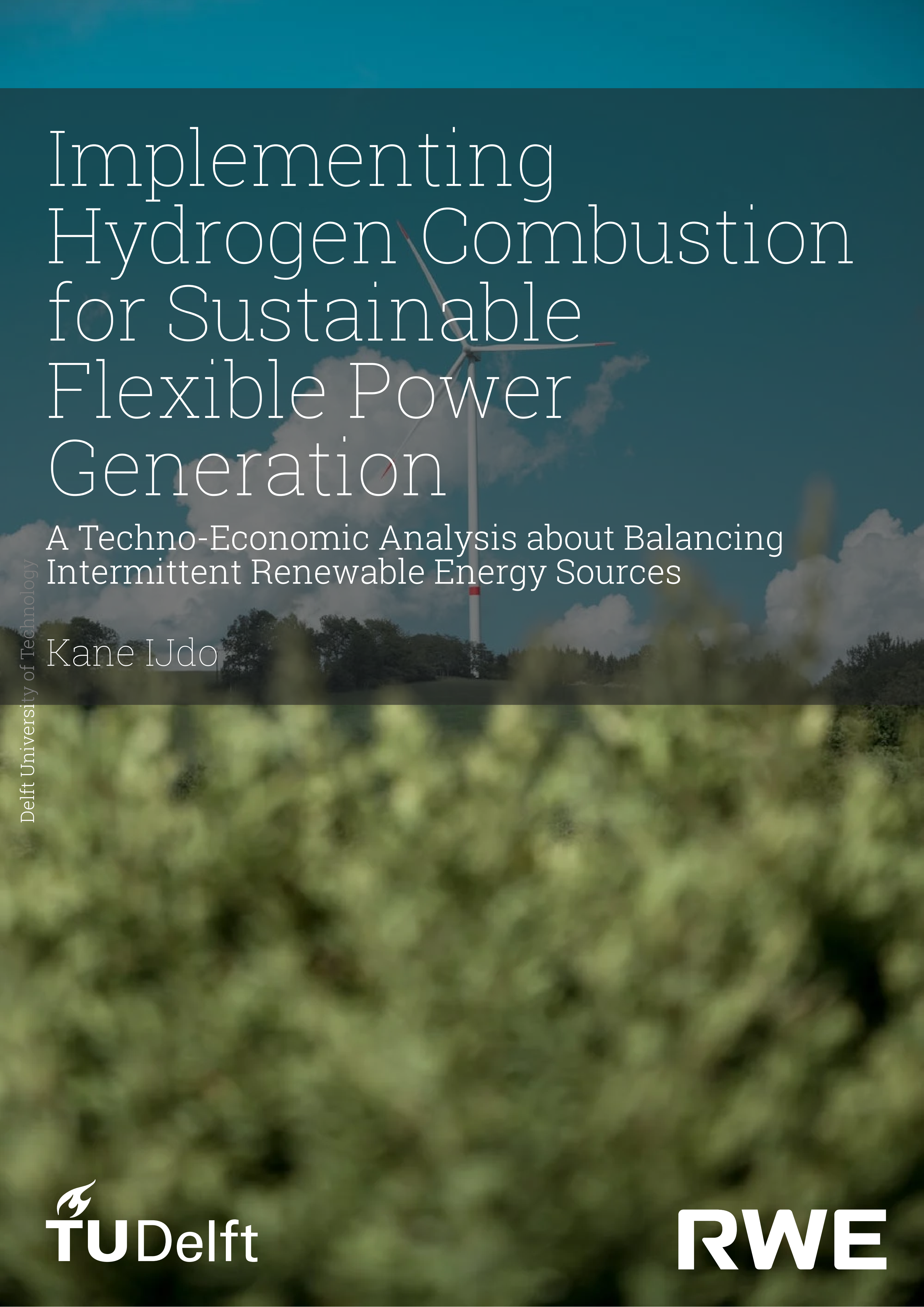

# Implementing Hydrogen Combustion for Sustainable Flexible Power Generation

## A Techno-Economic Analysis about Balancing Intermittent Renewable Energy Sources

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RWE

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by

Kane IJdo

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# Acknowledgements

At first I would like to thank my supervisors Dr. Ir. R.A. Hakvoort, Dr. Ir. G. Bekebrede, and Dr. J. Marschewski for helping me and supervising me throughout my thesis. Their help resulted in a thesis that I am proud to present. I would also like to thank RWE for the internship and the team I was part of for all the help, enthusiasm, and the overall great time I experienced at the company. Also I want to thank my family and friends who helped me during the occasionally difficult times and challenges of writing a thesis and motivated me throughout the process.

My thesis started with a general interest for hydrogen and sustainability. After getting in contact with RWE, the problem of flexible energy generation became apparent. What resulted in this thesis topic. Due to my background in mechanical engineering, I was more confident in quantitative research and less in qualitative research. During this research I wanted to step out of my comfort zone and use both quantitative and qualitative research. This resulted in conducting a multi-criteria analysis where I wanted to gather the data for the criteria via both quantitative and qualitative methods.

I really enjoyed doing the quantitative part of this research. The gathering of the data, writing the optimisation code, and the analysis of the quantitative results. I felt very comfortable with these methods and spend a lot of time on this part of the research. However, although I liked conducting the interviews for the qualitative research, I felt less confident coding and drawing conclusions from these interviews. This also led to the qualitative part of this research taking more time than I initially expected. Overall I am happy that I used a combination of both qualitative and quantitative research as it led to results I would initially not have expected. However, in future research I would prefer to only use quantitative research.

This thesis marks the end of my academic journey. Overall, I look back at a great time where I learned a lot about many different things and met many great people. Not only when writing my thesis, but also during my bachelor's and master's as a whole.

# Summary

This research focuses on establishing the most effective way to provide flexible power generation via gas turbines with hydrogen in 2040 from a techno-economic perspective. Assisting policymakers and energy companies in making informed decisions about future strategies. The increase in intermittent renewable energy capacity increases the pressure to have flexible dispatchable energy generation to bridge the gaps when there is no solar or wind energy available. Currently this flexible power generation can be produced via Combined Cycle Gas Turbines (CCGT) that run on natural gas, producing green house gasses in the process.

To conduct this research, a multi-criteria analysis is performed on the CCGT in Moerdijk for the year 2040. This method established a systematical approach to evaluate and compare different alternatives based on multiple criteria, while aiding to narrow the knowledge gap in understanding the combined effect that different technologies have on flexible power generation. This analysis resulted in the continuation on natural gas as a fuel for the CCGT being the top performer across three forecasts used in this research. However, assuming the need for a sustainable alternative, the top performer was different for each forecast. In the forecast with a low installed capacity of renewable energy, the top performing option is to use blue hydrogen as a fuel. In the central forecast, the alternative that combines blue and green hydrogen as a fuel is the top performer, whereas in the high forecast, green hydrogen takes the lead.

Two sensitivity analyses, decreasing the impact of capital expenditure and overall system efficiency in the analysis, revealed a decrease in the performance of natural gas and an increased performance of green hydrogen as a fuel source. The results show that the lack of adaptability problems and capital expenditure are one of the main reasons that the continuation of using natural gas as a fuel for the CCGT does not outweigh the large CO2 emissions and CO2 related costs. Regulations, development or incentives to decrease the capital expenditure of alternatives where the CCGT runs on hydrogen as a fuel, can greatly stimulate the development towards more sustainable flexible power generation.

The multi-criteria analysis compares three alternatives with the continuation of the current alternative: running on natural gas. Based on the research boundaries, the following alternatives are established: one alternative relying fully on blue hydrogen, another alternative relying fully on green hydrogen, and an alternative relying on a a blend of blue and green hydrogen.

To perform the analysis, the energy demand for the CCGT in Moerdijk in 2040 is determined based on three different forecasts for the year 2040. Using electricity data from the CCGT in Moerdijk, along with solar and wind generation data, and energy consumption figures from 2023, three running profiles are established for the CCGT in 2040. This revealed that the running profiles are bound by the limitations of the

CCGT across the forecast, resulting in similar running profiles.

For each of these alternatives, the total annual cost is calculated by optimising the production capacity of hydrogen storage, the storage capacity itself, and the hydrogen flow for each hour throughout the year using the Pyomo optimisation language. Showing great differences in capital expenditure across the alternatives. While in order to reveal the problems and opportunities associated with implementing the alternatives for the year 2040, interviews with professionals in the energy sector are conducted. These interviews showed great challenges towards the technical and infrastructural adaptability of implementation of the hydrogen based alternatives, and great challenges for the alternative on natural gas from operational longevity and dependability perspective.

# Relevance of the Research

## Relevance to Society

This thesis addresses the implementation of hydrogen combustion in combined cycle gas turbines in order to provide flexible power generation to balance the increase in intermittent renewable energy sources. The increase in electricity consumption and intermittent renewable energy to reach climate goals, puts great pressure on the demand for sustainable flexible power generation. Making this research significant for society. This research is mainly relevant because of three different aspects. These are: the environment, economics and energy security. Environmentally this research plays part in reaching the targets set by governments in order to stop or slow down global warming. This research helps to preserve the world for future generations. It also contributes to increase the air quality by decreasing green house gas emissions. Increasing the health and well-being of the population. This research also contributes to society from an economic perspective. The research addresses the cost of sustainable flexible energy production. Which is directly related to the energy pricing for consumers. Researching the cost structure of sustainable flexible energy production aids in understanding how to minimise energy prices to prevent energy injustice. The research also contributes to securing the availability of energy. Providing flexible power generation enables the balancing of fluctuations in the energy grid caused by intermittent renewable energy sources. It helps providing the ability to generate energy when there is no intermittent renewable energy available. Contributing to the constant availability of energy for society.

## Relevance to Management of Technology

The master Management of Technology at the Technical University of Delft teaches students to explore and understand how firms can use technology to design and develop products and services that help to improve the outcome and performance of the firm or increase the satisfaction of the customer. This research provides exactly that. Researching the possibility and effects of switching to hydrogen helps energy production companies with combined cycle gas turbines in their portfolio to utilise their own and other companies their technologies more effectively. This results in improved outcomes by reducing greenhouse gas emissions and lowering energy production costs, while considering technical and adaptability challenges.

