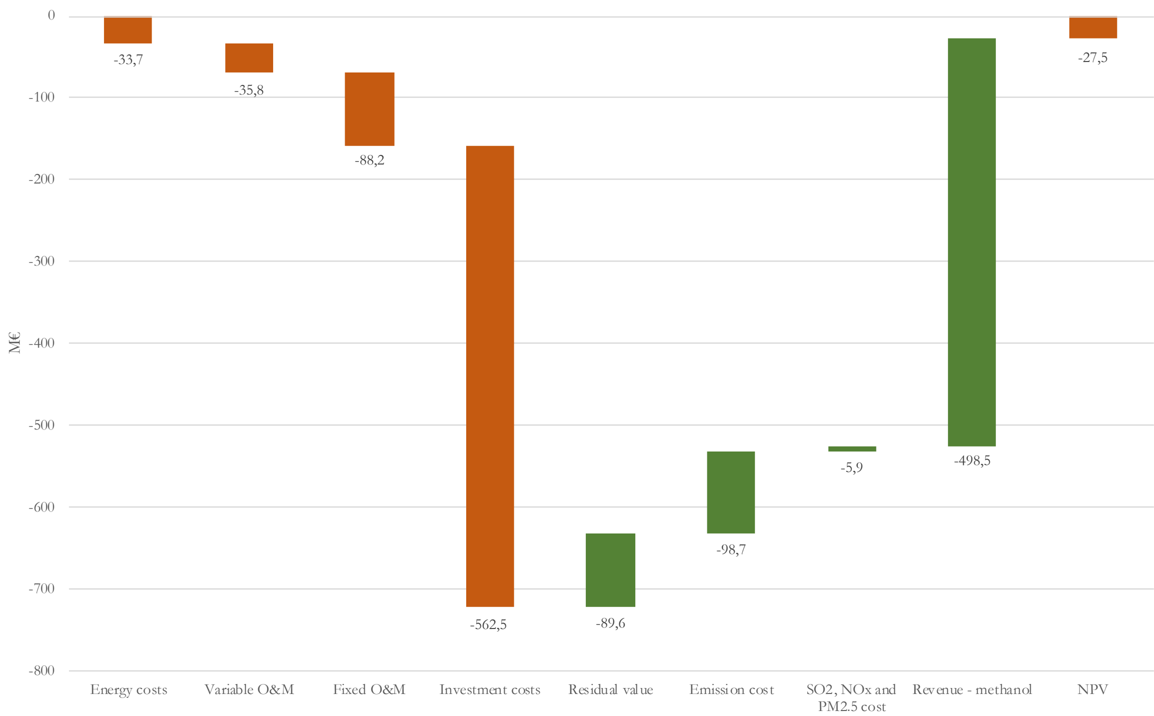

Figure 31: Waterfall diagram of NPV producing methanol from Imarsuup Isua.

Similarly, as for Qaqortoq the tax distortion factor is included in CAPEX and OPEX. Again, it is evident that the investment costs make up the majority of the total costs. Therefore, a cost-breakdown chart visualising the different investments for the methanol production is shown in Figure 32.

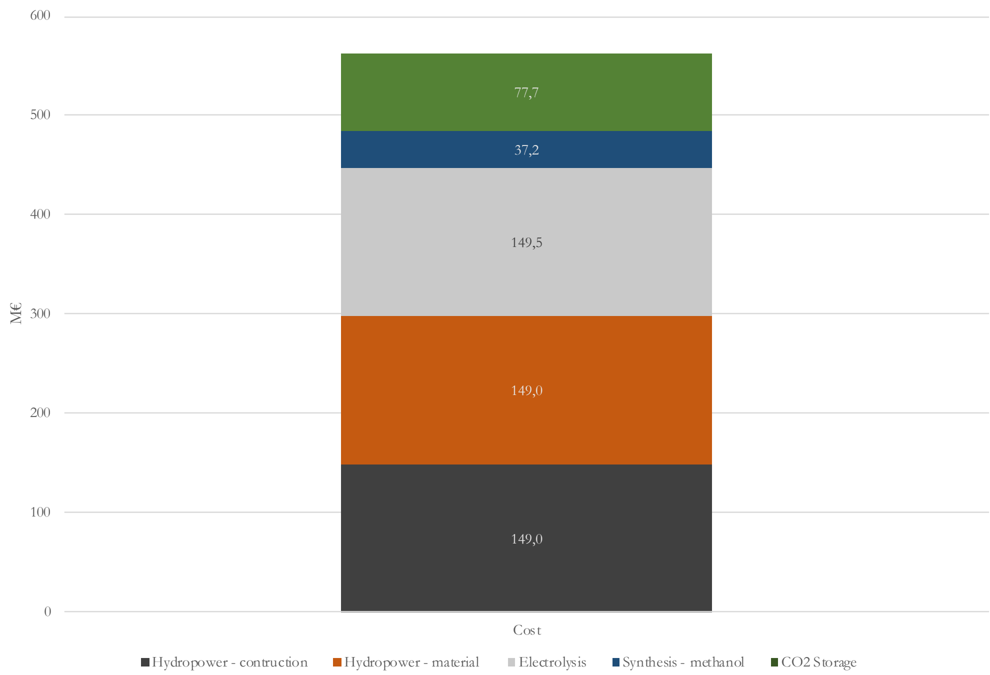

Figure 32: Cost-breakdown chart of different investments for methanol production from Imarsuup Isua.

Also, for this alternative the hydropower investments dominate the total investment accounting for more than half. The PtX system is assumed to have a flexible synthesis, which enables to meet the output from the hydrogen production and therefore no need for hydrogen storage. The long-term marginal cost of methanol was identified to 61 €/MWh for this scenario, which means that methanol will economically beneficial from 2034 and onward compared to gasoil.

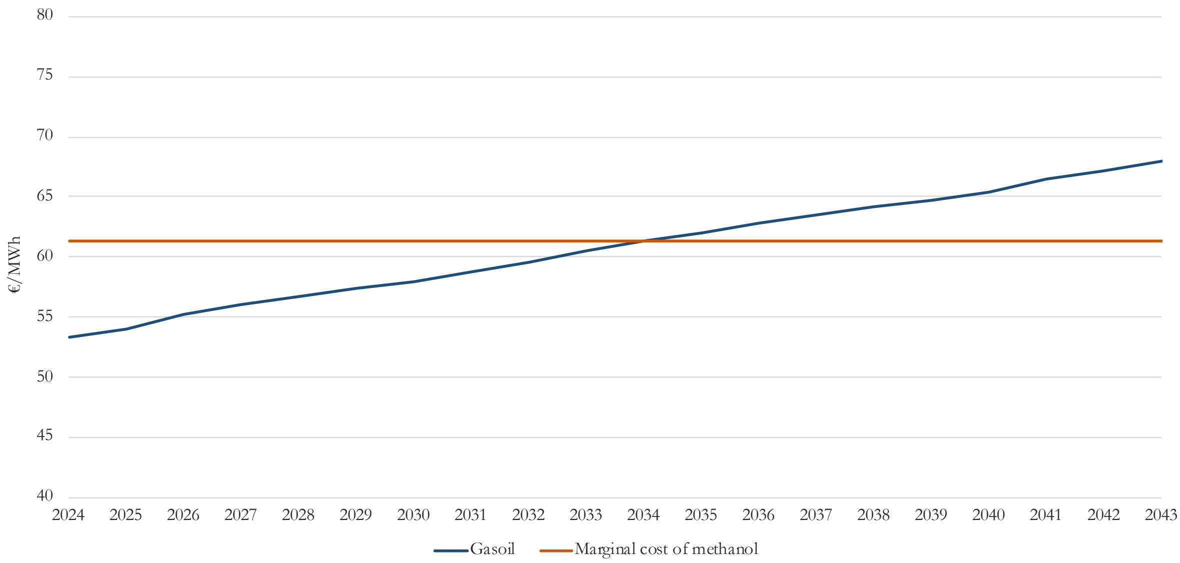

Figure 33: Long-term marginal cost of methanol produced from Imarsuup Isua compared to gasoil.

6.4.3 Maniitsoq

The lake Tasersiaq about 150 km from Maniitsoq constitute the largest hydropower resource in Greenland. This reservoir is therefore likewise very interesting to investigate in relation to an electrofuel production. As the city's energy demand is based exclusively on fossil fuels today, an establishment of a hydropower plant at Tasersiaq should be used to supply both the heating and electricity in Maniitsoq. Similar to Qaqortoq/Narsaq, the population in Maniitsoq are declining by around 1% each year, which means that the city is expected to have a population of 2,000 by 2043 (Grønlands Statistik, 2020b). It is consequently considered that a production of electrofuels from the Tasersiaq reservoir could be stable throughout the entire analysis period. Contrary to Nuuk, there is no major point discharge source of CO_2 and therefore only imported carbon dioxide and nitrogen captured from the ambient air is considered in the following scenario. It should be stressed that since the reservoir is located far from Maniitsoq, excess heat from the PtX process is assumed not to be utilised for district heating.

6.4.3.1 Tasersiaq

As clearly displayed by the figure below, there is an enormous surplus electricity from the Tasersiaq reservoir after supplying Maniitsoq with both electricity and heat. An estimated total production potential of 3,756 GWh enables a 439 MW hydropower plant to operate 8,560 hours a year. In relation to the city's total energy demand, this amounts to a surplus of 3,695 GWh annually, which is distributed over the year to take into account peaks in energy demand and to achieve a full utilisation of the production potential from the reservoir. This leaves a huge unexploited energy potential for the production of electrofuels, as evident from the figure.

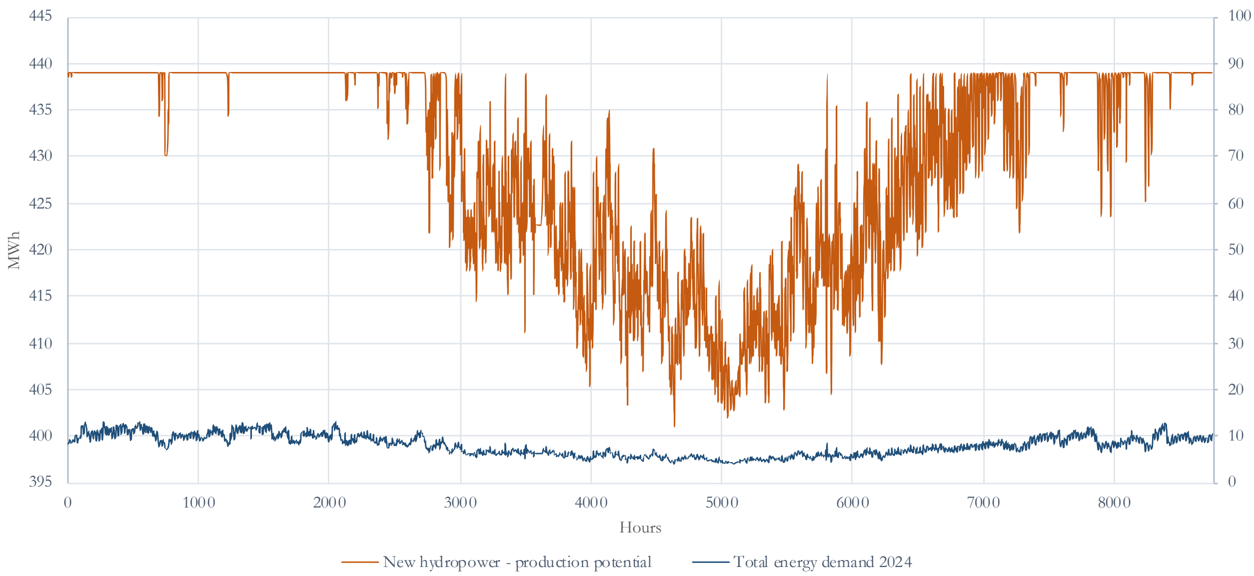

Figure 34: Total energy demand in Maniitsoq in year zero of analysis and the hydropower production potential from Tasersiaq reservoir.

The possible production volume for the various electrofuels utilising all surplus electricity from Tasersiaq is presented in Figure 35. It can again be seen that it is possible to produce more methanol, while a Fischer-Tropsch diesel production will cause the least number of MWh annually. Due to the population decrease, these quantities can be produced continuously over the analysis period.