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# Nomenclature

## Abbreviations

| Abbreviation | Definition |
|---|---|
| ACC | Annual cost of capital |
| CAPEX | Capital expenditure |
| CCGT | Combined cycle gas turbine |
| CCS | Carbon capture and storage |
| CO2 | Carbon dioxide |
| CRF | Capital recovery factor |
| GW | Gigawatt |
| H2 | Hydrogen |
| K | Kelvin |
| kg | Kilogram |
| km | Kilometre |
| kW | Kilowatt |
| L | Litre |
| MCA | Multi-criteria analysis |
| MJ | Megajoule |
| MW | Megawatt |
| MWh | Mega Watt per hour |
| OPEX | Operational expenditure |
| PEM | Proton exchange membrane |
| RWEG | RWE Generation |
| SMR | Steam methane reforming |
| WACC | Weighted average cost of capital |

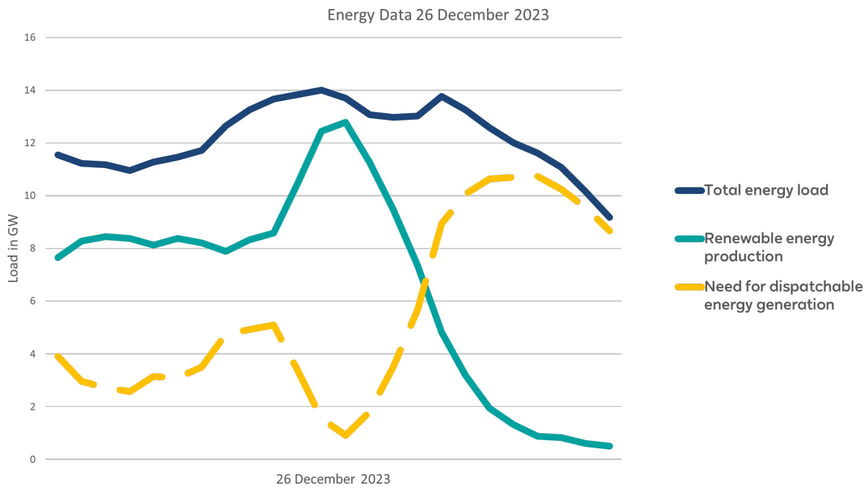
# 1 Introduction

Over the past years and the expected future, the demand for energy keeps on rising. More carbon is emitted in this process, trapping the heat of the sun, and causing climate change. ”Leading to hotter temperatures, more severe storms, increased drought, rising of the ocean, species going extinct, less available food, an increase in health risks, and an increase in poverty and displacement” (United Nations, n.d.). The goal of the Netherlands is to reduce carbon emissions by 95% before the year 2050 as laid down in the Climate Act on May 28, 2019 (Ministery of Economic Affairs and Climate Policy, 2020). This is agreed upon to slow down climate change. Making it essential to reduce carbon emissions and enhance carbon capture efforts, resulting in a rising demand for sustainable energy sources. Which translates into increased adoption of wind and solar energy. The downside of this increase in wind and solar energy is that these energy sources are intermittent. The variability in wind speed and sunlight availability causes fluctuations in power output.

This variable delivery of power can cause technical problems related to grid stability, providing power demand, and the allocation of storing energy. The problem with providing the power demand is that at times when demand is highest, renewable energy production might be low. When renewable energy generation is at its optimum, the demand is not. This difference between demand and production can in certain cases even be so high, that there is more renewable energy generation than there is demand. This difference in load and renewable energy production can be seen in Figure 1.1 based on data provided by Nationaal Klimaat Platform (n.d.) and ENTSO-E (2024b).

Currently there is already a lot of total solar and wind energy production in the Netherlands, combined totalling 50TWh of energy (Centraal Bureau voor de Statistiek, 2023). This already has to increase rapidly by 2030, as the goal of the Netherlands is to supply a minimum of 35TWh of sustainable energy via solar and wind energy on land and to supply 49TWh of offshore wind energy. This combined will mean that 84TWh of sustainable energy will be supplied by wind and solar energy sources, a 68% increase in wind and solar energy within the next 7 years. This increase is part of the plan of the Dutch government to decrease carbon emissions by at least 49% in 2030 (Rijksover-

**Figure 1.1:** Energy data of a winter day (ENTSO-E, 2024b) (Nationaal Klimaat Platform, n.d.)




heid, 2019). Besides this, the goal of the Dutch government is to reach almost 100% reduction in carbon emissions by 2050 as mentioned before. To realise this goal, the government sees great potential in the increase in offshore wind energy, aiming to generate between 170 and 325 TWh exclusively from offshore sources (Ministerie van Economisch Zaken en Klimaat, n.d.). Although wind energy on land theoretically does not have to increase to reach the goals and demand of 2050, it can be expected to still increase in the coming years. Similarly, large solar energy farms can maintain their current capacity until 2050. However, there is an expectation that installation of solar panels on rooftops will continue (Vendrik et al., 2023). Furthermore, in addition to expanding the overall installed capacity of renewable energy, there is also a push towards the electrification of industries. This shift is reducing the dependence on fossil fuels while at the same time increasing its dependence on electricity. Projections indicate that industrial electricity demand in the Netherlands could quadruple compared to its 2022 consumption levels (TKI Energie en Industrie et al., 2024).

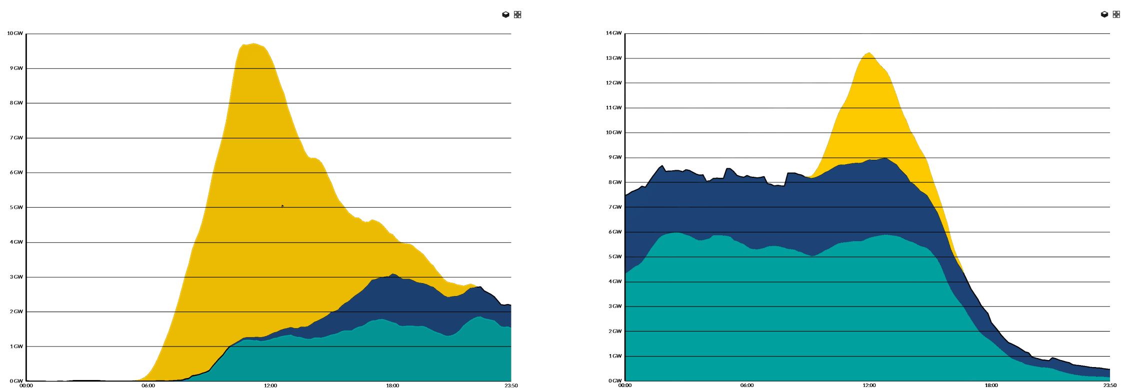
The increase in the placement of solar panels may be driven by another important factor towards a more sustainable future, namely the price of energy. The higher cost of solar panels can be seen as a barrier for consumers and small businesses to switch to solar power, limiting their ability to provide and use more sustainable energy. In order to solve this problem, the government tries to stimulate the use of solar power by implementing certain incentives to stimulate their use. These incentives for instance include a tax rebate for the placement of solar panels, or the crediting of electricity supplied to the grid (Ministry of Economic Affairs and Climate Policy, n.d.). These incentives can reduce the cost of electricity for consumers, or even be profitable in some cases. Making the reduction in costs one of the main incentives for consumers and small businesses to use solar power. Showcasing the importance of cost reduction. Minimising the cost of ownership, and the cost of operation will greatly impact the increase in solar power (Werther et al., 2020).

Figure 1.2 shows the division of renewable energy production via three different energy sources. The yellow part is the total amount of solar energy produced in the

Netherlands, while the blue part is offshore wind energy, and the green part is wind energy on land (Nationaal Klimaat Platform, n.d.). It can be seen that these energy sources can vary a lot during the day, sometimes not even producing any energy at all. When the total capacity of these renewable energy sources increases, so will the peaks of energy that they produce. This means that the minimum output will still be 0, making the difference between the energy peaks and troughs even greater. Combining this generation pattern with the increasing electricity demand in the Netherlands, may result in significant discrepancies between renewable energy production and energy demand. These gaps between renewable energy production and energy con-

**Figure 1.2:** Division of different renewable energy sources on a summer and winter day in the Netherlands (Nationaal Klimaat Platform, n.d.)

**(a)** Renewable Energy Sources 22 June 2023 **(b)** Renewable Energy Sources 26 December 2023



sumption can lead to problems with frequency balancing, adequacy and congestion management (ENTSO-E, 2024a).

In order to prevent these gaps, the demand can be altered to fit the renewable energy production by demand-side management (Panda et al., 2023), or the gap between renewable energy production and demand can be filled by quick reacting dispatchable energy sources. These energy sources must be flexible when producing energy, and therefore quickly be able to scale their energy production up or down. Filling the energy gap between renewable energy production and total energy demand, providing needed stability in the energy grid.

Currently, a lot of this flexible power generation is achieved through combined cycle gas turbines (CCGT) powered by non-renewable energy sources such as gas or coal. A CCGT is a power generator that consists of two cycles. In the first cycle a fuel, such as natural gas, is burned to drive the turbine. The second cycle captures waste heat from the first cycle to produce steam. This steam drives a steam turbine to increase the overall efficiency of the CCGT. The high efficiency, combined with the fast ramping capabilities of electricity production makes it a great option for flexible power generation. However, the CCGT's emit a lot of greenhouse gasses in the process. In the last few years, a lot of research has been done towards sustainable energy production, but little research is focused on the flexibility of such an energy source and its system integration. This flexibility is becoming more important with the increase in intermittent energy sources and the electrification of the world.

The problem statement becomes: *The increase in intermittent energy sources will pressure the need for flexible power generation to sustain grid stability. Currently, most of this flexible power generation is fuelled by gas and coal, emitting greenhouse gasses in the process. These flexible power generators must become more sustainable to reach the targets set in the Climate Act on May 28, 2019. All while keeping the generation costs as low as possible, in order to maintain competitive electricity prices for balancing the increase in renewable energy. Not limiting the increase and development of intermittent renewable energy sources. There is still very little research focused on the sustainability and economics of flexible power generation, resulting in uncertainty and higher risks for policymakers and energy companies to make well informed decisions about future strategies.*

A way to decrease the greenhouse gas emissions of these flexible power generators is to run the turbines on hydrogen instead of natural gas. This change to hydrogen instead of natural gas faces some difficult challenges and questions that still need to be answered. There are many different factors to take into account when running the turbines on hydrogen. There are different hydrogen sources to consider, the import or production, the storage, the infrastructure, and the changes to the generators themselves.
This leads to the research objective: *To Investigate the implementation of hydrogen for flexible power generation in the Dutch energy system from a techno-economic perspective for the year 2040*

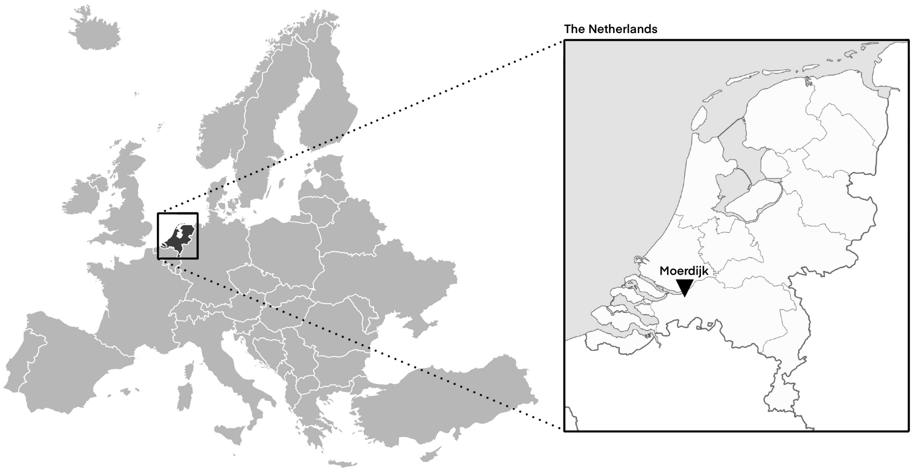
## 1.1. Research Boundaries

This research is conducted in collaboration with RWE Generation (RWEG). RWEG is an energy company based in Germany, that operates one of the largest, flexible power plant parks in Germany, the UK and the Netherlands while bundling the hydrogen activities within the RWE Group. This research geographically focuses on the energy generation by the electricity plant in Moerdijk operated by RWEG and a system implementation in the Netherlands.