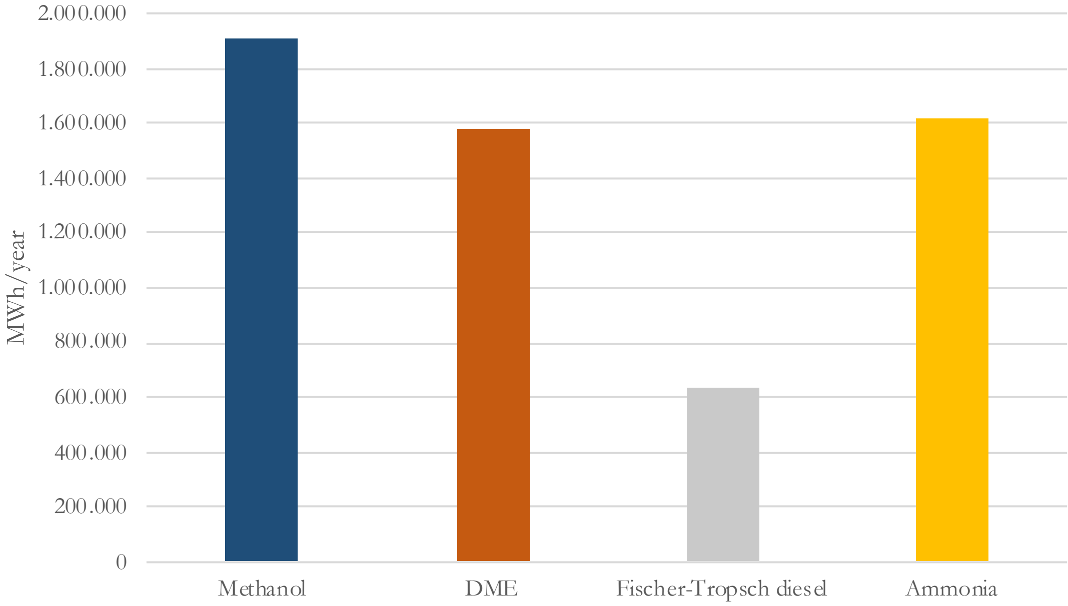

Figure 35: Potential electrofuel production from the Tasersiaq reservoir.

Similar to the productions in Qaqortoq/Narsaq and Nuuk, methanol enables the highest production of energy. DME and ammonia are almost producing the same quantity whereas the production of Fischer-Tropsch diesel is below half of the energy output from DME. In order to utilise the entire surplus of electricity for an electrofuel production, large quantities of imported carbon dioxide or nitrogen captured from the ambient air using an ASU is required. The exact production quantity of the various electrofuels as well the amount of CO_2 and nitrogen needed for the respective productions are presented in Table 24 below together with the degree of self-sufficiency and the NPVs in accordance to the three criteria.

Table 24: Quantity of electrofuel possible to produce from Tasersiaq and required CO_2 and nitrogen for the production.

Electrofuel	GWh/year	CO_2 import/year (kt)	N_2/year (kt)	Self-sufficiency share (GWh/year)	NPV (M€)
Methanol	1,909	474	0	1,434	260.1
DME	1,577	375	0	1,202	22.3
Fischer-Tropsch Diesel	633	201	0	432	-734
Ammonia	1,620	0	516	1,620	12.5

The performance of the alternative producing methanol from Tasersiaq is identified as the best solution on the basis of the criteria. The production of ammonia performs less good in regard to fuel quantity and NPV, while performing better in terms of self-sufficiency. However, the overall performance of methanol is found to be more beneficial while also exhibiting the greatest NPV. The flow diagram below displays the integration of the PtX system at Tasersiaq including capacities of the various units as well excess heat from the process etc.

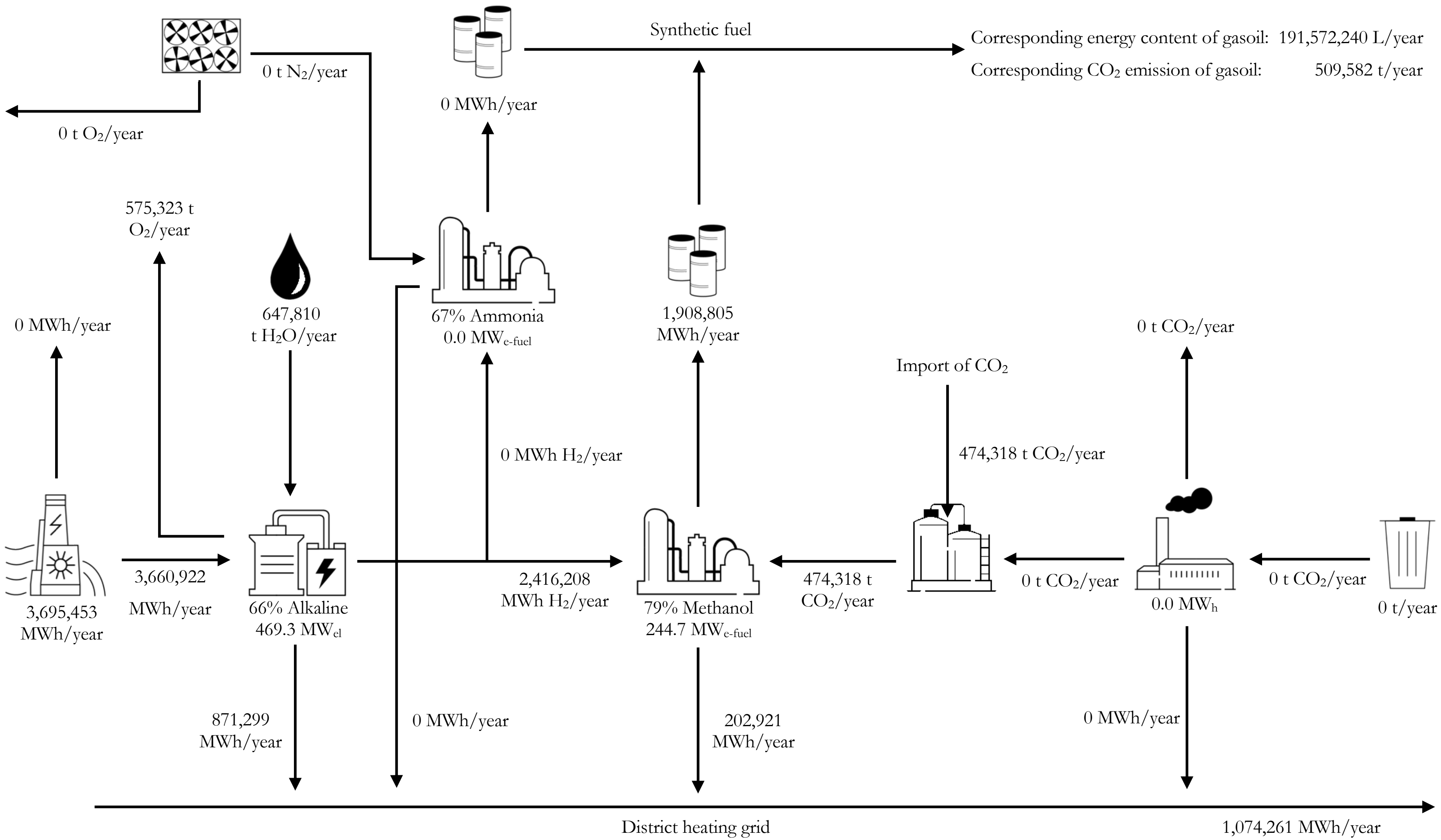

Figure 36: Flow diagram of the PtX system from Tasersiaq producing methanol.

As evident from flow diagram, a large amount of fossil fuels is displaced by this methanol production, while also a large amount of heating could potentially be utilised. This is however considered not to possible due to the long distance between the Tasersiaq reservoir and Maniitsoq. The NPV for the methanol production from Tasersiaq is presented in the as waterfall diagram in Figure 37.

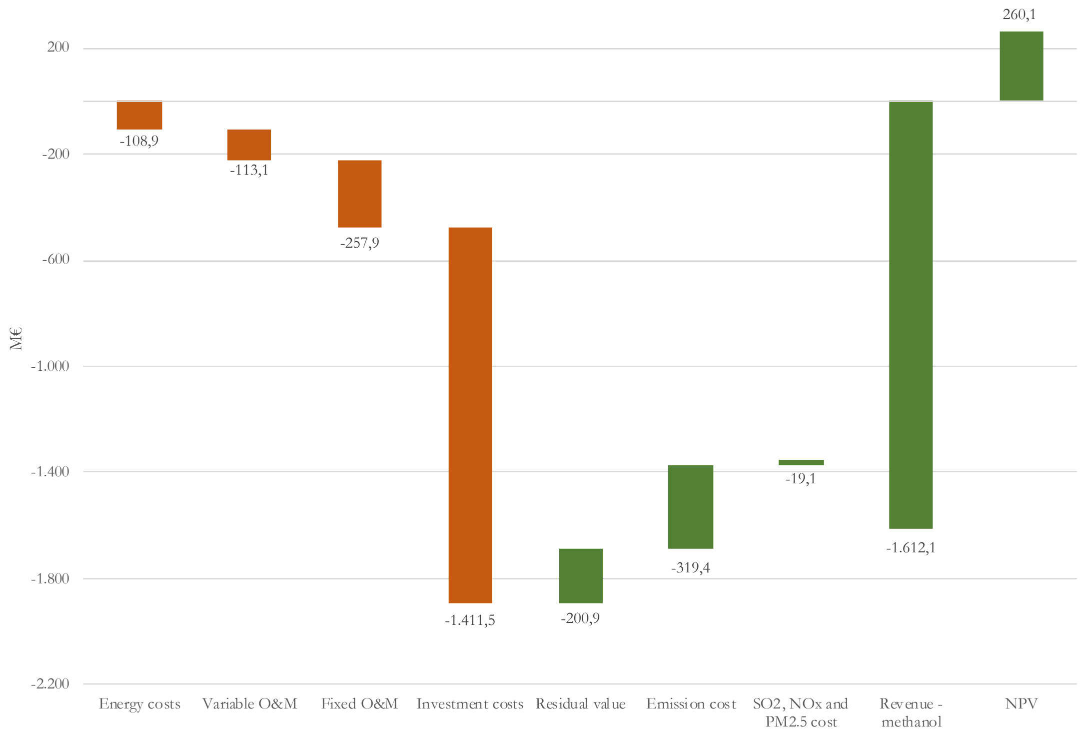

Figure 37: Waterfall diagram showing the costs and revenues for producing methanol in connection to Maniitsoq.

The methanol production from Tasersiaq generates a positive NPV whereas the saved expenses almost equals the investment costs. However again the investment costs clearly constitute the most significant part of the costs. Therefore, these are shown in a break-down chart in Figure 38 in order to identify the largest shares of costs.

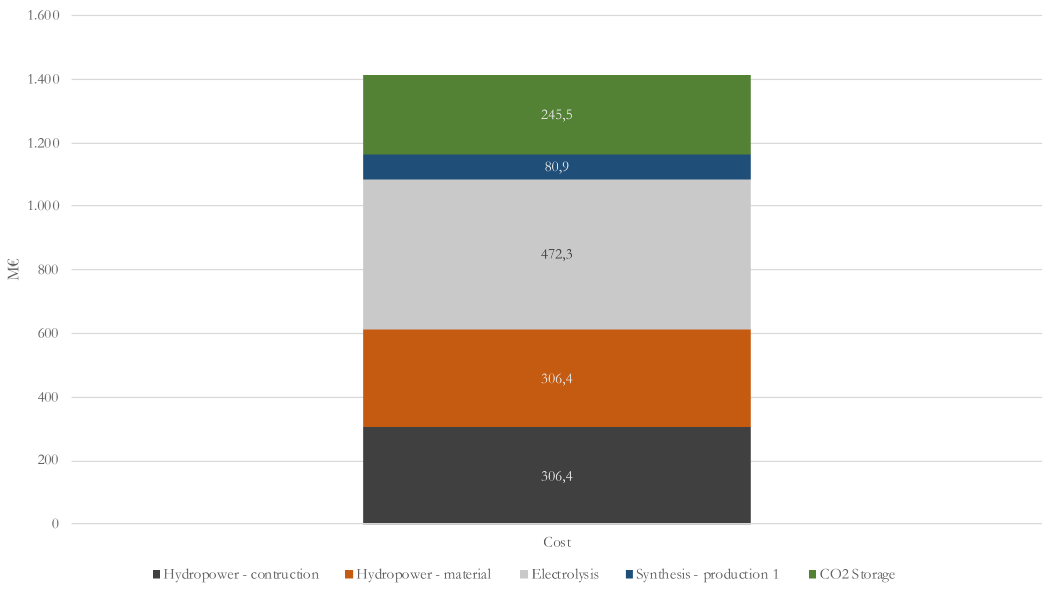

Figure 38: Cost break-down of investment costs producing methanol from Tasersiaq.

Again, the total hydropower investments constitute the largest share of investments. However, in this alternative both the electrolysis and storage capacity constitute almost the same share as the hydropower each. This production has a positive NPV and is competitive with the cost of gasoil presented in Figure 39. The Long-term marginal cost of 50 €/MWh for producing methanol from Tasersiaq is compared to the gasoil price in the figure below. As evident, this scenario constitutes a very interesting opportunity.