The location of this plant and the Netherlands compared to Europe can be seen in Figure 1.3. In this research, the Netherlands is viewed as an island and is assumed to be fully self-sufficient in the generation, transport and storing of electricity and hydrogen. Taking the Netherlands as an island also means that there are no interconnection with other countries. This minimises uncertainties and variables resulting from future goals and plans of other countries, making the research more feasible in the given time frame. It is also chosen as the objective of this research is to focus on flexible power generation in the Dutch energy system. Taking the Netherlands as an island in this research showcases the ability of independence of the Netherlands in the case of flexible power generation.

For this research, it is chosen to focus on the system that is between the sourcing of hydrogen and the production of electricity with this hydrogen. Running a CCGT on hydrogen involves several technical requirements. Hydrogen must at first be produced

**Figure 1.3:** Location of the Netherlands and Moerdijk




and transported to the CCGT before it can be used to generate electricity. This production and transport of hydrogen can happen via different methods. However, there can be a timing problem between hydrogen production and the combustion in the CCGT, implying the need for a method of storing hydrogen. Figure 1.4 shows a schematic overview of the system boundaries for this research. The text in the green squares and circles in the schematic overview are taken into consideration in this research. The red squares and circles in the schematic overview are not taken into consideration. Everything in between these boundaries is within direct, or indirect, reach of RWEG. RWEG has the ability to select their hydrogen source or produce it themselves, with its scope ending when delivering the electricity to the grid. The exact technical detailed boundaries, such as the hydrogen type, are based on the scale at which RWEG produces energy and the future environmental target to minimise emissions.

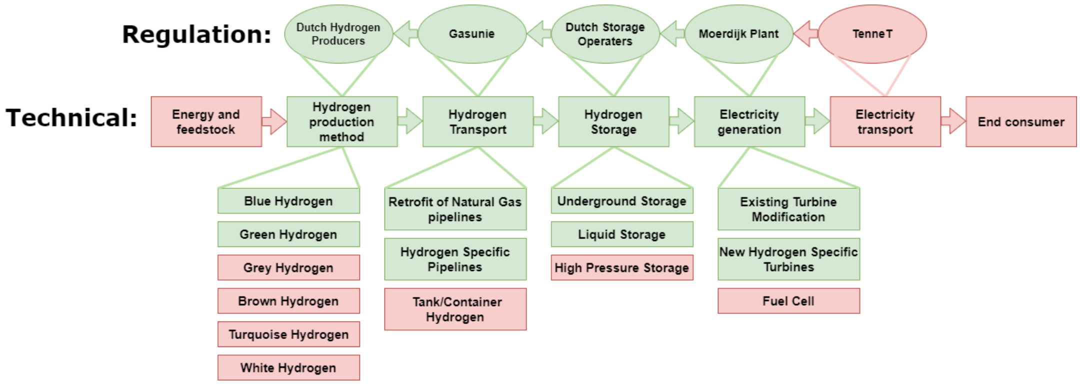
From a technical perspective, this work only looks at the inputs in the technical system and the output of such an technical system. For instance in the case of production of green hydrogen, the input in the technical system are renewable energy and $H_2O$, while the output is $H_2$ and the resulting emissions. Still some parameters are needed to convert the input to an output (such as conversion efficiency, maximum conversion capacity and emission rates), but the engineering behind the technologies is not in the scope of this research.

## 1.2. Research Question

The objective of this research, together with the knowledge gap, little research on the implementation of sustainable flexible energy generation, and the system boundaries, the main research question becomes:
*What is the most effective way of generating electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective?*
To answer this question the following sub-research questions have to be answered:

- *What is the expected electricity demand profile in Moerdijk in 2040?*
    - This question gives a better understanding of the electricity production char-

**Figure 1.4:** The system boundary of the focus of this research




acteristics that are needed in Moerdijk. This profile is needed in order to design alternatives that are capable of producing this electricity demand profile.

- *What are possible alternatives for flexible hydrogen-powered energy generation via the gas turbine in Moerdijk?*
  - This question helps to build different possible alternatives that in theory can be used to balance the energy grid with the gas turbines via hydrogen. These alternatives have certain benefits and downsides compared to each other and different capital costs associated with them. This question therefore gives a clear overview of the different possibilities that there are for using hydrogen compared to natural gas.
- *What are the implications for the adaptability, longevity and dependability of the implementation of each alternative for expected infrastructure in 2040?*
  - This question helps to give a better understanding of the problems and opportunities and their respective magnitude when implementing hydrogen combustion in the turbine in Moerdijk or continue running on natural gas.
- *What is the total annual cost in 2040 of flexible produced energy associated with the implication of hydrogen in the Moerdijk plant for each alternative?*
  - This question identifies the different costs of energy production over the year 2040. This helps to identify the alternative that has the lowest costs of energy based on the total amount of energy produced and total annual cost over the year.

# 2 Methodology

In order to answer the research question: *What is the most effective way of generating electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective?*, a non-participatory simplified additive weighting multi-criteria analysis is conducted, later referred to as MCA. During this MCA, the sub-research questions are answered. Contributing to the overall conclusion of the research question.

This MCA method is chosen as a simplified model offers a high level of flexibility and adaptability in the case of any difficulties or problems, while the additive weighting method is a model that is widely known and straightforward to use. The analysis is conducted by one person, making it a non-participatory MCA (Dean, 2022). This research will follow the steps outlined in the MCA by Kennisportaal Klimaatadaptatie (n.d.), with an adaptation that involves the identification of objectives in step 2, as detailed by Dean (2022). Additionally, steps 3 and 4 are interchanged.

These changes lead to the following MCA steps:

1. First the context for this analysis is derived. This will help to identify the stakeholders, the current, and future situation.
2. Secondly the objectives of the analysis are identified.
3. After this, the different criteria are established based on the objectives.
4. Fourth, alternatives are identified.
5. Next, the criteria have to be standardised.
6. Next, the weights are assigned to the different criteria.
7. After the weights are assigned, the scores are multiplied with the weights for the different alternatives. Ranking the different alternatives.
8. Lastly, a sensitivity analysis is performed.

For this research, the MCA is divided into three different phases. The first phase will add context and reason to the research. This will include the first four steps of the MCA and also answer the first two sub-research questions. Next, phase two will gather and process the data that is needed to score the alternatives to the different criteria. Phase 2 will therefore contain step 5 and 6 of the MCA, answering the next two sub-research questions. The last phase will contain steps 7 and 8, concluding the MCA and answering the main research question.

## 2.1. Methodology phase 1: Establishing the Context of the Analysis

The first phase of the MCA starts by establishing the context for the first step. To do this, the information gathered in the background study is used combined with consultations and advice from professionals within the RWEG. This context will highlight the problem that has to be solved, as well as the stakeholders involved and relevant technical, environmental, and economic aspects. Besides this, the first sub-research question is answered, namely: *What is the expected electricity demand profile in Moerdijk in 2040?* This question is answered using running data of the Moerdijk CCGT, energy data from 2023, as well as future energy forecast data for the year 2040. With this data, the intermittent renewable electricity production and total electricity demand for 2040 is established. What is used to estimate when there is a need for dispatchable energy generation. Which is scaled to an electricity running profile for the CCGT in Moerdijk.

Next the list of objectives is made. This is done by analysing the situational context and the background literature research, as well as following the guidelines and targets of RWEG, the operator of the CCGT in Moerdijk, and the guidelines and goals set by the Dutch government to reduce emissions. The objectives are divided into three different aspects related to the research question: the environmental, economic, and technical aspects.

To establish the criteria needed in step three of the MCA, each objective identified in the previous step is formed into a criteria. This is done by taking into account the key goals of each objective and find the measurable aspect of the objective. This measurable aspect is used to decide if a low or higher value is preferred in order to reach the objective. Based on the objective and the corresponding measurable aspect of the objective a criteria is formed. To keep the research manageable (Dean, 2022), the amount of criteria is kept to a maximum of 10.

The next step in the MCA is to answer the second-research question: *What are possible alternatives for flexible hydrogen-powered energy generation via gas turbines in Moerdijk?* Findings from the background literature, combined with the results from the previous steps in the MCA are used to form different alternatives that enable the current CCGT to run on hydrogen to provide flexible power generation. The alternatives will each vary on different components of the system to analyse the different impacts that these components have. These alternatives will vary on the type of hydrogen that is used, the origin and production method of the hydrogen, the transport distances and routes of hydrogen, the location of hydrogen storage, and the method of hydrogen storage.

## 2.2. Methodology phase 2: Scoring of the Criteria

The second phase will start by gathering the quantitative results needed to answer the sub-research question: *What is the total annual cost in 2040 of flexible produced energy associated with the implication of hydrogen in the Moerdijk plant for each alternative?* These results are gathered by building an optimisation code using the Pyomo optimisation language. The Pyomo optimisation language is chosen as it offers great flexibility in the solvers that can be used, the ability to use a many different Python libraries, and because of past experience with Python and Pyomo coding. This code optimises the minimal annual operating cost based on the running profile of the CCGT in Moerdijk and the alternatives established in the previous steps. This helps to better understand the cost structure for each alternative and provide the total capital and operational expenses.

After the total annual costs are established and the research question is answered, the qualitative results are gathered. This gives an answer to the sub-research question: *What are the implications for the adaptability, longevity and dependability of the implementation of each alternative for expected infrastructure in 2040?* To answer this research question, semi-structured interviews are conducted with six different professionals inside the energy sector. These interviews start of with a general question related to implementing hydrogen combustion in gas turbines. Further questions are based on specific or interesting topics that are mentioned by the professionals, but made sure to cover aspects related to the different qualitative criteria. In the case that no interesting or specific topics are brought up, a list of prepared questions, that is shown in subsection A.6.2, is used.

These interviews are afterwards coded in order to identify any problems or opportunities that might have an effect on the implementation of each alternative.

To equally score the results in the MCA, they are standardised. The results thus have equal or no units.

To standardise the results, a minimum-maximum normalisation is used to scale quantitative data to a range between 0 and 1. Keeping the same distance between certain quantitative results (Pena et al., 2022). Where the best performing value is assigned to 1 and the worst performing value is assigned to 0. The values in between the minimum and maximum can be derived by the formula as can be seen in Equation 2.1 and Equation 2.2

$$\text{When higher data is better: } z_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \tag{2.1}$$

$$\text{When lower data is better: } z_{ij} = \frac{x_j^{max} - x_{ij}}{x_j^{max} - x_j^{min}} \tag{2.2}$$

This method is not directly possible for qualitative data. Based on the coding of the qualitative data, different problems and opportunities are derived. In order to quantify these problems and opportunities, the total amount of times the code of the problem or opportunity is mentioned with a positive or negative attitude is counted. This aids to get a better understanding of the topics importance. If multiple professionals more often mention a topic, it is presumed to be more significant. In contrast, if a topic is mentioned infrequently or only by a single professional, it is presumed to be of less significance. This method allows for the scoring of each problem or opportunity, which can then be standardised using the method mentioned before.

After standardising the results for the different criteria, the next step assigns weights to each criteria. This is an important task, as minor changes to the weights of the criteria can result in major changes in the outcome of the multi-criteria analysis. The weights are mostly arbitrary if decided fully by the analyst (Dean, 2022). In order to thus derive the weights as fairly as possible, a non-compensatory weighting technique is chosen. This is chosen as the weight itself should reflect the importance of the criteria itself (Dean, 2022). The exact technique chosen is the adapted ranking system of Dean (2022). The formula for this can be seen in Equation 2.3. This method is chosen as directly assigning weights to criteria can be challenging for the analyst. It is more feasible to rank the criteria from most important to least important. In order to rank the criteria, participants in the semi-structured interviews are also asked to rank the criteria based on what they think is the most important to least important. The final ranking of the criteria is established based on the median of the rankings provided by the participants.

## 2.3. Methodology Phase 3: Conducting the Multi-Criteria Analysis

Phase 3 covers the last steps of the MCA. This phase at first determines the best performing alternative in the MCA by multiplying the standardised scores with their respective criteria weights for each alternative. After which it combines all weighted scores across criteria for each alternative to identify the overall best performing alternative. To establish these weights related to the ranking of the criteria for the MCA, Equation 2.3 is used (Dean, 2022).

$$w_j = \frac{N - r_j + 1}{\sum_{j=1}^{N}(N - r_j + 1)} \tag{2.3}$$

Where:

$r_j$ : Ranking value for the j-th criteria
$N$ : Total number of criteria

After the top performer is established, three sensitivity analyses are conducted. These sensitivity analyses shows the importance (or lack thereof) of the alternatives in the case of a variation in one or more of the weights of certain criteria.

This is done by establishing a new ranking of the criteria to assign the weights to. This ranking is similar to the original ranking. However, in the sensitivity analysis, a single criterion is either moved to the bottom or top depending if the weight of the criteria increases or decreases, while the rankings of the other criteria remain unchanged.

For the three sensitivity analysis the criteria *Capital expenditure* and *Overall system efficiency* are moved to the bottom of the ranking, and the criteria *Carbon emission reduction* is moved to the top of the ranking. With these changed weights of the criteria, a new MCA is conducted.

The results of the original MCA and the effect that the sensitivity analysis has on the outcome of the MCA is used to answer the research question: *What is the most effective way of generating electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective?*

# 3
# Literature Review

To gain a better understanding of flexible power generation and its techno-economic related aspects, a literature review is conducted. This literature provides the basic knowledge that is needed to understand the context of this research. Besides this, the literature study identifies the knowledge gap that this research aims to address.

This literature review consists of three parts. Section 3.1 gives an overview of the current state of the literature regarding the problem at hand. Subsequently, section 3.2, explains the key concepts that are concluded from the existing literature, and are related to flexible power generation. Lastly, section 3.3 gives an explanation of the knowledge gap that exists in this field and thus give reason for the research question to exist.

## 3.1. Existing Literature

To find relevant literature, the search terms to find the literature can be seen in Table 3.1, together with the total results. From the results that showed potential in offering technical or economical insight in the technologies mentioned in the research boundaries, the abstracts are scanned in order to filter out the results that are relevant to the problem of this thesis. From these relevant results, the whole text is scanned. Besides using concepts related to the problem, such as hydrogen and energy generation in the Scopus search string, relevant terms from the scanned abstracts were used. For instance the search term "duck curve" and ramping products.

Of the 63 relevant articles based on the abstract, the full text is scanned. This results in 29 sources being used in the background literature study. These sources and their main focuses can be seen in Table A.1.

## 3.2. Key Concepts

In the background literature study, five main concepts are identified based on the main focus of the literature: Hydrogen Turbine electricity generation, Hydrogen storage, Hydrogen transport, Hydrogen Production, and Hydrogen economics. The relation of the sources to these concepts can also be seen in Table A.1.

**Table 3.1:** Literature results from Scopus search terms

| Scopus search terms | Total results | Relevant results |
|---|---|---|
| Hydrogen AND Energy Generation | 47 | 11 |
| Flexible AND Energy Generation | 23 | 6 |
| Duck Curve AND Flexible | 23 | 7 |
| Hydrogen AND Gas Turbine AND Flexible OR Flexibility | 12 | 3 |
| Hydrogen AND Turbine AND Generation | 32 | 8 |
| Hydrogen AND Transport AND Infrastructure | 15 | 5 |
| Flexible AND Ramping AND product | 54 | 9 |
| Sustainable AND Energy AND Economics | 43 | 7 |
| Hydrogen AND Techno-economics | 12 | 6 |
| Snowballed papers | | 8 |
| **Total** | **206** | **63** |

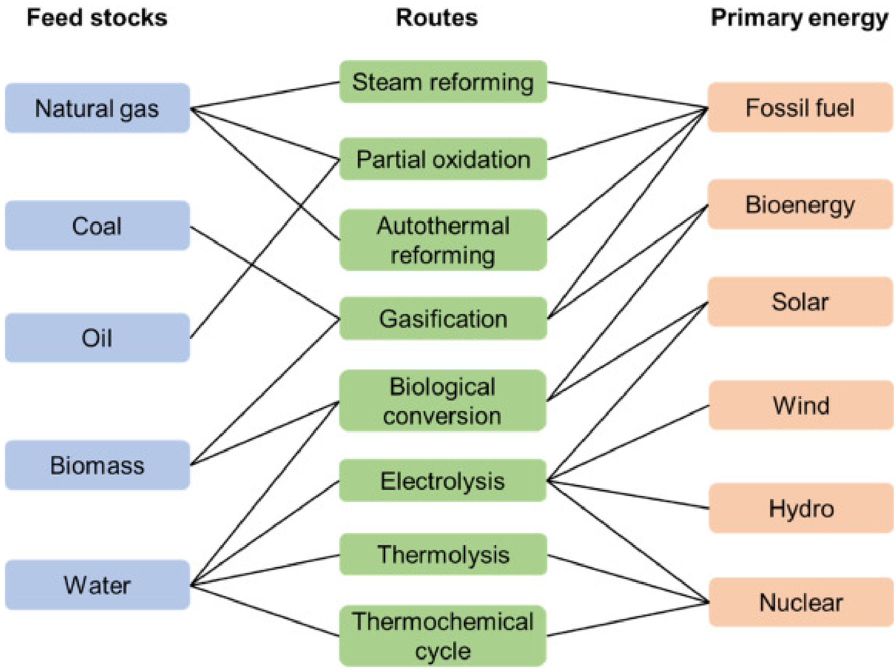
In the next parts, these concepts are explained in more detail. These concepts help to make informed decision when establishing the alternatives for the multi-criteria analysis.

### 3.2.1. Hydrogen Production

The first concept that is important to take into consideration, is the source of the hydrogen and how its production impacts the environment. The focus of this research is on the use of hydrogen for sustainable flexible energy production, therefore it is important to know how sustainable the production of hydrogen is and the consequences of each production method. It is not the goal of this research to focus on the understanding and knowledge of the technical aspects and workings of the production methods. Although hydrogen is one of the most common elements in the universe, hydrogen itself is almost exclusively found in compounds on the earth (Ji & Wang, 2021). Burning or processing hydrogen results in the emission of water, making it a clean energy source (Nowotny & Veziroglu, 2011). Although hydrogen itself is almost always combined with other materials, it needs processing to get clean and separated hydrogen. There are several ways to produce hydrogen, using both non-renewable energy sources and renewable energy sources. Ji and Wang (2021) mentions eight different routes for hydrogen production. These can be seen in Figure 3.1. Ji and Wang (2021) also mentions that light-based hydrogen production methods produce fewer waste emissions compared to other production methods, but they currently lose their advantage when taking into account cost and efficiency. Besides the routes that can be seen in Figure 3.1, Agyekum et al. (2022) also adds an additional route: photolysis.

Besides these hydrogen processes, AlZohbi (2024) describes that hydrogen can be divided into 7 different colours. The colours are Gray, Blue, Green, Brown, Turquoise, Yellow and White. Each colour represents the production method of corresponding hydrogen. Where grey and brown hydrogen are both produced using fossil fuels, emitting the carbon from the process into the air. Turquoise hydrogen is processed using a method where the carbon is emitted in a solid form, making it easy for the carbon to be repurposed. While white hydrogen is hydrogen found in the crust of the earth. Blue hydrogen also uses fossil fuels such as natural gas, but with little carbon emissions. A way to generate this hydrogen is via Steam Methane Reforming (SMR),

**Figure 3.1:** Production routes, energy sources and feedstock overview made by Ji and Wang (2021)




as this is currently the most economical and preferred way of hydrogen production according to Ali Khan et al. (2021). The downside of this process is that it emits a large amount of carbon. However, if this carbon emitted in the production process is captured and stored using Carbon Capturing and Storage technologies (CCS), blue hydrogen is formed (Ali Khan et al., 2021). Green and yellow hydrogen both produce hydrogen using renewable energy sources, the difference is that yellow hydrogen only uses solar energy. There are several methods to produce green or yellow hydrogen, but the most promising way to produce green hydrogen is via electrolysis supplied by green electricity according to Trattner et al. (2021). Based on the electrolyte used for the electrolysis of water, Trattner et al. (2021) mentions the following methods: proton exchange membrane electrolysis (PEMEL), anion exchange membrane electrolysis (AEMEL), alkaline electrolysis, (AEL or AEL-EL), high-temperature electrolysis (HTEL). For fluctuating power delivery such as wind of solar power, PEMEL and AEMEL are preferred. These methods manage the dynamic power delivery better compared to the other ways of producing green hydrogen (Trattner et al., 2021).

### 3.2.2. Hydrogen Transport

After hydrogen is produced, it is also important to be able to get the product from the location of production to the location of usage. This results in the next key concept, hydrogen transport. There are different possibilities for the large-scale high volume transportation of hydrogen.

One way to transport hydrogen is through the retrofitment of the current natural-gas pipelines (Haeseldonckx & Dhaeseleer, 2007). Another option according to Haeseldonckx and Dhaeseleer (2007) is the installation of a parallel pipeline network specifically for hydrogen. Murthy Konda et al. (2011), SMIT et al. (2007), Tezel and Hensgens

(2021), and Thawani et al. (2023) all mention that hydrogen transport is feasible on a large scale, at least for the Netherlands, although there are problems associated with this. In the case of transport via natural gas pipelines, there are still multiple aspects that have to be considered. Laureys et al. (2022) mentions the technical problems that might arise due to hydrogen embrittlement and problems with the ductility and fracture toughness of the steel pipelines. Thawani et al. (2023) also discusses the fact that there can still be safety concerns that would need policy changes. This is also in line with the conclusion of the report of Tezel and Hensgens (2021). In the case of a specific hydrogen pipeline network, the biggest problems are the costs and the space. SMIT et al. (2007) expected that the estimated cost for hydrogen pipelines in the Netherlands can go up to 20 billion euros. It is also mentioned that it would only be economically viable if the cost of hydrogen would be 0,5 euros per kilogram or less. Murthy Konda et al. (2011) also points out the benefits of pipelines concerning economies of scale. If the demand is high enough, investors might be willing to invest in the benefits of purposely built hydrogen pipelines.