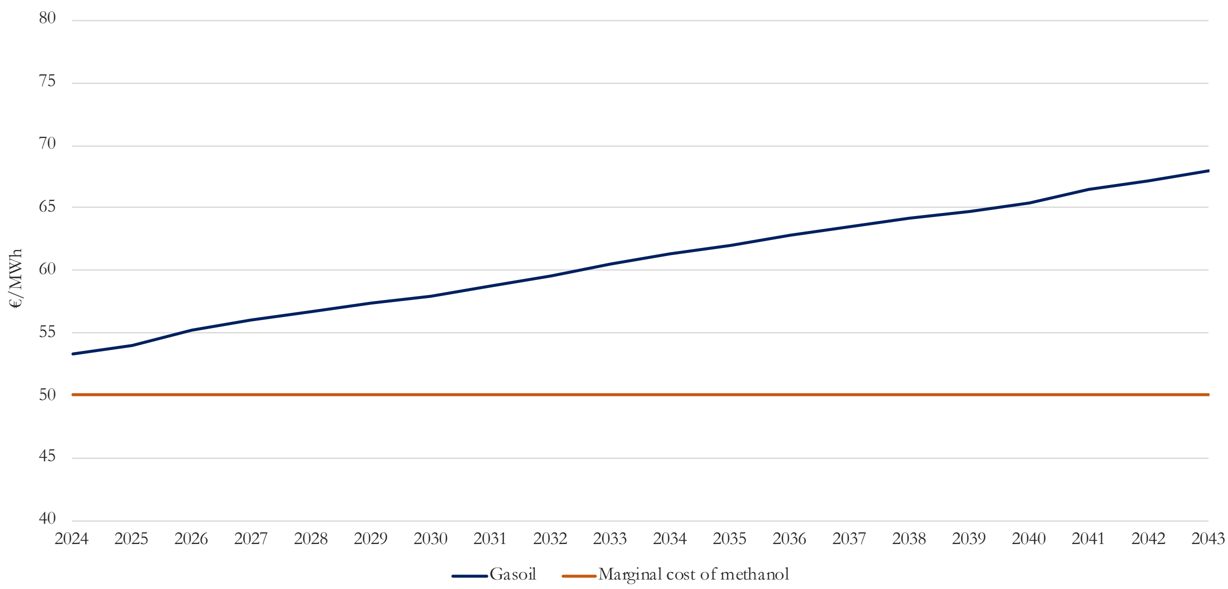

Figure 39: Marginal cost of methanol produced from Tasersiaq compared with the cost of gasoil.

6.5 Results and sensitivity analysis

The electrofuel production potential in Greenland has based on the most interesting hydropower potentials identified been examined. With the purpose of answering the research question of this master's thesis, the following will evaluate the three most promising alternatives identified above in regard to how electrofuels from hydropower can help Greenland meet their renewable energy goal in 2030. This will be followed by a section examining the sensitivity of the economic results.

6.5.1 Results

In relation to the scenario of Qaqortoq/Narsaq, the most promising electrofuel production was identified to be methanol although ammonia is a larger contributor to increase the self-sufficiency degree in the country. This is because of the larger production volume of methanol compared to ammonia and because of its higher NPV compared. The diagram below displays the national primary energy supply with a methanol production in Qaqortoq/Narsaq producing 112.5 GWh annually. It can be seen that a production of this scale can contribute to supply 5% of the total demand for energy in Greenland. In addition, it can be seen that the share of energy from hydropower has increased to 18% from 15% previously. This is due to the conversion to electricity in the two cities from the new hydropower plant at Johan Dahl Land in this scenario.

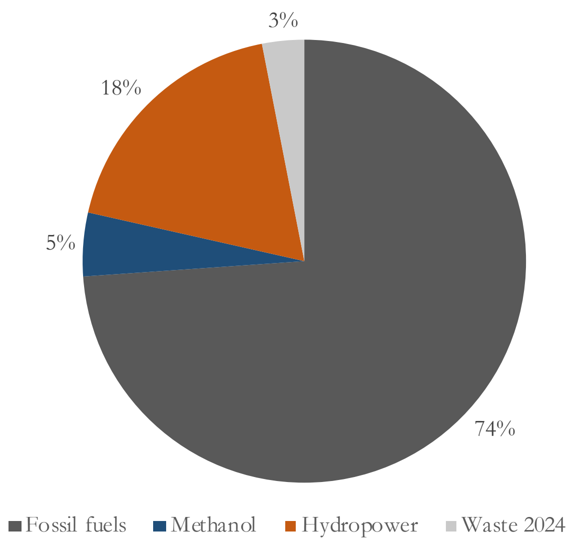

Figure 40: New total primary energy supply in Greenland when establishing a methanol production in Qaqortoq/Narsaq.

Totally, this means that the share of renewable energy as well as the self-sufficiency degree in the country increases by 8% from before. It can thus be deduced that a such methanol production in Qaqortoq/Narsaq to a lesser extent can contribute to help Greenland meet their governmental objective of being supplied by renewable energy sources to the widest extent possible by 2030.

In regard to the methanol scenario at Imarsuup Isua identified to be the most promising for Nuuk, it is clear that this opportunity has a larger impact on both the country's TPES as well a lesser negative NPV compared to ammonia. It was found that this production is capable of producing 604 GWh of ammonia a year, which amounts to 25% of the total energy demand. Simultaneously the conversion of the remaining energy demand in Nuuk from fossil fuels to electricity from the new hydropower plant at Imarsuup Isua increased the share of electricity from hydropower to 20%.

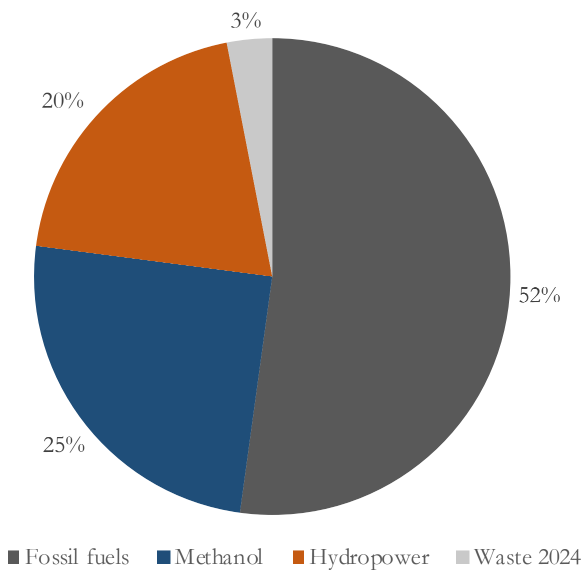

Figure 41: New total primary energy supply in Greenland with a methanol production from Imarsuup Isua near Nuuk.

A methanol production from Imarsuup Isua near Nuuk will overall mean that the share of renewable energy and the self-sufficiency degree in Greenland rises to 48% from 18% today. This is a relatively large increase and this opportunity thereby constitute an interesting possibility for Greenland. However, this scenario displayed a negative NPV of -27.5 M€.

The last and largest scenario treated in the analysis is the potential of an electrofuel production from Tasersiaq close to Maniitsoq. Here methanol was likewise found to be the most optimal electrofuel to produce. This scenario enabled a production of 1,909 GWh of methanol, which together with the conversion to electricity in Maniitsoq results in an almost full substitution of the gasoil in Greenland leaving a demand of only 799 MWh remaining in the energy demand.

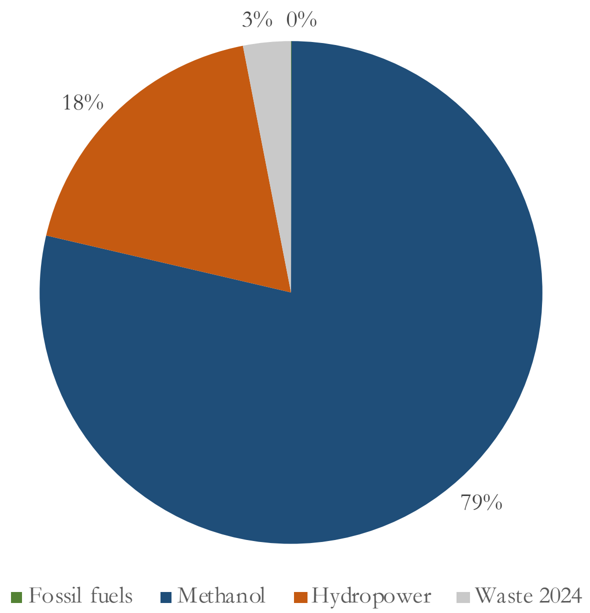

Figure 42: New total primary energy supply in Greenland with a methanol production from Tasersiaq.

Thereby, the energy demand in Greenland will almost be entirely covered by renewable energy with 79% of the TPES supplied by methanol. However, this is not the case in terms of self-sufficiency degree as only a proportion of the methanol production will strengthen this due to the need to import CO_2 for the methanol production. This means that country's degree of self-sufficiency will be 80% while the remaining 20% is attributable to the need for external CO_2 import.

6.5.2 Sensitivity analysis

In the following section sensitivity analysis are carried out in order to test the robustness of the three electrofuel productions of concern. As mentioned in Chapter 3 Lund (2014) suggests that the sensitivity analysis are performed on technical, institutional and political parameters. Testing the sensitivity of CAPEX and OPEX represents technical analysis where uncertainty related to the performance and development of the newer technologies is addressed. The political and institutional parameters are embedded and addressed in the other tested variables e.g. the discount rate and tax distortion factor are politically decided by the governing institutions.

In relation to this market institutional barriers should be identified in accordance to step three of Choice Awareness also to test the robustness of the results. These barriers are equal to the difference between the results of the socioeconomic feasibility study and the private economic feasibility study. In the analysis conducted in this study, the difference between the socioeconomic and the private economic feasibility study is composed of the taxes attributed to the consumption of gasoil, the tax distortion factor of 15% as well as the emission cost of carbon dioxide equivalents. In the table below, the difference between the results of the private economic and socioeconomic feasibility study conducted is presented.

Table 25: Identified market institutional barriers for the three scenarios of concern.

	Socioeconomic result (M€)	Private economic result (M€)	Market institutional barrier (M€)
Johan Dahl Land	-11.8	-8.3	-3.5
Imarsuup Isua	-27.5	-32.2	4.7
Tasersiaq	260.1	187.9	72.2

As evident for the scenario concerning Johan Dahl Land reservoir, the private economic result is less negative compared to the result of the socioeconomic. This is because the investment cost associated to the socioeconomic feasibility study is higher compared to the private economic feasibility study due to the tax distortion factor. Moreover, the fuel price of gasoil in the private economic feasibility study is subject to tax, which is not the case in the socioeconomic, making the saving for displaced gasoil is higher in the private economic study. This means in this case that it is more advantageous to save gasoil in the private economic study compared to the socioeconomic study. However, in relation to the larger scenarios of Imarsuup Isua and Tasersiaq the CO_2 equivalent cost imposed has a major impact on the socioeconomic performance as very large amounts of carbon dioxide are displaces in these scenarios causing the performance of the socioeconomic study better compared to the private. As, previously explained in Section 4.4, including emission costs of carbon dioxide in socioeconomic feasibility studies is not normal procedure in Greenland and this method will therefore be discussed in Section 7.2.2 of the discussion. It can therefore be inferred that the taxes associated to gasoil, the tax distortion factor as well as the costs of emitting CO_2 equivalents constitute a potential market institutional barrier in relation to a realisation of these projects, respectively.

In the following figures, sensitivity analysis of central parameters concerning the methanol production in the various scenarios are presented.

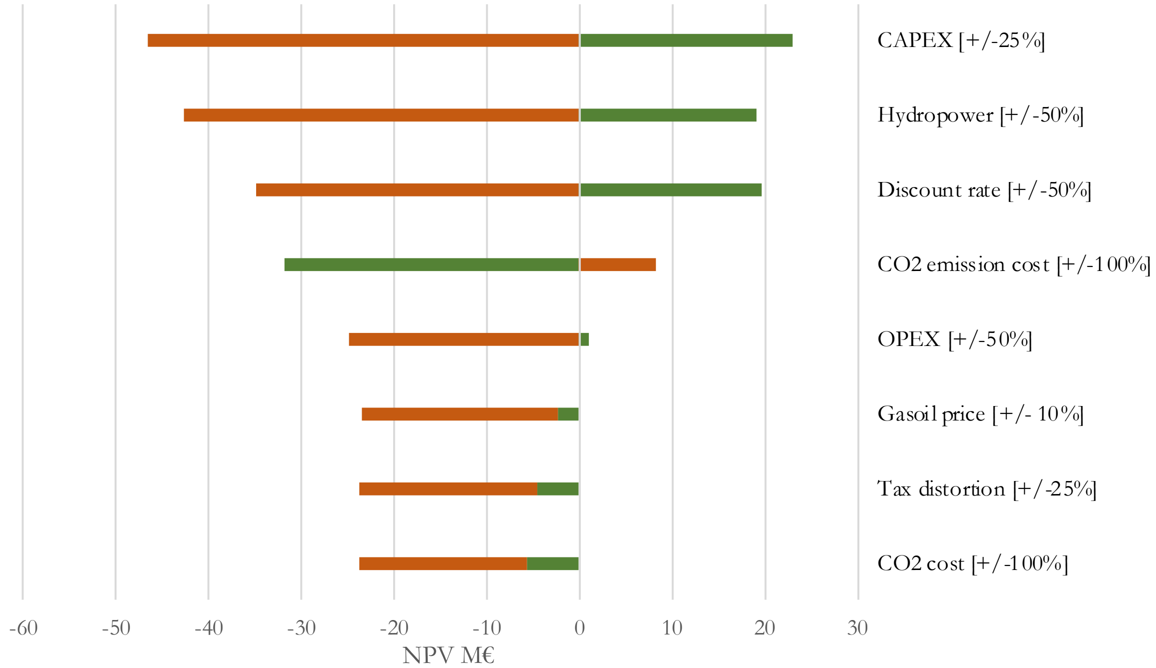

Figure 43: Sensitivity analysis of central parameters concerning methanol production in Qaqortoq from hydropower plant Johan Dahl Land.