In the Netherlands, Gasunie provides the hydrogen network in the future years. This network will consist for 85% out of existing natural gas pipelines and 15% out of specific hydrogen pipelines. The network will become available in phases starting from 2025. The network will connect large-scale hydrogen facilities, domestic and foreign businesses, and harbours (Gasunie, 2023). Gasunie also estimates that the costs for this network based on existing natural pipelines and new hydrogen-specific pipelines will cost 1,5 billion euros (Gasunie, n.d.-b). This is very little compared to the previously mentioned 20 billion euros for a fully hydrogen-specific network.

### 3.2.3. Hydrogen Storage

As the production and usage of hydrogen are not equal at all times, it is also important to have the ability to store hydrogen. Therefore the third key concept is hydrogen storage.

According to Sikiru et al. (2024) and Zhang et al. (2016), there are three different ways of storing hydrogen. These three can be defined as physical storage as compressed gas, physical storage as cryogenic liquid hydrogen or as materials-based storage. These methods can take place above ground or under the ground. Materials-based storage is not suitable for high demands and has a significant impact on the environment according to (Sikiru et al., 2024). Therefore this research focuses on the first two mentioned methods.

It is often preferred to store large amounts of hydrogen under the ground. The storage capacity of underground storage spaces is large and has a reduced explosion risk by removing the direct link between hydrogen and the oxygen in the atmosphere (Sikiru et al., 2024). There are different options for storing hydrogen underground. For instance the use of aquifers, depleted oil and gas reservoirs or the use of salt caverns (Muhammed et al., 2022), (Lackey et al., 2023). One of the most often used ways to store large amounts of hydrogen underground is with the use of salt caverns as compressed gas. These caverns are chosen as they have some favourable perks like being able to withstand high pressure and temperatures, are easily accessible, and have little microbial activity (Muhammed et al., 2022). Besides this, salt caverns are cost-effective and capable of facilitating multiple injection and production cycles (Sainz-Garcia et al., 2017), (Ershadnia et al., 2023). Making salt caverns capable for seasonal energy mismatches according to Sainz-Garcia et al. (2017).

There is also the possibility to store the hydrogen above ground. One of the most popular methods of hydrogen storage above ground is via high-pressure gas (up to 700 bar) in suitable tanks or cylinders. This is often chosen because of the simplicity and the rate at which the tanks and cylinders can be filled and released (Zhang et al., 2016). However, Zhang et al. (2016) also mentions that the problem is that the volumetric density of hydrogen gas does not scale linearly with its pressure.
Hydrogen can also be cooled and liquefied at a temperature of -253 °C and stored in its liquid form (Sikiru et al., 2024), (Zhang et al., 2016). The higher density results in more energy storage per volume unit. Zhang et al. (2016) even mentions that the cost for low-pressure liquid hydrogen tanks can be low. The downside however is that to form the hydrogen in the liquid state, it takes a lot of energy and resources (Sikiru et al., 2024), (Zhang et al., 2016). This results in a larger amount of energy loss compared to the compression of hydrogen gas. Where the energy loss is almost 4 times as high (estimated at 40% compared to compressing hydrogen gas) (Sikiru et al., 2024).

Overall, the energy efficiency of converting hydrogen to a liquid state for storage and afterwards re-expanding it into a gas remains low and requires improvement. AlZohbi (2024) mentions that the efficiency can be as low as 32% while still having a much higher cost of storage compared to petroleum fuels. Highlighting the need for innovation and research with respect to hydrogen storage.

### 3.2.4. Hydrogen Turbine Electricity Generation

In order to turn the hydrogen back into electricity, turbines can be used. Öberg et al. (2022a) mentions that the use of hydrogen-fueled gas turbines is mostly competitive in energy systems that have a large share of wind power. The reason is that the characteristics of turbine energy generation are best suited for the intermittent fluctuations of wind power. This is in line with the goals of the Dutch government that are mentioned in chapter 1. This leads thus to the last key concept: Hydrogen turbine energy generation.

A turbine generates energy by first compressing air after which a fuel source is injected under pressure. This mixture of air and fuel is ignited and expands. This expansion drives the turbine that is connected to a generator creating electricity. In the case of combined cycle gas turbines, the heat generated by burning the air and fuel mixture is used to generate high-pressure steam. This high-pressure steam is expanded over a steam turbine that is also connected to a generator creating electricity. This way the efficiency of the energy generation increases.

To generate energy via hydrogen-fueled turbines, two options are possible: building a new turbine to run on hydrogen, or re-purpose an existing turbine to run on natural gas. First, Some challenges must be overcome to run an existing turbine on hydrogen. Because hydrogen has different properties compared to natural gas, modifications have to be made to the turbines. According to www.dieselgasturbine.com (2021) hydrogen ignites and burns more quickly, together with a higher fuel-to-air ratio compared to natural gas. Therefore certain equipment has to be changed in order to be optimised for this ratio and burning characteristic. Due to the faster ignition, the flame moves towards the burner. This has to be changed as it can lead to unwanted and uncontrolled burning characteristics. Also, the ventilation and gas detection systems must be changed to accommodate the burning of hydrogen, as well as the flow of the gasses that have to be optimised for the new characteristics that hydrogen has compared to natural gas. All materials have to be checked of they are suitable for the use of hydrogen, and if they are not, be replaced with suitable materials. www.dieselgasturbine.com (2021) also mentions the fact that all these changes and checks can be performed during regularly scheduled maintenance time. It must also be noted that in the case of certain turbines, the starting procedure of the turbine may still use natural gas, or need a different starting procedure.

If it is not feasible or possible to alter an existing turbine to run on hydrogen, new hydrogen-specific turbines can be installed. Siemens-Energy (n.d.) already showed the possibility of having a new turbine work on 100% hydrogen fuel, reducing greenhouse gas emissions to near 0.

### 3.2.5. Hydrogen Economics

Energy is an essential good that justifies the discussion of energy and fuel poverty (Madlener, 2020). The depleting of fossil fuel deposits combined with the goals of a more sustainable future, raises the question how the economy will adjust to the new and changing circumstances (Frieling & Madlener, 2017). This therefore also relates to the availability of hydrogen as a future fuel source. The production of renewable hydrogen has some great challenges associated with it. One of these challenges has to do with the high production costs and infrastructure needs, especially taking into account the gasification and steam methane reforming methods that currently dominate the production of hydrogen (Nemitallah et al., 2024). Currently the cost of green hydrogen is 2-3 times as much as of hydrogen based on fossil fuel, such as grey hydrogen. The downside is that the price competitiveness of green hydrogen is hindered by techno-economic factors. The future perspective and competitive pricing of green hydrogen strongly depends on the reduction of investment costs and financial risks (Benalcazar & Komorowska, 2024). The costs of green hydrogen can vary a lot, but PEM electrolysis aims for a cost below $2.30/kg (Nemitallah et al., 2024). In order for green hydrogen to reduce in costs, stable investments and ongoing development would be needed. According to Parkinson et al. (2018) steam methane reforming is the most cost-effective process for producing hydrogen. However, Parkinson et al. (2018) also suggests that due to the cost disparity between hydrogen produced with renewable electricity and hydrogen produced via fossil-based fuels, methane pyrolysis will be an cost-effective means during the transition period towards a fully renewable hydrogen production process. Although geothermal, biomass, and nuclear-driven electrolysis and thermochemical technologies show competitive potential, hydrogen based on fossil fuels remains the most cost-effective way of hydrogen production for a more sustainable future (El-Emam & Özcan, 2019).

## 3.3. Knowledge Gap

From this literature review shown in section 3.1, combined with the plans of the Ministery of Economic Affairs and Climate Policy (2020) that are mentioned in chapter 1, show the existence of a knowledge gap, as well as the need to address this knowledge gap.

The literature study is divided in five key concepts that are essential for designing the alternatives needed for flexible electricity production using gas turbines with hydrogen. It can be seen that for each key concept individually there is already ample amount of research to be found. Discussing the technical, economic and environmental aspects of these concepts in detail. The problem that occurs is that there is currently little research on the interconnection of these key concepts and how they effect each other. From the 27 sources that are used in this research, only 5 sources make in some way a connection between at least two different key concepts. Murthy Konda et al. (2011) being the only source in this research to make a connection between four of the five different key concepts mentioned.

Despite the growing interest in hydrogen as an energy carrier, there exists little research on the connection of several technologies needed for electricity generation via hydrogen. Especially when the focus is on sustainable electricity generation via gas turbines for flexible power generation from a techno-economic perspective. The issue is that these key concepts are most often implemented together. However, the lack of research about the interconnection between these concepts can lead to sub-optimal use of the total system. Therefore, a research that considers all the different key concepts and how they interrelate can provide valuable insights into the implementation of hydrogen. The lack of this research can lead to uncertainty and higher risks for policymakers and energy companies to make well informed decisions about future strategies.

From a technical perspective, the optimal approach might be to increase the efficiency of each individual technology in order to achieve the highest possible overall system efficiency. However, this might not be the most economically feasible solution. This can be mainly related to the economics of energy production. In order to provide energy for the lowest price, the cost of production should be as low as possible. Although a lot of research is put in making technologies more efficient, it does not necessarily mean that the cost will go down. Even if the operational or capital cost of specific technologies goes down, does not directly lead to lower overall production cost. If for instance a specific hydrogen production method is able to produce hydrogen at a lower cost, it might require the need for more hydrogen transport or storage facilities. Increasing the overall cost of energy production.

Therefore the main research question: *What is the most effective way of generating electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective?* helps to reduce this knowledge gap.

## 3.4. Considered Technologies

This literature review concludes with the selection of eight different technologies: two for hydrogen production, two for hydrogen transport, two for hydrogen storage, and two for electricity generation.

For the hydrogen production method, the production of green hydrogen via electrolysis, and the production of blue hydrogen via SMR. These methods are considered as they produce hydrogen via completely different means, while both delivering low carbon intensive hydrogen. The use of both of these distinct hydrogen production methods in this research will reveal the advantages and disadvantages of each production characteristic.

For the transportation of hydrogen, pipelines are considered in this research. Due to the quantities of hydrogen that has to be transported each hour, pipeline transport is most suitable. Therefore the use of retrofitted natural gas pipelines, and new hydrogen specific pipelines are considered.

For the storage of hydrogen, two methods are considered. The first method is to storage large quantities of hydrogen in underground salt caverns. Salt cavern hydrogen storage is chosen as it offers great perks for large scale hydrogen storage and are cost-effective. The downside of this storage method is that is restricted to areas with large salt deposits. Therefore it is also chosen to consider hydrogen storage in liquid form in an above ground tank. Although this method seems more expensive and energy intensive, it gives the flexibility to store hydrogen on location.