The reference value of the sensitivity analysis for Qaqortoq was a negative NPV of around -12 M€. It is clear from Figure 43 that the methanol production is most sensitive to changes of CAPEX, the hydropower investment and the discount rate. The hydropower investments are known well however it might be a political decision to decide exactly how the investment structure of a hydropower plant can be performed.

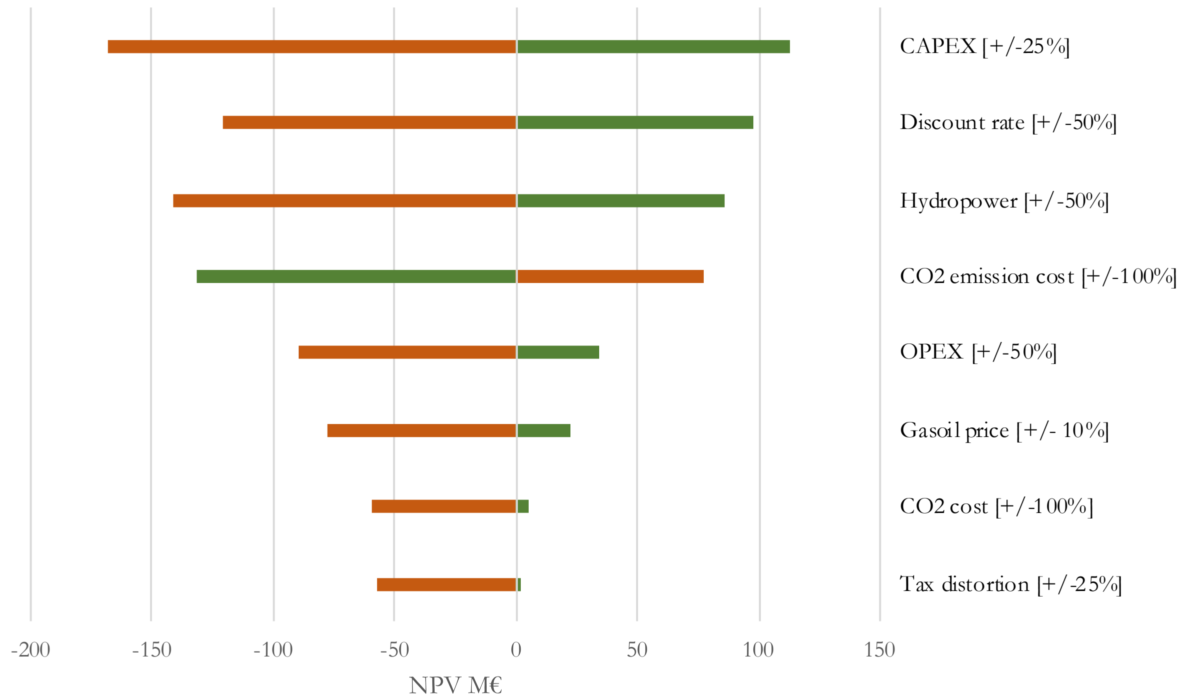

Figure 44:Sensitivity analysis of central parameters concerning methanol production from the hydropower plant Imarsuup Isua in connected to Nuuk.

The reference value producing methanol from Imarsuup Isua connected to Nuuk was NPV of around -28 M€. All of the seven examined parameters presented in Figure 44 are able to turn the project positive. However, it requires a reduction of the examined parameters. The analysis shows predominantly negative generation of the NPVs.

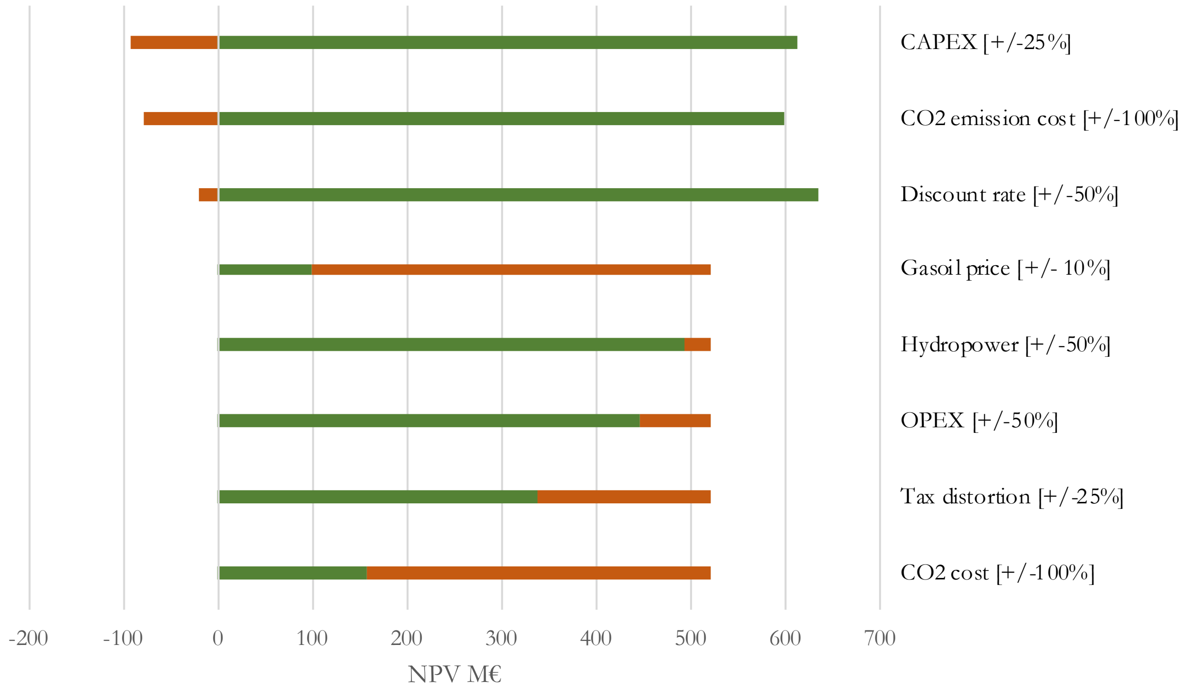

Figure 45: Sensitivity analysis of central parameters concerning methanol production from the hydropower plant Tasersiaq in connection to Maniitsoq.

The reference value for methanol production from the Tasersiaq hydropower plant connected to Maniitsoq was around 260 M€. In Figure 45 most predominantly part of tested parameters is positive. However, increasing CAPEX and discount rate as well as setting the CO_2 emission cost to zero will cause negative NPVs. The methanol production implies a dependence on imported CO_2 and therefore the cost of CO_2 is included as parameter for this sensitivity analysis. It shows however that doubling the cost of CO_2 would still make the production positive.

7. Discussion

Throughout the analysis the best electrofuel production potential in relation to Qaqortoq/Narsaq, Nuuk and Maniitsoq has been identified. This has been carried out through evaluation based on the objectives from Naalakkersuisut concerning integration of more renewable energy, increasing the degree of self-sufficiency through energy related investments improving the socio-economy in Greenland. Therefore, in order to address other possible challenges implementing such electrofuel productions, the results of the analysis will be discussed along with the greatest uncertainties and limitations. This will be followed by a discussion of regulatory and organisational barriers.

7.1 Discussion of results

The results from the analysis are concerning large productions that enables improvement of the aforementioned objectives from Naalakkersuisut. However, all of the results are based on the assumption that the produced electrofuel can be applied in the energy systems in Greenland. Based on interviews with professor Jesper Scramm from Danish Technical University, Klaus Petersen from MAN Energy Solutions and Tage Lindegaard and Bjarne Lykkegaard from Polaroil combined with statistical data from the Ministry of Industry, Energy, Research and Labour the possible substitutions without performing any major alteration of the current infrastructure are presented in Table 26. Note that it is elaborated in Appx. 10.6.

Table 26: Potential of substituting domestic fossil fuels without alteration or new investments.

Electrofuel	Potential domestic substitution of fossil fuels without alterations
Methanol (GWh)	5.8
Ammonia (GWh)	0

The 5.8 GWh methanol represent the possible blend allowed of 3% methanol into gasoline. The regulatory framework in this regard will be further discussed in the section of regulatory and organisational barriers (Section 7.4). Ammonia cannot fit into the current energy infrastructure without carrying out alteration or new investments.

It should be stressed that the potentials presented in Table 26 are only concerning compatibility with the current energy infrastructure in Greenland as it is today. Therefore, in order to utilise the electrofuels produced in the three scenarios presented in the energy system in Greenland, either some alteration or new investments in energy consuming units should be carried out. According to Petersen (2020), modifying an existing power generator in Greenland today would be around the same cost as investing in a new generator running on methanol. This is assumed to be the same case for ammonia. Therefore, modifying existing power and heating generators is not considered a feasible way to introduce electrofuels in the energy system of Greenland if it is desired to do the implementation in the most cost-efficient way. However, the methanol production from Tasersiaq could generate a positive NPV of 260 M€ which could contribute to modify existing infrastructure.

In order to avoid new investments in the current infrastructure and make electrofuels operative in the energy system, it is considered more feasible to invest in heat and power generators when existing conventional generators are to be replaced anyway. This would however be a moderate introduction of electrofuels and also a gradual fulfilment of the governmental objectives. A slow-paced conversion of the infrastructure could also imply gradually lower costs of methanol or ammonia engines and generators due to technological refinement, which both Petersen (2020) and (Scramm, 2020) are researching. Such gradual conversion would imply that the other quantities should be sold elsewhere in order to make the results of the analysis valid. This would imply only a gradual national improvement of the share of renewable energy and degree of self-sufficiency. Therefore, the results from the analysis will first be valid when a transition sufficient enough to accommodate the quantity of electrofuel produced has taken place.

As mentioned, the Swedish ferry Stena Line is already running on methanol with the two-stroke dual-fuel engine delivered by MAN ES. Such cases could increase the demand for methanol and make export possible or maybe even Greenlandic shipping companies could have an interest in converting their coaster to run on methanol. It is stressed by Methanol Institute (2020) that the methanol can be used in other sectors to produce plastic, glue and paint etc. The prospects for exporting ammonia could even be better compared to methanol as there are already a well-established international market where ammonia is shipped worldwide for the production of fertilisers and used as refrigerant.

7.1.1 The best alternatives

Throughout the analysis the three main objectives from Naalakkersuisut (2017) has been weighted equally and all alternatives has been compared based on the performance of these objectives. Production of methanol has in all three cases shown to be the most advantageous electrofuel to produce in accordance to the criteria. Especially the methanol production from Tasersiaq contributes positively on each of the objectives where the productions connected to Qaqortoq and Nuuk both have negative NPVs. However, the applied simplified methodological approach may leave out nuances relevant to consider. It is therefore important to stress that this simplified selection should not be the decisive parameter alone. In general, methanol performed better in terms of energy produced and NPV whereas producing ammonia contributes more in relation to the governmental objective of increasing the degree of self-sufficiency. The NPV has been weighted on equally terms to the two other objectives favouring alternatives with higher. However, if weighing increased self-sufficiency higher would cause an ammonia production to be favoured. It was found that an ammonia production could constitute 67% of the total national energy supply with a positive NPV of 12.5 M€, as previously presented (Section 6.4.3.1). In the declaration of national objectives in regard to public energy and water supply by Naalakkersuisut (2017), it is only a requirement that the alternative of concern has a positive NPV. Therefore, the higher increase of self-sufficiency from an ammonia production may be of more importance for the society of Greenland compared to the higher NPV of the methanol production.