For electricity generation, energy production via combined cycle gas turbines on hydrogen are considered. Both new hydrogen specific turbines, or the retro-fitment of existing turbines to run on hydrogen are considered. The use of these turbines offers the ramping capabilities and on demand availability needed for flexible energy production.

# 4

# Phase 1: Establishing the Context of the Analysis

The first Phase sketches the context of the problem and forms the different alternatives for the multi-criteria analysis. Giving an answer to the first two sub-research questions: *What is the expected electricity demand profile in Moerdijk in 2040?* and *What are possible alternatives for flexible hydrogen-powered energy generation via the gas turbine in Moerdijk?* The first phase provides the objectives and requirements of the analysis, as well as the related criteria. The requirements are used to design and optimise the alternatives for the multi-criteria analysis, while the criteria are used to score the alternatives. Phase 1 therefore focuses on step 1 up to and including step 4 of the multi-criteria analysis.

## 4.1. Energy Production in the Year 2040

Mentioned before in chapter 1, the increase in intermittent renewable energy combined with the increase in energy demand leads to large gaps between electricity production and electricity demand. The focus of this research is on the year 2040, which allows for time to implement this research findings into strategies or policies while providing plenty of time to reach the sustainability goals set by the Dutch government for 2050. To better understand the need for the flexibility of CCGT energy production, there must be an estimate of the size and frequency of these gaps and the periods in which these gaps occur most often. This should be scaled to the needs and capacity of the plant in order to showcase the demand for flexible energy generation. This is also needed in order to conduct the multi-criteria analysis, and to answer the first sub-research question *What is the expected electricity demand profile in Moerdijk in 2040?*

### 4.1.1. Running Profile Moerdijk

To solve this sub-research question, an estimation for the running profile of Moerdijk in 2040 is made in order to get a better understanding of the amount starts and stops that have to be made, and the periods when the demand for flexible power generation is high or low. For the running profile an granularity of an hour is used, as it provides great detail while still keeping the total amount of data manageable. This running profile is used in order to minimise the total annual cost of energy production. What is used to score different criteria. Three running profiles are established on the basis of future estimations of installed capacity and consumption of energy. This data is part of energy forecasts for the year 2040 provided by Aurora Energy Research (2024). One running profile is established where there is a large increase, and thus a high installed capacity of installed solar, onshore wind, and offshore wind energy in 2040. This is the high forecast running profile. Another running profile where there is a minimum increase of these energy sources is established, resulting in a minimum installed capacity of solar, onshore wind, and offshore wind energy in 2040. This is the low forecast running profile. Last a central forecast running profile that is in between the previous two mentioned running profiles is established. It is chosen to use the low, central and high forecast data by Aurora Energy Research (2024) in order to have a better understanding of the implementation of the different alternatives in the two extreme low and high cases, as well as the central case to better understand how the alternatives change from the low to the high forecast. This helps to better understand and estimate the feasibility of the alternatives in 2040 across a range of predictions for the year 2040.

It is important to know the exact data from 2023. To get this data, first the monthly hourly load values aggregated by country are gathered to establish the energy demand profile of the Netherlands (ENTSO-E, 2024b). After this data is gathered and filtered to just show the hourly load values of the Netherlands, the hourly data of the production of intermittent energy sources in the Netherlands are gathered. This is done with the use of Gasunie and TenneT (n.d.) via use of the Nationaal Energie Dashboard. The raw data is requested with the use of an API, while a visualisation of this data can be seen in Nationaal Klimaat Platform (n.d.). Via this API, the energy production data from solar energy, onshore wind energy, and offshore wind energy, are gathered separately.

The next step in establishing the running profiles is to estimate the load and renewable energy data in 2040, based on the 2023 data. For the increase in renewable energy generation, first the installed capacity of solar and wind energy sources provided by Centraal Bureau voor de Statistiek (2024) is compared with the expected installed capacity for the low, central and high forecast provided by Aurora Energy Research (2024). An overview of this data can be seen in **confidential appendix**. The same is done for the expected total energy demand. First the total energy demand in TWh from 2023 was calculated based on the energy data provided by (ENTSO-E, 2024b). The total energy demand is compared to the low, central and high forecasts of Aurora Energy Research (2024), both resulting in a percentage increase in total energy demand.

The hourly data for renewable energy production and total energy demand are all scaled with their respective and corresponding percentage increase. Resulting in a low, central and high forecast estimated data for the production of renewable solar energy, energy from wind on land and energy from offshore wind. The same method is used for a high, central and low forecast for the total energy demand per hour.

For the low, central and high forecasts cases, the total production of these renewable energy sources in 2040 is removed from the corresponding total energy demand. Resulting in the total energy needed form dispatchable and flexible energy generation in the Netherlands for the year 2040.

Specific limitations provided by RWEG staff are considered in the establishment of the running profiles. The total amount of yearly running hours for the CCGT should not exceed 2000 hours. Besides, the minimum generation capacity is 205 MW, and the maximum is 441,6 MW. In order for the CCGT to run, it must run for at least 4 consecutive hours and be turned off for a minimum of 5 hours. This is also in line with the hours mentioned by Nelson and Wisland (2015). The CCGT is assumed to be able to ramp from minimum to maximum capacity with 50MW/min if needed. This results in less than 5 minutes to ramp from minimum generating capacity to maximum capacity. Because the running profile is established with the granularity of an hour, the 5 minutes of ramping are assumed to be negligible and the ramping is thus taken as instantaneous in the running profile. The same holds for the startup of the CCGT. The moment that the CCGT has to run at full or minimum capacity is predicted with the granularity of an hour, it is thus assumed, for the purpose of this research, that the CCGT is able to run at the specified capacity at the given time.

After verification with industry experts, and for the simplification of this research, these limitations are considered as a given. These limitations are applicable to all the alternatives tested in the multi-criteria analysis, and are taken to be the same for a non-modified, a modified, or a new turbine. An overview of the limitations can be seen in Table 4.1.

**Table 4.1:** CCGT Moerdijk Profile Limitations

| | **Maximum running hours** | **Minimum generation capacity** | **Maximum generation capacity** | **Minimum down time** | **Minimum running time** |
|---|---|---|---|---|---|
| Limitations | 2000 hours | 205 MW | 441,6 MW | 5 hours | 4 hours |

The total hours when there is a need for dispatchable flexible power generation is more than 2000 hours. The need for dispatchable flexible power generation is more than the limitation set for the maximum running hours for the CCGT. The running profile therefore only generates during the largest gaps between intermittent renewable energy production and total energy demand in the Netherlands in 2040.

Keeping within the limitations of the CCGT in Moerdijk an iterative process is used to form a running profile that consists of 2000 running hours. This is done by first taking the highest 2000 values of the need for flexible energy generation and replacing the other values with 0. This data is next altered to satisfy the minimum down and running time by replacing series of 3 or less consecutive values with 0 and replacing series of less than 5 0's between the generation values with the CCGTs minimum generation capacity of 205 MW. This results in a total amount of running hours. Based on this total, the lowest value in the running profile that is not 0 or 205 is replaced by 0 if the total amount of running hours is more than 2000, or the next highest value from the original total need for flexible energy generation data that is not yet in the running profile is added if the total amount of running hours is less than 2000. After this, the data is again altered to satisfy the minimum down and running time. This is done until the profile has 2000 running hours for both the low, central, and the high forecast data provided by Aurora Energy Research (2024).

Now there is almost a complete running profile with the times when the CCGT in Moerdijk should generate. The values in this profile still represent the total need for flexible power generation in the whole Netherlands. This should be scaled down to the capacity that Moerdijk should generate.

To estimate this scaled down need for flexible power generation, the installed capacity of Moerdijk is compared to the expected total installed capacity available for flexible power generation for the low, central, and high forecast. To calculate the expected total installed capacity, the installed capacity of hydrogen, oil and gas peakers, gas and hydrogen CCGT's and DSR (Demand Side Response) are added together. These technologies are chosen as these technologies provide the ability to flexibly produce energy, or flexibly lower the demand of energy. Thus flexibly reducing the gap between renewable energy production and energy demand. An overview of the installed capacity of these technologies can be seen in **confidential appendix**.

Scaling the need for flexible energy generation in the running profile of Moerdijk with the ratio found by dividing the maximum capacity of Moerdijk with the expected total installed capacity of technologies available for flexible power generation resulted in generation values that were all still higher than the maximum generation capacity of Moerdijk as is mentioned in Table 4.1. Therefore if the values are higher than the maximum generation capacity of the CCGT in Moerdijk, they are replaced by the maximum generation capacity. This results in a running profile that can be interpreted as an on-standby-off switch for the generator. Where the CCGT only runs on its maximum capacity, runs on its minimum capacity to stand by, or is turned off.

This results in three different running profiles based on the high, central and low forecasts for 2040. The running profile consists of 8759 values, the average of these values per month is shown in Figure 4.1, and some key characteristics of the profiles can be seen in Table 4.2. The three running profiles give an answer to the first sub-research question: *What is the expected electricity demand profile in Moerdijk in 2040?*

In Figure 4.1 and Table 4.2 can be seen that the three running profiles are similar for each forecast, this has to do with the fact that even in the low forecast there is already more than 2000 hours of need for dispatchable energy generation. This not only showcases the need for flexible energy generation, but also the lack of dispatchable energy generation available for flexible power generation. This implies the need for an increase in installed capacity of dispatchable energy sources in the year 2040 beyond the expected installed capacity of dispatchable energy sources and the modification of the CCGT.