Also, other aspects are relevant to discuss in relation to the two fuels methanol and ammonia. Producing ammonia can prevent the national dependence of CO_2. However also CO_2 emissions can be avoided as the only emissions from ammonia is nitrogen and water vapor (see Section 5.4.4). As ammonia are produced from renewable hydropower in all of the examined scenarios, this electrofuel is carbon neutral. The source of carbon dioxide used for the methanol production are determining for the climatic impact. When capturing CO_2 from a waste incineration plant, a share of the CO_2 is fossil carbon dioxide which means that the proportion of CO_2 in the atmosphere will increase. One may argue that this is not caused by the electrofuel but rather the fact that waste is generated and incinerated. This perspective might be valid however it is argued by Geels (2019) that such practices can create a lock-in. A situation of a lock-in is where status quo is maintained concerning innovation in existing systems and regimes and only enables incremental and path-dependent changes (Geels, 2019). Carbon capture at a waste incineration could be the incremental improvement where the CO_2 consumption from the methanol production helps locking the system. It should be mentioned that using direct air capture for producing carbon-based electrofuels would be categorised as being CO_2-neutral like CO_2 obtained from biomass, if the energy used is from renewable energy sources (Dinca et al., 2018).

Both methanol and ammonia possess threats to human health if one is being exposed to high concentrations and entails some safety measures to consider. Ammonia might be the most toxic fuel compared to methanol and should be handled by professionals. However, ammonia is a well-known product across several sectors, therefore experiences has already been transformed into precautionary measures such as doubled walled storage tank and pipes as well as monitoring measures and ventilation (see Section 5.4.4).

7.2 Uncertainties of results

Throughout the analysis the assumptions and prerequisites applied has been kept conservative in order to lower the uncertainties. Therefore, some economic parameters may be less costly compared to the figures applied however also vice versa. In order address the most uncertain parameters of the analysis, these will be discussed in the following.

7.2.1 CO_2 import and availability

All of the methanol productions presented throughout the analysis are assumed to be supplied and dependent on imported CO_2. The first uncertainty to address is whether it is possible to find a well-established supplier of CO_2 in these quantities of concern. Firstly, if ARC will make a full-scale carbon capture, they would be able to supply the needed quantity of CO_2 in all cases of the scenarios examined. Secondly, as described in the SOA chapter the focus on carbon capture has in general increased in recent years and is expected to increase further due to the reports from European Commission (2019), IRENA (2019a), CCC (2018) and IEA (2019) amongst others. It is therefore considered possible to find a permanent supplier of CO_2. However, this is still an uncertain parameter. Next uncertainty is regarding the cost of CO_2 which is considered to have great level of uncertainty. As this cost has not been possible to detect through reports or scientific articles, the estimate is solely based on the article from Wittrup (2020). Therefore, this parameter has been included in the sensitivity analysis where the price of CO_2 is doubled. The doubled price of CO_2 only shows a positive NPV producing methanol from Tasersiaq.

7.2.2 Emission cost uncertainty and inclusion

The CO_2 emission costs is an attempt to represent the damage that CO_2 equivalent emissions are expected to entail (Danish Energy Agency, 2018b). Global impacts and abstract feedback mechanisms however makes the quantification of future damage cost extraordinary difficult to estimate. Therefore, such projections are inevitably subject to some uncertainty. In the sensitivity analysis it is clear that all of the three alternatives are affected by removing the emission cost and it makes each of the methanol productions turn negative in terms of NPV. The CO_2 emission cost has been included in the socioeconomic analysis although it is usually not the procedure when performing socioeconomic analysis in Greenland. It is however stressed by both Boardman et al. (2011) and Danish Energy Agency (2018) to include and is moreover considered a helpful measure for fulfilling the Greenlandic objective of implementing more renewable energy. However, such inclusion is considered important to highlight as it is not part of the usual procedure in Greenland in order to ensure transparent results.

7.2.3 Fuel cost projections

The revenue of substituted fossil fuel is calculated by applying the alternative cost which is assumed to be gasoil. The projections of the gasoil price therefore constitute a central part of the socio-economic evaluation. The projections are made on the basis of historical data concerning imported fuel and price differences as well as estimates concerning additional price charges and deductions (Danish Energy Agency, 2019a). As presented in the sensitivity analysis the results are highly sensitive to the gasoil price. This is especially clear in regard to the production from Tasersiaq, which shows that when the gasoil price is reduced by ten percent, the societal surplus of the PtX production is reduced significantly. These projections are considered being reliable however it is still projections.

7.2.4 Development of technologies

From the sensitivity analysis it is clear all of the productions that the results are sensitive to CAPEX. The hydropower investment constitutes the greatest share. However, this cost is not considered to be related to any extraordinary level of uncertainties. In contrast, the investment costs of the PtX technologies are considered to be an uncertain parameter, although these costs are based on a comprehensive review. The uncertainty is related to the state of commercial immaturity that several of the technologies are in. However also the cost reductions are difficult to project. Such reductions could make changes in the economic results but also change the scenarios fundamentally e.g. if the costs of DAC (see Appx. 10.2.5) is drastically reduced, the aspects of self-sufficiency degree and climate impacts, concerning methanol, would improve significantly. These uncertainties also play a major role in regard to how fast commercial methanol and ammonia engines will be available on the market. And thereby how fast the produced electrofuels could be applied in the energy system.

7.3 Limitation of analysis

As the scope of this study has been focused on the role of electrofuels only, other energy technologies or energy savings has not been considered at all. Energy savings, however, might be a favourable investment to carry out. Also, it could be interesting to examine whether the hybrid plants consisting of windmills, photovoltaic and batteries could complement the use of electrofuels in the settlements. However only energy from hydropower has been considered in this study.

Also, alteration has been partly limited from this study for several reasons. Firstly, the alteration costs identified in the comprehensive literature review has only been concerning alteration of a refuelling station. Thereby some major assumptions would have been required in order to quantity the costs, which would have increased the level of uncertainty of the various results. Secondly, performing alteration is not considered to be the most cost-effective way of integrating. Instead a gradual implementation proportional with the replacement of old engines and generators would be suggested if possible. For these reasons it is not considered as a drawback of this study.

In order to follow the Choice Awareness research method an environmental impact assessment should be carried out (Lund, 2014). This is also a requirement according to Naalakkersuisut (2017) in order to be a part of the decision-making process. However, such environmental impact assessment is considered being highly important in order to illuminate all consequences of the examined alternatives.

7.4 Regulatory and organisational barriers

In accordance to step three of the choice awareness theory, the public regulatory framework and potential barriers are examined in this section including a discussion of improvements to consider. The section is primarily based on the conducted interview with Allan Bertelsen from the Ministry of Energy, Industry, Research and Labour supplemented by reports and articles.

As PtX is a relatively new technology that has not yet been widely commercialised, nor widely tested in arctic conditions, the Government of Greenland is not ready to invest in and thus take the financial risks of being a first-mover of such solutions yet due to their responsibility towards the management of public funds paid by taxpayers. It is thus necessary that knowledge and experience of technology and economics from other projects is shared across nations as such partnerships would help the management of risks, as also proposed by IEA (2019) and IRENA (2019). Subsequent projects would benefit significantly from exchanging best practices. Moreover, as stressed by (Naalakkersuisut, 2017), it is important that the project has a positive NPV as decision-makers and citizens will otherwise be particularly sceptical about the project unless is displaces a large amount of CO_2. It is worth noting that some of the scenarios examined has proven both to be economically positive while also substituting a substantially amount of fossil fuel. In this context, it is important that the government take into account the environmental challenges and prioritise their energy investments in technology that can contribute to sustainable development.

It is suggested that an enabling opportunity for the investment in an electrofuel production could be to export the fuel to other countries and industries such as marine fuel or agricultural fertilisers until a conversion of the existing infrastructure has been performed and the electrofuels can be applied domestically. Whereas the investment costs of PtX technologies are relative high today, there exists significant cost reduction potentials that can enable technically viable and affordable solutions to decarbonise sectors lacking alternative options. It would be unlikely for the Government of Greenland to invest in the development of commercial PtX projects. The Government of Greenland has a focus on achieving the objectives of the Sectoral Plan for Energy and Water Supply, where a core objective for the Government of Greenland is to increase the amount of renewable energy in the public energy supply by 2030. Private entities and other interested parties could potentially enter into partnership agreements with Greenland's public utility company Nukissiorfiit, whose primary task is to uphold and ensure the supply of energy and water to the citizens and private enterprises in Greenland. As argued by Lund (2014), when considering a radical technological change, new organisational and institutional compositions might be necessary in order to accommodate the new technological solution. This constellation could be an advantageous way to introduce PtX in Greenland in the beginning.

It is also important to stress that investors and end users will only consider these solutions if it is cost-effective to do so. Therefore, the Greenlandic government could accommodate such investment in the future by making it more cost-effective, for example through tax exemptions or higher carbon emitting prices. The electricity consumption of the electrolysis constitutes the vast majority of the energy cost in all of the respective scenarios. Thus, cheap renewable electricity is crucial for an electrofuel production to be profitable and therefore lowering the tariffs for utilising a hydropower resource for the production of electrofuel constitute an opportunity as well, as also pointed out by (Energinet, 2019). It is suggested by IEA (2019), that countries in this context can take advantage of looking at how other countries are handling their tariffs.

Another solution in order to encourage investments in an electrofuel production of methanol could be to increase the restriction on the blending of methanol into gasoline from today's 3% to 15% as this is technically possible without any modifications of modern combustion engine (Methanol Institute, 2010). Also, an increase of even

85% is possible with minor modifications (Skøtt, 2019). This decision is however being taken at a European level by the Fuel Quality Directive. A such modification of the restrictions would in Greenland cause significantly more methanol from the various scenarios to be disposable. Alternatively, setting out mandatory targets for a sustainable PtX production in Greenland or implementing a renewable energy directive incorporating electrofuels can be applied to promote investments.

Specific requirements and regulations are available in the "*Act for Greenland on Exploitation of Hydropower for the Production of Energy*" where all requirements for obtaining a licence are listed (Greenlandic Parliament, 2018). These are present for various scenarios and important to align with, if an electrofuel production is to be carried out.

8. Conclusion

This study has examined how electrofuel production from hydropower can contribute to accommodate the governmental objective of being supplied by renewable energy to the largest extent possible by 2030 and contribute to modernise the energy system in Greenland. The focus on electrofuels evolve from the geographical challenges prevailing in the country with long distances between cities and settlements as well as the cold climate. On the basis of the Choice Awareness theory, this study seeks to illuminate a technological alternative to the currently dependence on fossil fuels in the energy system of Greenland in order to raise the awareness of other potential solutions and thereby contribute to the decision-making process.

A thorough examination of the hydropower resources in Greenland has been carried out in order to designate the most interesting hydropower potentials in relation to an electrofuel production in the country. These hydropower potentials together with the CO_2 resources available provide the basis for a thorough study of the electrofuel production potential in the country. The respective potentials from the various reservoirs has been estimated applying the energy-economic model, developed in order to evaluate the 51 alternatives examined. This has been carried out based on how much electrofuel that can be produced, how the degree of self-sufficiency is affected and how the alternatives perform in terms of socio economy.

It can be concluded that electrofuels could constitute a major role in the transition towards more renewable energy sources in Greenland. In all cases, the electrofuel production would contribute with substantial amounts of energy substituting large quantities of fossil fuels. Moreover, the electrofuel production could be able to increase the degree of self-sufficiency significantly. However, in two of the three scenarios examined, the socioeconomic requirements set by the government cannot be met due to their negative NPV. In contrary to this, the largest scenario examined could provide an interesting solution as both producing methanol and ammonia exhibit a positive NPV. It was found that producing methanol from import of CO_2 was capable of supplying 79% of the total national energy demand with a positive NPV of 260 M€. Alternatively, producing ammonia from domestically captured nitrogen would be able to supply 67% of the demand and showed an NPV of 12.5 M€. An ammonia production enables entirely independence of any import of resources. For this reason, a prioritisation between increasing the amount of RES in the energy system and the self-sufficiency degree should be considered.

An implementation would however imply a transition of the current infrastructure is carried out. A gradual replacement of engines and generators is therefore suggested in order to avoid large alteration costs and accommodate future technological and economic progress. This could be enabled by exporting the produced methanol or ammonia in the beginning until the infrastructure has been transitioned. It would thus be possible to get ahead of the development and take advantage of future technological refinements and reductions in cost. Such approach would imply only a gradual national improvement of the share of renewable energy and self-sufficiency degree. Therefore, the results from the analysis will first be valid when a transition sufficient enough to accommodate the quantity of electrofuel produced has taken place.

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10. Appendices

The appendices are presented in this chapter.

10.1 Fuel properties

Table 27: Fuel properties for methanol, DME, Fischer-Tropsch diesel, ammonia and gasoil (Chala, Aziz, & Hagos, 2018; Engineering ToolBox, 2007, 2008b, 2008a, 2018a; García et al., 2019; Gill et al., 2011; Grannell, Assanis, Bohac, & Gillespie, 2008; Tower & Mukthar St, 2017; Valera-Medina, Xiao, Owen-Jones, David, & Bowen, 2018; Yang & Lee, 2018).