The demand for more than 2000 hours of dispatchable energy generation signifies that the running profiles are limited by their total running hours for all forecasts. Making all the running profiles similar with slight changes due to their distribution of the highest

**Figure 4.1:** Monthly average generation Moerdijk for the year 2040

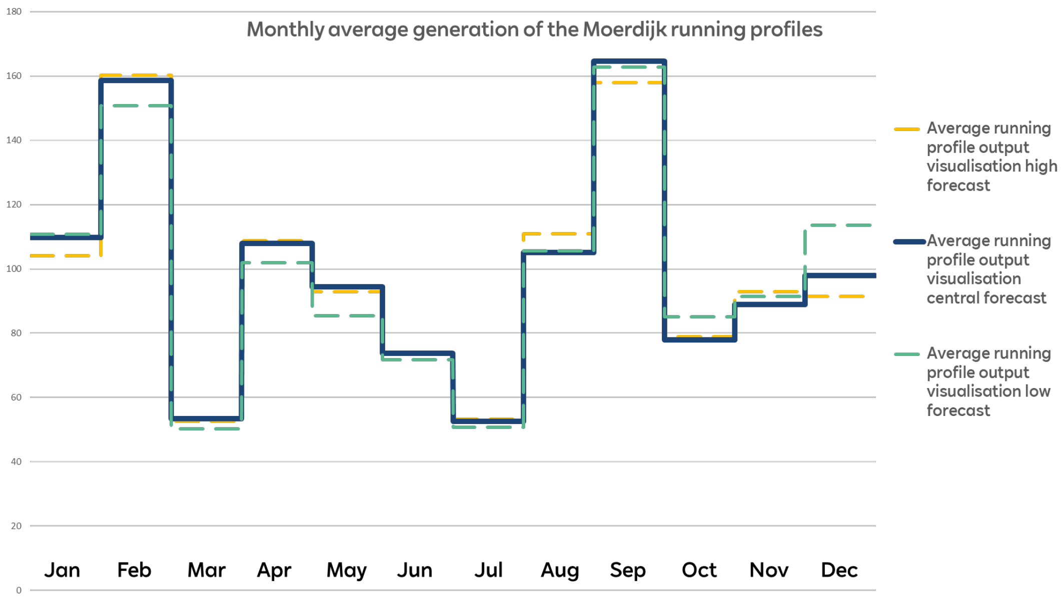



**Table 4.2:** Key factors of the Moerdijk running profiles for the year 2040

| | **Low Forecast 2040** | **Central Forecast 2040** | **High Forecast 2040** |
|---|---|---|---|
| Minimum Turbine power output | 205 MW | 205 | 205 MW |
| Maximum turbine power output | 441,6 MW | 441,6 MW | 441,6 MW |
| Total energy production | 861441 MWh | 864990 MWh | 859548 MWh |
| Total amount of starts | 168 | 159 | 154 |
| Full load running hours | 1908 | 1923 | 1900 |
| Minimal load running hours | 92 | 77 | 100 |

gaps between renewable energy supply and total energy demand. Because of this similarity, only the central forecast running profile is considered in this research.

### 4.1.2. Limitations and Assumptions of the Running Profile

Although utter care is taken in order to estimate the running profile as accurately as possible, there are some limitations regarding the running profile. A first limitation is for instance the fact that the running profile is directly based on the energy data from 2023. This thus takes into assumption the exact weather data from 2023 would occur in 2040. Because it is near impossible to predict accurate weather data for the year 2040, it is chosen to use the most recent available energy generation data for the predictions and base the new running profiles on this data, and thus also on the weather data for 2023.

Another limitation is the granularity of the data. For this research the data is on an hourly basis. The value of that corresponding data-point is the average value taken over the hour. It is taken into assumption that the data is constant throughout the whole hour and thus equal to the average of that hour. This is not fully realistic, as there can be variations within the hour. This problem can be lessened by taking a higher granularity. For instance increasing the granularity from 1 hour to 10 minutes. This increases the amount of data points by 6 times to more than 52000 data points. Because the goal of estimating a running profile for 2040 is to get a better estimate of the total amount of energy that has to be produced, in what periods most of this will be produced, and how often the CCGT will have to be started and stopped, the hourly basis provides enough data for the scope of this research.

The last limitation, that is already shortly mentioned before, is that fact that the start and ramping time of the CCGT are taken as instantaneous. This is chosen as the starts can be predicted and thus the start time can be planned accordingly, while the time it takes to ramp is little compared to the granularity that was chosen for this research. With a ramping rate of 50MW/min the CCGT can ramp from minimum to maximum capacity in less than 5 minutes. Resulting in less than 10% of the time that the data point covers is spent on ramping. If the granularity is increased, the effects of ramping are more noticeable because the ramping time is a larger part of the overall time that is covered by the data point. If the granularity is increased to 10 minutes, the ramping time is almost 50% of the time covered by the data point. Resulting in the ramping of the CCGT having a more significant impact on the value of the data point.

Overall the accuracy of the running profile can be increased by using a higher granularity, include the ramping of the CCGT, and use data from alternative weather predictions. This is not done as these implementations are not feasible in the time frame of this research. While these implementations also result in a running profile that outreaches the needs of the already established running profiles.

## 4.2. Objectives

For the analysis it is important to at first state the main objectives and requirements in order to establish the criteria. The goal of this research is a techno-economic analysis to help reach specific environmental goals. Therefore, the objectives are split into three different categories. These categories are: environmental, technical, and economical objectives.

### 4.2.1. Requirements

The most important are the requirements. These requirements must be met for the alternatives to even be considered in the analysis. These requirements are therefore used to design the alternatives. These requirements are:

- There must be a decrease in carbon and nitrogen oxide emissions compared to the current alternative on natural gas.
- The new alternative must be able to provide enough electricity to balance the intermittent energy sources and energy demand expected in 2040 for Moerdijk by being able to ramp to its maximum capacity at any given time.

### 4.2.2. List of Objectives

In order to establish the objectives, the targets of the RWEG are discussed, together with researching the goals laid down in the Climate Act on May 28, 2019 (Ministery of Economic Affairs and Climate Policy, 2020).

This in combination with the requirements mentioned above results in the first two environmental objectives. The target of RWEG is to be carbon neutral by 2040 (RWE, 2021) therefore the company tries to minimise carbon emissions as much as possible, resulting in the objective: *Minimise carbon emissions*. However, RWEG can only achieve this goal if it can stay competitive to keep the CCGT operational. Besides this, the goals laid down in the Climate Act on May 28, 2019 (Ministery of Economic Affairs and Climate Policy, 2020) state a large increase in installed capacity of solar and wind energy sources. A variety of different technologies are used to balance these intermittent renewable energy sources, including CCGT's. The need for balancing these intermittent renewable energy sources leads to the second objective: *Help to balance intermittent renewable energy and demand*.

From the technical perspective, the objectives are identified via consultations inside RWEG and the website of RWE (RWE, 2021). The objectives are formed on the basis of the targets , and the availability of resources of RWEG. The company strives to make the largest positive impact while minimising costs, and ensuring operational feasibility.

Therefore the first technical objective becomes: *Minimise technical complexity of hydrogen conversion*. This objective allows the company to use their valuable resources, such as research and development, across more and different projects. The second technical objective becomes: *Minimise infrastructural changes that have to be made*. This objective helps to reduce the resources that have to be used for such projects related to the infrastructure that is needed to run the CCGT on hydrogen. All while trying minimising the impact on the local environment, as large projects such the placement of hydrogen storage facilities can be very challenging and resource intensive. Minimising the infrastructural changes and difficulties associated with this objective helps to keep the conversion to hydrogen technically manageable, while minimising disruptions. The third objective is: *Ensuring long-term operation*. This objective helps RWEG to future proof systems. Ensuring a longer payback period for investment costs, decreasing the levelised cost of electricity, and maximising the systems relevance and usefulness over an extended period of time. The last technical objective is: *Be as efficient as possible*. Energy is a valuable resource and an efficient system ensures that this valuable resources is allocated as best as possible not wasting any energy and money.

For the economical category, the objectives become to *minimise the variable and investment costs*, *Reduce the risk of dependency*, and to have a *stable operational cost*. RWEG strives for minimal cost, ensuring the ability to sell the product for the lowest possible price and play a competitive roll on the energy market. This also relates to the stability in operational costs. The future is difficult to predict, therefore it would be beneficial if the operational costs are less dependent on the future perspectives. Stable operational costs predictions help to build more predictable company strategies, concluding the objective: *Stability in operational costs*. The last objective, *Reduce the risk of dependency*, relates from problems that might results in the dependency on other actors or sources. Being depended on specific resources and external stakeholders can lead to unexpected changes in costs or the availability of necessary resources.

An overview of these objectives can be seen in Table 4.3. Due to the techno-economic nature of this research, social objectives are not taken into consideration.

## 4.3. Criteria

These objectives are converted into different criteria, which are scored using qualitative and quantitative data. To form these criteria, four different rules described by Dean (2022) are followed. These rules state that the criteria should cover all important aspects of the problem. The criteria should be manageable, keeping the amount of different criteria to a minimum. The criteria must also be measurable as clearly as possible and be non-redundant. Meaning that the criteria must be different from another. An overview of these criteria with their corresponding objective can be seen in Table 4.3.

**Table 4.3:** Multi-criteria analysis criteria

| **Environmental** | **Objective** | **Criteria** |
|---|---|---|
| 1 | Minimise carbon oxide emissions | Carbon emission Reduction |
| 2 | Help to balance intermittent renewable energy and demand | Running profile conformance |
| **Technical** | | |
| 3 | Minimise technical complexity of hydrogen conversion | Technical adaptability |
| 4 | Minimise infrastructural changes that have to be made | Infrastructural adaptability |
| 5 | Ensuring long-term operation | Operational longevity |
| 6 | Be as efficient as possible | Overall system efficiency |
| **Economical** | | |
| 7 | Minimise variable costs | Operational expenditure |
| 8 | Minimise investment cost | Capital expenditure |
| 9 | Reduce the risk of dependency | Dependability |
| 10 | Stability in operational costs | Operational expenditure stability |

These criteria are scored partly on a qualitative base and partly on a quantitative base. If it is scored qualitatively of quantitatively depends on the ability and accuracy in which the data can be gathered. In Table 4.4 the division of the criteria can be seen based on if they are scored on a quantitative or qualitative approach.

**Table 4.4:** Criteria divided based on their quantitative or qualitative research method

| Quantitative | Qualitative |
|---|---|
| Carbon emission reduction | Technical adaptability |
| Running profile conformance | Infrastructural adaptability |
| Overall system efficiency | Operational longevity |
| Operational expenditure | Dependability |
| Capital expenditure | |
| Operational expenditure stability | |

### 4.3.1. Emission Reduction

The first criteria is: Emission reduction. This criteria compares the total Carbon dioxide emissions of each alternative with the emissions of that in the case of running the CCGT on natural gas and the current natural gas infrastructure. The emissions are measured by estimating the total amount of emissions per kg that are emitted over the whole year of energy production.

### 4.3.2. Running Profile Conformance

This criteria checks whether or not the CCGT in Moerdijk is technically able to follow the running profile for 2040 whilst conforming to the limitations set by the different alternatives. This is checked while optimising the different alternatives. With the different limitations and constraints found in literature and provided by RWEG, it is checked if a there is an (optimal) solution for the best configuration of the technical systems. If there is a solution, the alternative is scored with one, otherwise it is scored with a zero.

### 4.3.3. Technical Adaptability

The criteria technical adaptability refers to minimising the technical complexity related to the conversion to hydrogen. The criteria helps to get an indication of the technical difficulty and the problems associated with the technical changes. This is scored based on interviews and discussions with professionals in the energy sector. These interviews help to get a better estimate of total amount of problems and opportunities related to the criteria. The respective magnitude of the each problem or opportunity for each alternative is measured by how often there is a negative or positive association with a problem or opportunity resulting in an attitude score. Based on these findings, each alternative is given a total score depending on the total amount and attitude scores of the problems and opportunities related to the criteria.

### 4.3.4. Infrastructural Adaptability

Infrastructural adaptability is similar to Technical adaptability. This criteria focuses on minimising the impact of infrastructural changes that have to be made to each alternative. Again, just as the technical adaptability, this is scored based on interviews and discussions with professionals inside the energy sector. Based on these interviews the amount of different problems and opportunities is counted, together with the magnitude of the problems and opportunities. This helps to understand the difficulties that there might be when adapting the infrastructure to run the CCGT on hydrogen. Based on these findings, again, each alternative is given a total score depending on the total amount and attitude scores of the problems and opportunities related to the criteria.