	Hydrogen	Methanol	DME	Fischer-Tropsch diesel[a]	Ammonia	Gasoil/diesel[a]
Formula	H_2	CH_3OH	CH_3OCH_3	$C_{12}H_{24}$	NH_3	$C_{12}H_{26}$
Appearance (at STP)	Colourless and superficial gas	Colourless and odourless liquid	Colourless gas, sweet ether odour	Colourless liquid	Colourless gas, pungent odour	Colourless or yellow liquid
Molar mass (g/mol)	2.02	32.04	46.07	168.3	17.03	184.43-200
Density (kg/m^3)	71	786.3	664	~776	696	803-887
Flash point (°C)	-	12.2	-41	~59	132	52
Ignition temperature (°C)	585	470	350	225	630	315
Octane number	130	100	-	-	130	-
Cetane number	-	5	55-60	~75	-	40-55
Boiling point (°C)	-252.9	64.7	-23.6	50 vol% 295.2 90 vol% 342.1	-33.3	369

Melting (freezing) point (°C)	-259.1	-97.6	-141	-35	-77.7	-32
Energy density (GJ/m^3)	0.01	15.8	19.2	34.4	15.6	36
LHV (MJ/kg)	120	19.9	28.9	43.3	18.6	43.74
H_2 content (wt%)	100	12.5	13	14.3	17.6	13-16
CO_2 content (wt%)	-	37.5	52.2	85	-	84-87
Flammable	Yes	Yes	Yes	Yes	No	Yes

Note: For easier comparison the values of density and energy density for all fuels are given in the liquid phase. Liquid phase of hydrogen is -259.1 °C or a pressure exceeding 350 bar, DME is -23.6 °C or five bar and ammonia is -33.3 °C or 20 bar. [a] Since diesel fuels consist of a varying mixture of higher hydrocarbons (e.g. depending on the specific production conditions through HTFT or LTFT), the fuel properties may vary in quality. The given values are for fuels with the given density.

10.2 Supplementary material for state-of-the-art

10.2.1 Electrolysis

Water electrolysis uses electricity to split water into hydrogen and oxygen in accordance to Eq. (1).

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2,\ \Delta H = +285.8 kJ/mol \quad (1)$$

This process is highly endothermic, which means that the energy required for the reactions is high. Around nine litres of water are required to produce one kilogram of hydrogen, while eight kilograms of oxygen is produced in this process as by-product. This oxygen can at smaller scale be used in the health care sector or at larger scale for industrial purposes (IEA, 2019d). An electrolyser consists of two electrodes, an anode and a cathode, separated by an electrolyte. The electrochemical process can be distinguished into two reactions. The formation of hydrogen takes place at the negatively charged cathode, while the evolution of oxygen occurs at the positively charged anode. Depending on the respective electrolysis technology, the charge carrier can be either OH^-, H_3O^+ or O^{2-} (Götz et al., 2016), but the principle of the reaction is the same.

10.2.2 Hydrogen storage

One of the main challenges regarding the hydrogen economy and applications is hydrogen storage as the light hydrogen might cause leakage when under pressure, which poses a threat regarding safety measures, as previously illuminated (Abe, Popoola, Ajenifuja, & Popoola, 2019; Xueping et al., 2019). According to Abe *et al.* (2019), the main reasons are inadequate materials for stationary hydrogen storage tanks, safety measures and economic feasibility. In this section only stationary tank storages are presented, although salt cavern storage is considered to be the superior large-scale hydrogen storage technology. However, it is stressed by Joakim Andersson & Grönkvist (2019) that salt cavern storage have some geological requirements that are not present in all regions. These geological requirements are not present in Greenland and for that reason salt cavern storage is not considered any further. Hydrogen refuelling stations and tank storages are commercial products, however they are still considered to be rather immature at commercial level (Apostolou & Xydis, 2019; Nel Hydrogen, 2020).

Today, there are many approaches to storing hydrogen in both gaseous-, liquid-, and solid-state (Abe et al., 2019). Some of the technologies within these different phases count: compressed gas, metal hydride hydrogen storage, carbon nanotube adsorption hydrogen storage, liquefaction, etc. (Rather, 2020; Xueping et al., 2019). An overall comparison of gaseous and liquid storage shows that gaseous storage is cheaper compared to liquid hydrogen storage (Mayyas & Mann, 2019). A lot of the challenges are caused by the low energy density of hydrogen (see App. (Fuel properties). According to IEA (2019c), storing hydrogen at 700 bar pressure has only 15% of the energy density compared to gasoline. Compensating for this would require almost seven times the space of storing gasoline. The global number of hydrogen refuelling stations (HRS) increased from 320 in 2017 to 375 in 2019, indicating that HRS storage is an established and well-known technology (Apostolou & Xydis, 2019).

Table 28: Technoeconomic key figures for hydrogen tank storage (Danish Energy Agency, 2018a).

Technical data	Hydrogen storage
Lifetime (year)	25
Capacity (kg)	500
Financial data	
CAPEX (M€/unit)	0.95
OPEX (€/year)	8,250

10.2.3 Carbon capture

In this section the carbon capture technologies mentioned in Section 5.2 will be described more in depth including the current state of the technologies including a detailed presentation of the technical and economical parameters.

The concept of ‘carbon capture’ can be separated into two main categories: carbon capture and storage (CCS) and carbon capture and utilisation (CCU) (Mikulčić et al., 2019). The total CCS projects globally amounts to 40 Mt/year (European Commission, 2019). The concept of CCU is concerning a utilisation of the captured carbon dioxide. There is a demand for carbon dioxide in some industries, such as from fertilizer and calcium carbonate producing companies as well as greenhouse factories. However, also CCU for electrofuel production has received a significant increase of interest among scientists, politicians and companies (Bui et al., 2018; Ferrari et al., 2019; German Environment Agency, 2016; Hussin & Aroua, 2020; Mikulčić et al., 2019; Sorknæs et al., 2020). This section will only be concerning CCU technologies.

10.2.4 Oxyfuel-combustion carbon capture

Oxyfuel-combustion is a method to generate CO_2-rich flue gas by removing the nitrogen from the air, which is led to the combustor (Ortiz et al., 2018; Toftegaard et al., 2010). The oxyfuel-combustion carbon capture technology has a TRL at seven (Mikulčić et al., 2019).

This method requires an air separation unit, usually based on cryogenic separation or pressure swing absorption. These ASU technologies implies a parasitic power load reducing the total efficiency of the plant (Mikulčić et al., 2019).

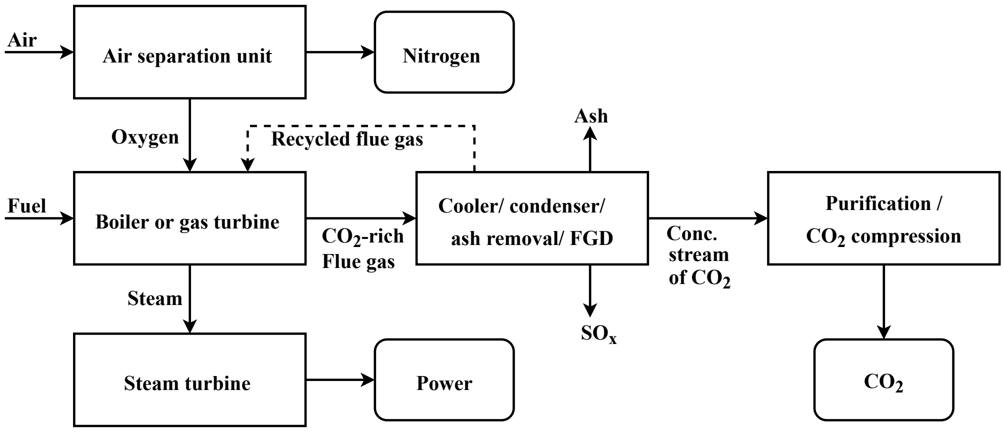

Figure 46: Oxyfuel-combustion carbon capture process. Adapted from (Wall, 2007).

The removal of nitrogen improves the combustion of the fuel, as the high level of oxygen increases the temperature in the combustor. Therefore, as shown in Figure 46, the flue gas is recycled and led into the combustor in order to reduce the temperature to more conventional levels (Haykiri-Acma, Turan, Yaman, & Kucukbayrak, 2010). This increases the level of CO_2 in the flue gas from around 10-15% to around 85% (Song et al., 2019). The oxyfuel technology has mostly been applied burning fossil fuels, however it enables better conditions burning fuel with low calorific value, such as agricultural biomass and waste (Toftegaard et al., 2010).

10.2.4.1 Adsorption

The interest of the adsorption technology has remarkably increased from 2014 to 2018, measuring number of patents and scientific articles (Hussin & Aroua, 2020). Although there are several hundred patents and an annual generation of more than thousand scientific articles concerning, the adsorption technology is only at a TRL of seven (Mikulčić et al., 2019).

Adsorption is a technology which captures the carbon dioxide on the surface of the adsorbent. Adsorption should be distinguished from absorption as the CO_2 adheres to the surface of the adsorbent whereas the absorption happens everywhere of the absorbent (Ben-Mansour et al., 2016). An overall distinction between chemical and solid adsorbents is according to Zhao *et al.* (2019) that solid adsorbents in general do not pose any threats with regard to health measures (Hussin & Aroua, 2020). Moreover, physical adsorbents enable avoidance of water evaporation in the regeneration process reducing the energy consumption (R. Zhao et al., 2019). In Figure 47, the adsorption process is presented.

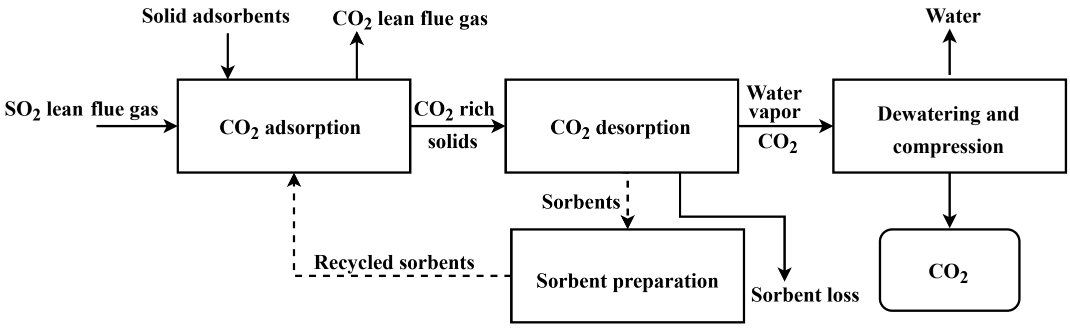

Figure 47: CO2 adsorption and desorption process. Adopted from Glier and Rubin (2013).

In the adsorber SO_2 lean flue gas on a temperature between 40 and 70 °C is required (Glier & Rubin, 2013). Pressure swing adsorption and temperature swing adsorption (TSA) most often applies solid adsorbents. The TSA increases the temperature whereas the PSA reduces the pressure in order to desorb the CO_2 rich solids (Jiang et al., 2020). If the pressure is reduced below atmospheric pressure, it implies the vacuum swing adsorption (VSA) method. The three latter technologies are considered to be feasible at industrial scale whereas the recent electro-swing adsorption (ESA) is expected to be competitive technology in the future (Ben-Mansour et al., 2016; Voskian & Hatton, 2019).

10.2.4.2 Membrane

The membrane carbon capture is a rather immature technology but has gained increased focus in recent years (Song et al., 2019). According to Mikulčić et al. (2019), polymeric membranes applied at power plants has a TRL at six, while polymeric membranes used for natural gas processing has a TRL at seven. According to Kárászová *et al.* (2020), there are six commercial membranes tested with flue gas, however all of them still needs to be tested at large-scale.

Despite that membranes for CO_2 capture in general are rather immature, the method is considered to be a promising alternative to the well-known technologies (Janakiram, Ahmadi, Dai, Ansaloni, & Deng, 2018; Kárászová et al., 2020; Song et al., 2019). This expectation is due to several parameters, e.g. the absence of dangerous emissions and chemicals (Janakiram et al., 2018). The energy requirement is considered to be lower compared to the most mature technologies such as amine based absorption (Hussin & Aroua, 2020; Janakiram et al., 2018). In Figure 48, the two-step membrane CO_2 capture process is presented.

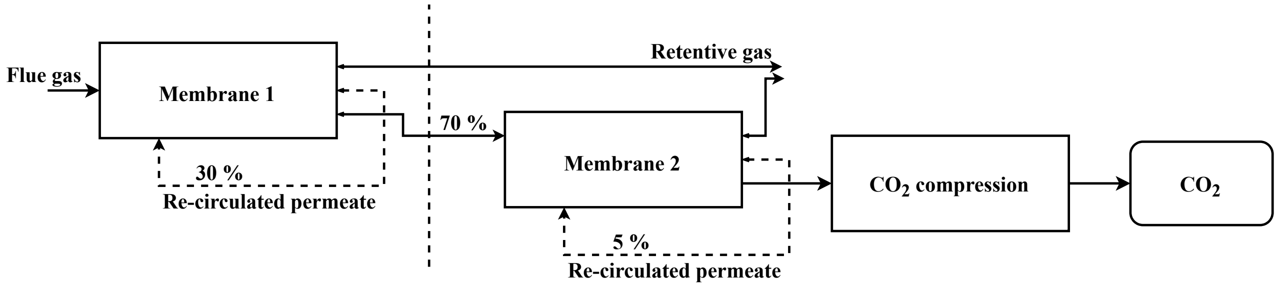

Figure 48: Membranes CO2 capture with recycled permeate. Adopted from Song et al. (2019).

The flue gas must be cooled down to below 100 °C before entering the membrane separation process. This is important as otherwise the structures of the membranes will rapidly be destroyed (Song et al., 2019). According to Asif *et al.* (2018), membranes has shown high efficiencies when the CO_2 concentration is above 10%. However, the optimal competitive conditions for membrane CO_2 separation technology is when the concentration is above 20%.

10.2.4.3 Cryogenic

Low temperature carbon capture is an approach from which a series of different technologies are developed. The cryogenic carbon capture is a mature and a large-scale technology with a TRL of nine (Leung et al., 2014; Toftegaard et al., 2010; H. Zhang et al., 2020).

This method uses the different condensation and desublimation properties of the molecules in flue gas to separate the carbon dioxide (Song et al., 2019). In Figure 49, the cryogenic separation process is assuming that there is a cold energy source available, which is a prerequisite for this technology to be competitive (Ebrahimi & Ziabasharhagh, 2017; Mikulčić et al., 2019; Song et al., 2019).

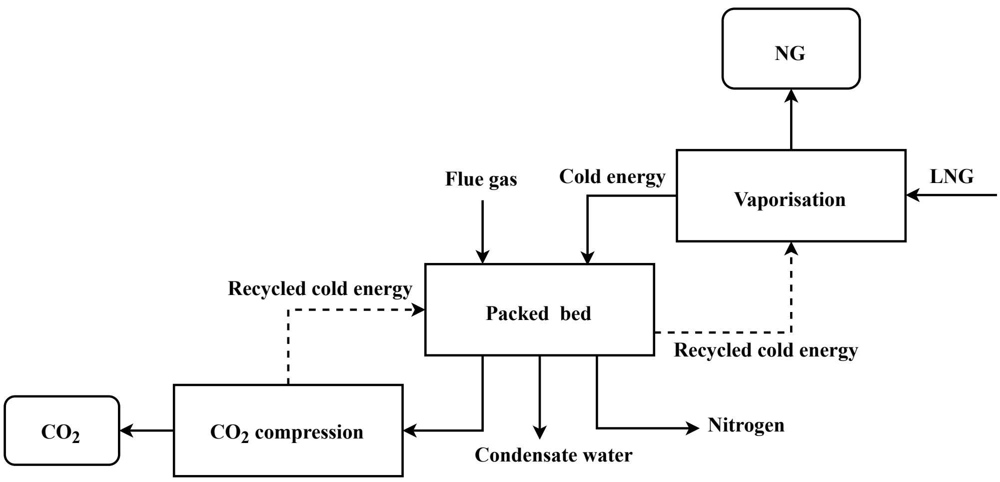

Figure 49: Cryogenic packed bed CO_2 capture with LNG vaporisation. Adapted from (Song et al., 2019). Note: The figure is simplified as one packed bed, however it is possible operating the system as dynamically in several beds.

This method enables separating and capturing the flue gas composing of 10 vol% CO_2, 89 vol% N_2 and 1 vol% H_2O. Cryogenic separation makes it possible to capture 99.9% of the carbon dioxide in a flue gas with a purity of 99.9% (Song et al., 2019). There is a risk of blockage due to the condensed water in the process (Mikulčić et al., 2019). The efficiency of the process is highly dependent on the operating temperature whereas a decreasing temperature would increase the efficiency (Song et al., 2019). However, the technology needs further commercialisation to perform economically (Babar et al., 2020).

10.2.5 Direct air capture

Direct air capture is defined as extracting carbon dioxide from the atmospheric air (Sanz-Pérez et al., 2016). The concept was introduced in 1999, whereas the technology according to Mikulčić et al. (2019) today has a TRL at seven. There has been build pilot plants to test the technology and in 2016 a small commercial DAC plant was established in Zurich (Azarabadi & Lackner, 2019; Evans, 2017).

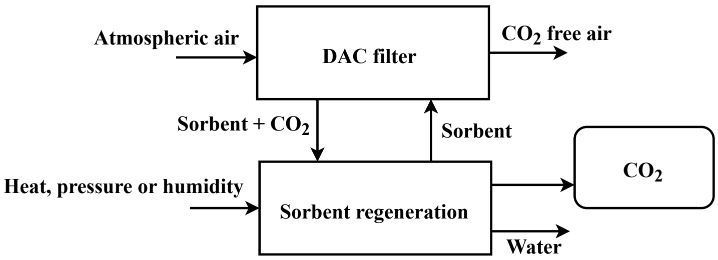

Figure 50: Showing DAC system from Climeworks. Adapted from (Azarabadi & Lackner, 2019).

Direct air capture enables a high level of flexibility. The DAC system is not limited to a flue gas but can be operating almost everywhere. Also, this technology makes possible to capture CO_2 which has already been emitted. Thereby, underground storage could be carbon negative whereas CCU from DAC could be carbon neutral (Bui et al., 2018; Dinca et al., 2018; Jiang et al., 2020). The low CO_2 concentration from ambient air is a disadvantage in regard to the energy efficiency (Sanz-Pérez et al., 2016). It is a sorbent-based system using an amine solution which only requires 100 °C in the regeneration process where after the sorbents are led back the DAC filter process (Azarabadi & Lackner, 2019; Fasihi et al., 2019). According to Bos, Kersten, and Brilman (2020) DAC could be optimised by increasing the working capacity and thereby reduce the heating demand and CAPEX.

Table 29: Costs and performance of low temperature direct air capture (Azarabadi & Lackner, 2019; Fasihi et al., 2019).

Indicators	Value
Maturity (TRL)	7
Technical	
Capacity (tCO_2/p.a.)	360,000

Lifetime (years)	20
CO_2 capture efficiency (%)	80
Electricity demand (kWh/t)	250
Fuel (heat) demand (typically, natural gas) (kWh/t)	1,750
Economics	
CAPEX (€/tCO_2/p.a.)	730
OPEX (% of CAPEX)	4

10.2.6 Synthesis

Hydrogenation of CO_2 provides a direct route for the production of e.g. methane, methanol and ethanol that all can be used as fuels or as a basis for more advanced fuels and chemical compounds. Catalytic hydrogenation is the most mature and well-known technology for this purpose (Leonzio, 2018). The Sabatier reaction is widely applied to produce methane and uses CO_2 directly as input, while other conversion routes, such as Fischer-Tropsch synthesis, starts with CO. In order to reduce CO_2 to CO, the reverse water-gas shift (RWGS) can be utilised using hydrogen in accordance to equation 4:

$$CO_2 + H_2 \underset{\text{WGS}}{\overset{\text{RWGS}}{\rightleftarrows}} CO + H_2O,\ \Delta H = \pm 41 kJ/mol \qquad (2)$$

This RWGS is endothermic, i.e. it consumes heat, and is thus favoured by high temperatures preferably exceeding 830 °C in order to achieve an almost full conversion of CO_2 to CO (Becker et al., 2012; Brynolf et al., 2018; Schemme et al., 2018). Alternatively, the inversely exothermic water-gas shift (WGS) reaction (see also Eq. 2) can be used to reduce H_2O to H_2 using CO (Graves, Ebbesen, Mogensen, & Lackner, 2011). This reaction can be utilised to produce synthesised gas, or shortly syngas, which is a gas mixture comprised mostly of hydrogen and carbon monoxide. Syngas is very important for the production of synthetic fuels as it can be used as feedstock for further processing into a wide range of hydrocarbon and alcohols (Graves et al., 2011; Leonzio, 2018; Nielsen & Skov, 2018; X. Zhang, Song, Wang, & Bao, 2017).

Conventionally, syngas is produced from natural gas steam reforming or gasification of coal (Bozzano & Manenti, 2016; Nakyai & Saebea, 2019), but there exist other more environmentally friendly routes for the production of syngas, such as through gasification of biogas that can be used to produce bio-syngas (Ail & Dasappa, 2016; Lan et al., 2012; Snehesh, Mukunda, Mahapatra, & Dasappa, 2017). Alternatively, SOEC electrolysers operating in co-electrolysis mode can also be used to combine CO_2 and steam to produce syngas (Ridjan et al., 2013; X. Zhang et al., 2017). The specific fuel produced from syngas depends on various conditions such as the catalyst, temperature and pressure of the synthesis.

10.2.6.1 Methanol

Methanol can be produced either from a synthesis of CO_2 and H_2 or from a synthesis of CO and H_2, which means that it can be produced from CO_2 in one of two steps. In the two-step process, the CO_2 is initially converted to CO in a RWGS reaction (Eq. 2) and then hydrogenated to methanol, whereas CO_2 is directly hydrogenated to methanol in the one-step process (Brynolf et al., 2018). The direct hydrogenation of CO_2 consists of three competing reactions occurring parallelly: the WGS reaction (Eq. 2) converting carbon monoxide in syngas into carbon dioxide, the CO_2 hydrogenation to methanol (Eq. 3) and the hydrogenation of CO to methanol (Eq. 4):

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O, \Delta H = -49.5 kJ/mol \tag{3}$$

$$CO + 2H_2 \leftrightarrow CH_3OH, \Delta H = -90.5 kJ/mol \tag{4}$$

The overall reaction of the methanol synthesis is represented by the latter reaction (Eq. 4).

10.2.6.2 DME

There are two distinct routes for the production of dimethyl ether, either directly from syngas or indirectly by dehydration of methanol. The indirect production route is the commonly used, while the direct synthesis route is presently not a commercially developed stage (Schemme et al., 2018). This route is however thermodynamically and economically more favourable compared to the indirect production route through dehydration of methanol (Brynolf et al., 2018; Prabowo et al., 2017).

The indirect route is through the synthesis of methanol which is then followed by a dehydration into DME in a separate reactor (Azizi et al., 2014; Prabowo et al., 2017). The methanol reaction can be seen in Eq. (4), while the methanol dehydration reaction is shown in Eq. (5).

$$2CH_3OH \rightarrow CH_3OCH_3 + H_2O, \Delta H = -23.5 kJ/mol \tag{5}$$

10.2.6.3 Fischer-Tropsch diesel

The FTS starts with CO as input, which can either be obtained from the RWGS reaction (see Eq. 2), from a co-electrolysis SOEC or from gasification of biomass producing bio-syngas (Ail & Dasappa, 2016; Becker et al., 2012; Decker et al., 2019; German Environment Agency, 2016; K. Zhao et al., 2018). The syngas is fed to the reactor in a continuous process to produce long-chain hydrocarbons in accordance to Eq. 7.

$2H_2 + CO \rightarrow –CH_2– + H_2O, \Delta H = -158.5kJ/mol$ (7)

Several reactions occur simultaneously in the FT process including the WGS reaction (see Eq. 2). The $–CH_2–$ is the chain growth molecule from which higher hydrocarbons build and the carbon number is defined by the length of C_n, which is correlated with the respective properties of the hydrocarbon. Each class of hydrocarbons contains different chemical and physical properties. Gasoline is composed of relatively lightweight hydrocarbons between C_4 and C_{12}, while diesel consists of heavier hydrocarbons between C_{10} and C_{20} (IEA-AMF, 2019).

10.2.6.4 Ammonia

Hydrogen is catalytically reacted with nitrogen captured from the air to produce ammonia in accordance to Eq. (8):

$N_2 + 3H_2 \leftrightarrow 2NH_3, \Delta H = -92kJ/mol$ (8)

The reaction is exothermic and therefore favoured by low temperatures and high pressures. The conversion rate per pass depends on the reaction temperature and pressure, but a near-complete conversion to ammonia is not achievable under commercial synthesis processes, making a significant recycling necessary (Rouwenhorst et al., 2019).

10.3 Key operational parameters of electrolysers

Table 30: Key operational parameters for AEC, PEM and SOEC electrolysis (Brynolf et al., 2018; Buttler & Spliethoff, 2018; El-Emam & Özcan, 2019; Götz et al., 2016; IEA, 2019d; Rouwenhorst et al., 2019; Schmidt et al., 2017; Schnuelle et al., 2019; Iva Ridjan Skov & Mathiesen, 2017).

	AEC	PEM	SOEC
Technology maturity			
TRL	9	8	5-6
Operating parameters			
Temperature (°C)	60-80	50-80	650-1000
Operating pressure (bar)	1-30	30-80	1
Current density (A/cm^2)	0.25-0.45	1.0-2.0	0.3-1.0
Flexibility			
Cold start-up time (min.)	<60	5-10	<60

Warm start-up time	1-5 min	<10s	15 min
Load flexibility (% of nominal load)	10-110	0-160	20-100
Electrolysis production ability			
Hydrogen production per stack (Nm^3/h)	1400	400	<10
Gas purity (%)	99.5	>99.99	99.9
Electrolysis structure			
Electrolyte	Alkaline solution (20-40 wt% KOH/NaOH)	Solid polymer membrane (e.g. Nafion)	ZrO_2 ceramic doped with Y_2O_3
Cathode	Ni, Ni-Mo alloys	Pt, Pt-Pd	Ni/YSZ
Anode	Ni, Ni-Co alloys	IrO_2, RuO_2	LSM/YSZ
Charge carrier	OH^-	H_3O^+/H^+	O^{2-}
Operation conditions			
Cell voltage (V)	1.8-2.4	1.8-2.2	0.95-1.3
Voltage efficiency ($\%_{HHV}$)	62-82	67-82	<110
Current system power consumption (kWh/m^3H_2)	4.5-8.2	4.5-7.5	-
Future system power consumption (kWh/m^3 H_2)	4.3-5.7	4.1-4.8	-

Advantages	• Mature technology • Available for large plant sizes • Non-noble materials • Low costs • Long lifetime • Long-term stability • Stacks in MW range available • High stability • Low water purity required • Low maintenance costs	• No corrosive substances • Capable of high pressure (>100 bar) • Capable of operating in dynamic and intermittent electricity systems • High current density • Fast start-up and ramping rates • Low minimum load requirement (>5%) • High gas purity (99.9-99.9999%) • Acceptable stability	• High electrical efficiency • Integration of waste heat possible • Potentially low energy requirement • Reversible operation possible • Use of low-cost materials

Disadvantages	• Low current density • Corrosive liquid electrolyte • Relatively low efficiencies • High minimum load required (>20%) • Slow dynamics • Low operating pressure	• High cost of components • Fast degradation • Low stack lifetime • Use of scarce materials • High purity water requirement • High maintenance costs	• New technology (not yet commercial) • Limited long-term stability of cells • High current cost (however potentially low cost due to low cost materials) • Expensive • Low stack lifetime • High temperature operation • High minimum load requirement (>30%) • Slow dynamics • Stack size in kW available

10.4 Carbon dioxide phase diagram

A phase diagram of carbon dioxide is presented below.

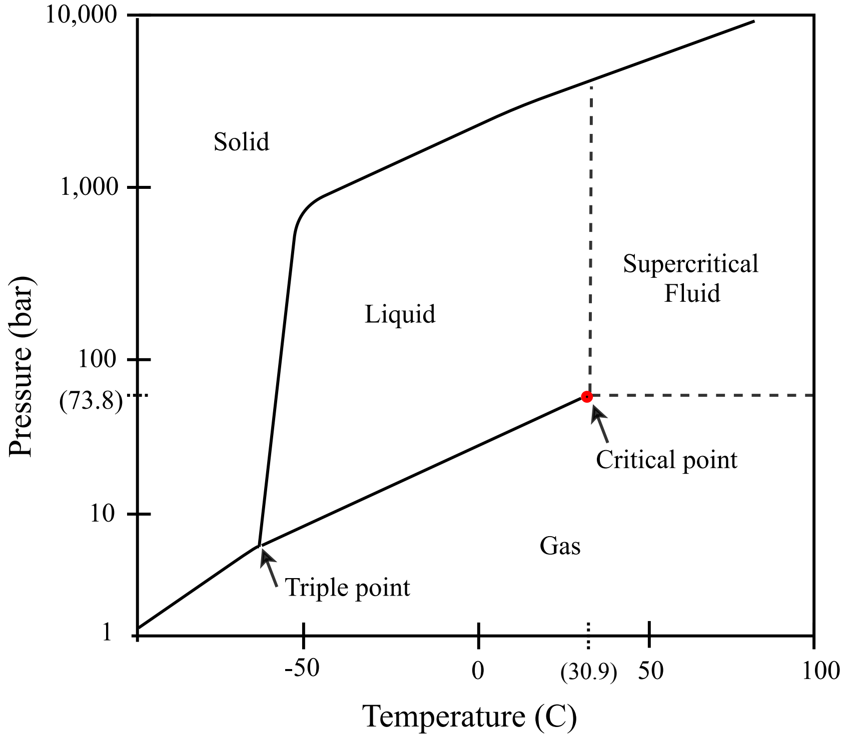

Figure 51: Carbon dioxide phase diagram (Engineering, 2018).

10.5 Nitrogen properties

The physical properties of nitrogen are listed in the table below.

Table 31: Physical properties of nitrogen (Engineering ToolBox, 2018b).

Properties	Nitrogen
Formula	N_2
Appearance (at STP)	Colourless gas
Molar mass (g/mol)	14.0067
Density (kg/Nm^3)	1.126[a]
Boiling point (°C)	-195.8
Melting (freezing) point (°C)	-210
Toxic	No
Flammable	No

Notes: [a] Assuming a temperature at 26.9°C.

10.6 Possible substitutions domestically without major alteration

This chapter provides an overview of the four fuels of concern in regard to identify how much fossil fuels the respective electrofuels are able to substitute domestically in Greenland. A replacement of all engines and fuel consuming units will be a massive investment for the society. Therefore, it is examined how the electrofuels will be able to fit into the existing energy infrastructure without any modifications or only with minor adjustments. The chapter builds on top of the state-of-the-art in Chapter 5 and is based on interviews with professor Jesper Scramm from Danish Technical University, Klaus Petersen from MAN Energy Solutions and Tage Lindegaard and Bjarne Lykkegaard from Polaroil.

The properties of methanol are close to the properties of gasoline. However, it is not possible to make a direct substitution of gasoline and run an engine on methanol without modifications. Making engines run solely on methanol or as dual fuel has been shown to be possible for instance the two-stroke engine ferry StenaLine in Sweden. However, Petersen (2020) from MAN ES stresses that modifying an existing engine to be run on methanol would be very costly and be around the same cost as investing in a new methanol running engine. Blending methanol into gasoline has comprehensively been tested around the world. Tests has been carried out in Sweden, Norway, Germany, New Zealand, California and China (Methanol Institute, 2020). The tests have shown that 15% of methanol can be blended into gasoline without any major modifications. As methanol is corrosive, corrosion additives are required if the blend volume exceeds 3%. Although it is possible to blend 15% of methanol different regulatory limits are applied around the world. In Greenland and the European countries maximum 3% methanol can be blended into the gasoline. In the USA upper threshold is 5% whereas in the Shanxi province in China, a blend of 15% is allowed (Methanol Institute, 2010, 2020). With the 3% threshold in Greenland 5.8 GWh methanol can annually be blended with gasoline.

Dimethyl ether is, compared to methanol, closer to have the same properties as gasoil, which accounts for 70% of the total fossil share in Greenland. However, as five bar pressure is needed to ensure a liquid state and as there is a need to change pipes and practice concerning lubrification, some alteration of the current infrastructure would be required (Scramm, 2020). As mentioned, Volvo has succeeded making a truck run on DME, but such engines are not considered to be on a mature scale (Iva Ridjan Skov & Mathiesen, 2017). According to Scramm (2020), DME is very similar to LPG and would fit into the current infrastructure. The use of LPG in Greenland is at a low level, which enables DME to substitute the current LPG consumption of 833 MWh.

The production of Fischer-Tropsch diesel can be performed to be compatible with the current infrastructure substituting gasoil (Petersen, 2020). However, the specific properties of the FT diesel depend on how production process is constructed. According to Scramm (2020), substituting gasoil with FT diesel only requires adjustment of the fuel injection which is a simple thing to do. As Fischer-Tropsch diesel is compatible with the current infrastructure that is run by gasoil 1,366 GWh can potentially be substituted.

Ammonia is not compatible with the current energy infrastructure in Greenland. According to Scramm (2020), a blend of ammonia with gasoil might be compatible with the current infrastructure. However, Scramm (2020) stresses that it is still uncertain as they have not tested it yet, but they are examining fuel blends with ammonia. As it would require great modifications or investments in new engines or fuel cells it is considered that there is no potential of substituting domestic fossil energy (Ikäheimo et al., 2018). The table below summarises the potential of substituting domestic fossil fuels without great alterations or new investments.

Table 32: Potential of substituting domestic fossil fuels.

Fuel	Potential substitution of domestic fossil fuels without great alterations or new investments
Methanol (GWh)	5.8
Dimethyl ether (GWh)	0.8
Fischer-Tropsch diesel (GWh)	1,366
Ammonia (GWh)	0

It is however in general stressed by Lindegaard and Lykkegaard (2020) from Polaroil that any water substances in the fuels and fuel blends can freeze and cause clogging in the fuel consuming units due to artic climate. According to Methanol Institute (2020), the tests they have performed on methanol has shown a low water content in the fuel blends. If a fuel blend with methanol is exposed to amounts of water higher than the water tolerance properties, the methanol blend will separate into two phases. To avoid this phase separation, one to two percent co-solvent alcohols, such as ethanol, propanol or butanol, can be added in the blend (Methanol Institute, 2020). It is recommended by the Methanol Institute (2020) to implement a good water monitoring practice of the fuel blend. Today, the gasoil used in Greenland contain additives to improve the cloud point of the fuel in order to resist the cold temperatures (Lindegaard & Lykkegaard, 2020). Such additives might also be necessary to add in the electrofuels. However, cloud point temperatures should be examined thoroughly and if needed, additives should be blended in to ensure no clogging.

10.7 List of relevant hydropower resources

Table 33: Relevant hydropower resources identified (Nukissiorfiit, 2005, 2019c, 2019b, 2020a).

City	Qaqortoq/ Narsaq	Paamiut	Nuuk (BAU)	Nuuk Extension			Nuuk	Nuuk	Maniitsoq	Qasigiannguit/Aassiat	Ilulissat/Uummannaq
Plant	Johan Dahl Land	Kangaarsuup Tasersua	Buksefjorden	Option 2	Option 3	Option 4[a]	Imarsuup Isua	Tasersuuq Isua	Tasersiaq	Kuussuup Tasia	Nussuaq
Planning stage[b]	IV	I	VII	V	V	V	IV	II	V	V	II
Plant capacity (MW)	40	65-125	45	+55 (100 in total)	+90 (135 in total)	+90 (190 in total)	154	65	300	21	45
Energy potential (GWh/a)	290	512-947	230	+537 (762 in total)	+445 (1,207 in total)	+445 (1,207 in total)	1,278	485	2,699	94	350
Reservoir capacity (hm^3)	225	2,160	2,050	2,050	2,350	2,350	1,080	2,350	2,240	314	850
Annual run-off (hm^3/a)	225	1,600-3,500	380	+1,000 (1,380)	1,000	1,000	1000	4,200	2,160	300	600
Fall height (m)	640	150	255	246	180	180	635	65	620	157	270
Proximity to city (km)	56 (Nar) ~65[d] (Qaq)	~80[d]	56.5	56.5	87	87	~130[d]	~110[d]	~150[d]	31 (Qas) 114 (Aas)	~140[d] (Ilu) ~100[d] (Uum)

CAPEX (€ million)	1	-	-	174[e]	287	353	-	126	400	149-161	-

Notes: [a] Prerequisite: Power station 2 and tunnel have been established earlier (06.a+b-1). [b] The planning stage from I to VII is estimated based on the descriptions listed in Nukissiorfiit (2005). [c] Possible annual operation is based on the plant capacity suggested by Nukissiorfiit. [d] Distances are estimated based on the maps appended. [e] Extension of the existing transmission line to enable this transmission is estimated to additionally € 52 million.

11. External appendices

11.1 Energy-economic model

11.2 Data sheet

11.3 energyPRO Qaqortoq

11.4 energyPRO Nuuk

11.5 energyPRO Maniitsoq

11.6 Interview guides

11.7 Klaus Petersen, MAN Energy Solutions

11.8 Jesper Scramm, DTU

11.9 Tage Lindegaard & Bjarne Lykkegaard, Polaroil

11.10 Allan Bertelsen, Ministry of Industry, Energy, Research and Labour

11.11 Jens S. Thomsen, Siemens Gamesa

11.12 Martin Frahm Jensen, Emil Andreas Tjärnehov, Yawar Abbas Naqvi, Halder Topsoe