### 4.3.5. Operational Longevity

This criteria focuses on the longevity of alternative implementation for the future after 2040. This criteria will for instance take into account future developments of in hydrogen production and pricing, the lifespan of certain technologies, or the availability of specific resources in the future. This information is again gathered with the interviews and discussions with professionals inside the energy sector. Just as with the previous two criteria, the problems and opportunities related to this are counted, together with the magnitude of these problems and opportunities. Based on these findings, just as with the previous qualitative criteria, each alternative is given a total score depending on the total amount and attitude scores of the problems and opportunities related to the criteria.

### 4.3.6. Overall System Efficiency

The overall system efficiency shows how much energy is needed in order to for the CCGT in Moerdijk to conform to its running profile in 2040. This includes the energy needed for the production of hydrogen, the storage of hydrogen, and the combustion of hydrogen in the CCGT in Moerdijk. This is calculated based on the total amounts of hydrogen produced and stored in 2040 and the total amount of energy produced by the CCGT in Moerdijk over 2040. This criteria is scored on the basis of the overall system efficiency in a percentage.

### 4.3.7. Operational Expenditure

The total operational expenditure gives an insight in the variable costs that occur with the production of energy. The total operational expenditure is calculated by optimising the total annual cost for conforming to the running profile for Moerdijk in 2040. The operational expenditure is calculated in euro's and consists of the cost of the hydrogen fuel or the variable cost of hydrogen, the cost of transporting the hydrogen, the variable cost for storing the hydrogen, the cost associated with the $CO_2$ emissions, and the variable costs of starting the CCGT. The criteria is scored on the total operational expenditure in euros. Where the lower the score, the better.

### 4.3.8. Capital Expenditure

The capital expenditure consists of the total investment costs that have to be made for the alternative to function. The total capital expenditure is calculated in euro's. This is calculated by optimising the alternatives for the lowest annual cost. This cost also includes the annual cost which is calculated by multiplying the total capital investment of an asset with its Capital Recovery Factor. Using this, the optimal size or capacity of an asset is determined and with this, its capital investment needed. Giving the ability to calculate the total investment costs of an alternative. This criteria is scored on the total capital expenditure in euros. Where again, the lower the score, the better.

### 4.3.9. Dependability

The criteria dependability helps to score the risk associated by being dependent on external factors and partners for the operation of the CCGT and the production of energy. Also taking into account how important or difficult these are to replace if needed. This is researched based on interviews with professionals in the energy sector. These interviews help to identify the problems and opportunities associated with the dependability of each alternative. After after these interviews, each alternative is given a total score depending on the total amount and attitude scores of the problems and opportunities related to the criteria. This is the same as with the previous qualitative criteria.

### 4.3.10. Operational Expenditure Stability

Operational expenditure stability represents the difference that there is in the operational costs between lowest and highest forecast for renewable energy. This is researched by comparing the differences between the operational costs for each alternative for both the highest and lowest forecast. Measuring the difference that there is between operational expenses between the different forecast for an alternative in euros. These differences for each alternative are then compared to each other in order to establish which alternative has to lowest variance in operational cost, and thus scores best.

## 4.4. Alternatives

In order for the multi-criteria analysis to have alternatives to compare against the continuation of running the CCGT on natural gas, the alternatives have to be established. In this research, an alternative entails the technology and processes involved in energy production via a CCGT, gas transportation, storage, and ultimately hydrogen combustion in the CCGT.

In section 3.4 it is mentioned that for each technical system, two technical options are considered in this research. Each technical system can consist of one of these technical options, or the combination of both of these technical options. Resulting in 3 different options for each technical system, except for the technical system: electricity generation, for which the combination of both technical options is not possible. This therefore results in $3^3 \times 2 = 54$ theoretical alternatives. Although the technical systems: Hydrogen transport and Hydrogen storage, depend on the chosen hydrogen production method. This decreases the number of options to $3 \times 2 = 6$.

After consultation with RWEG staff, based on prior research within the company and an increase in new CCGT prices, it is chosen to design three alternatives based on their hydrogen production method. If the existing CCGT gets the correct required maintenance and modifications there are no significant benefits for the placement of a new hydrogen specific CCGT compared to modifying the existing CCGT to run on hydrogen. This therefore results in an alternative with blue hydrogen as energy source, an alternative with green hydrogen as energy source, and an alternative with a mix of blue and green hydrogen.

### 4.4.1. Blue Hydrogen

The first alternative is based on the usage of blue hydrogen as a fuel for the CCGT. The blue hydrogen is for this research sourced from a theoretical blue hydrogen plant in Rotterdam. This theoretical hydrogen plant is based on a plant of Air Products (Air Products, 2023). The location near Rotterdam is chosen as Air Products has plans to build one of the largest blue hydrogen facilities in Europe (Martin, 2023), and is located strategically near Moerdijk. Therefore, this theoretical blue hydrogen plant will also be located near Rotterdam. The blue hydrogen in this research is produced via SMR, as mentioned in subsection 3.2.1. The theoretical blue hydrogen facility is able to produce up to 134000m$^3$ of hydrogen per hour at a fixed price for 24 hours a day, 7 days a week. This production rate is again based on a facility of Air Products (Ratan et al., 2010).

A downside of using blue hydrogen, is that it is produced with a steady outflow. Therefore the input of blue hydrogen to the company is also steady through-out the year. For the purpose of this research it is assumed that by contract the purchase of hydrogen is equal for every hour of the year, which can be the maximum of the plants capacity of 134000m$^3$ of hydrogen per hour (Ratan et al., 2010), independent of other customers. This plant transports hydrogen via the hydrogen backbone provided by Hynetwork, a subsidiary of Gasunie. Via this network, hydrogen is transported over both new specific pipelines, and retrofitted natural gas pipelines, as talked about in subsection 3.2.2 (Gasunie, n.d.-a), (Hynetwork, n.d.-a), (Hynetwork, n.d.-b).

Via this network hydrogen is transported from the blue hydrogen facility in Rotterdam to the CCGT in Moerdijk for direct use, or to a salt cavern based hydrogen storage facility in the North East of the Netherlands near Veendam based on the findings described in subsection 3.2.3. This location is chosen as it there are currently already pilots for hydrogen storage in salt caverns, and is located near the hydrogen backbone (Hynetwork, n.d.-b), (Hystock, 2023). The size of this cavern can go up to 1000000m$^3$ and are located at a depth between 1000 and 1500m below the surface according to Groenenberg et al. (2020). They also mention operational pressures op to 200 bar in salt caverns, which this research assumes.

If the direct supply of hydrogen from the blue hydrogen facility in Rotterdam does not suffice, the hydrogen stored at the salt cavern is used as well.

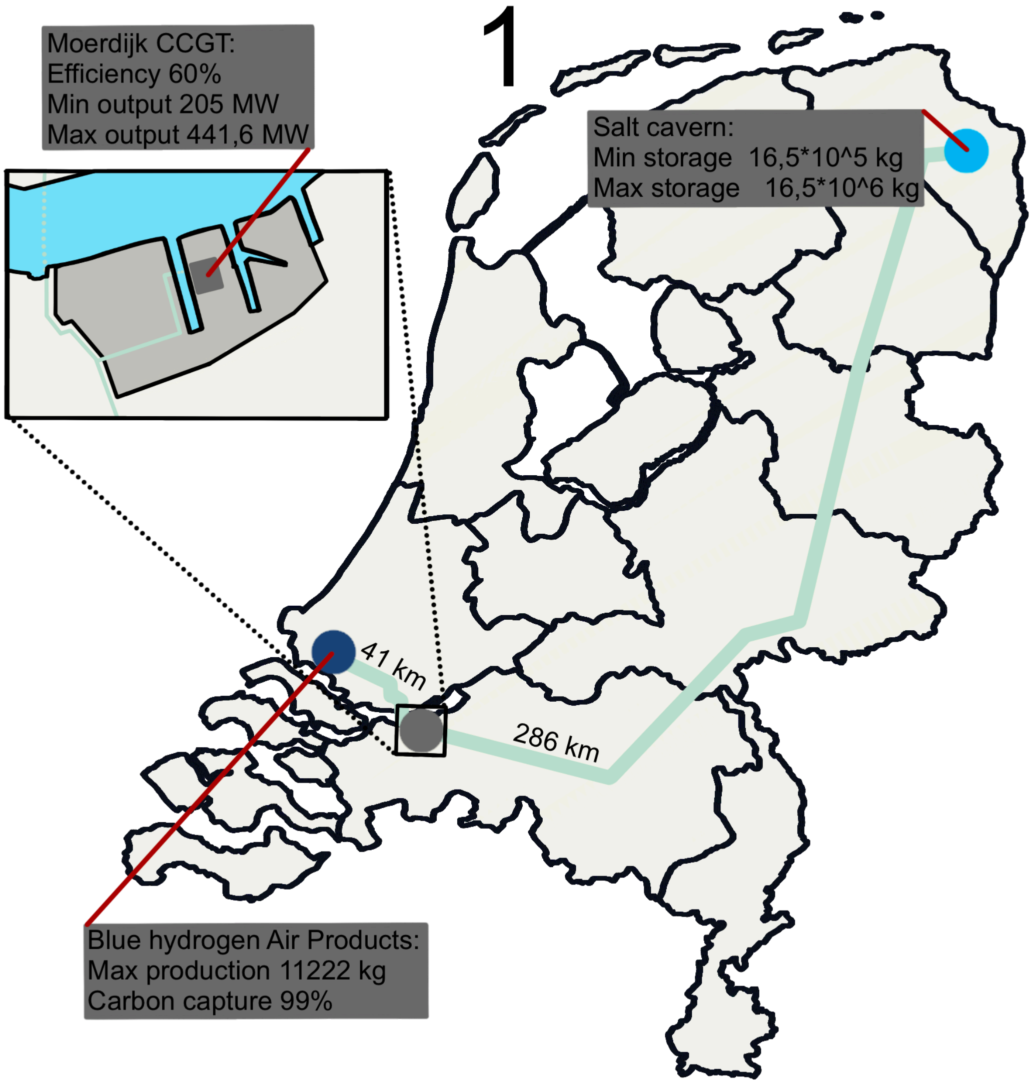
A visualisation of this alternative can be seen in Figure 4.2

### 4.4.2. Green Hydrogen

The next alternative fully relies on the use of green hydrogen that is produced near the CCGT in Moerdijk. The green hydrogen is produced with the use of Proton Exchange Membrane (PEM) electrolyzers due to their ability to rapidly scale the production of hydrogen based on the findings in subsection 3.2.1 and by Dermühl and Riedel (2023). This is well suited to be combined with the increase in intermittent renewable energy sources.

Next to the CCGT in Moerdijk, in the vicinity of the plant, there is an available area of 99000m$^2$ estimated with the use of Google Maps. This land can theoretically be used for the placement of the electrolyzers. According to Ripson and van 't Noor-

**Figure 4.2:** Visualisation alternative Blue hydrogen



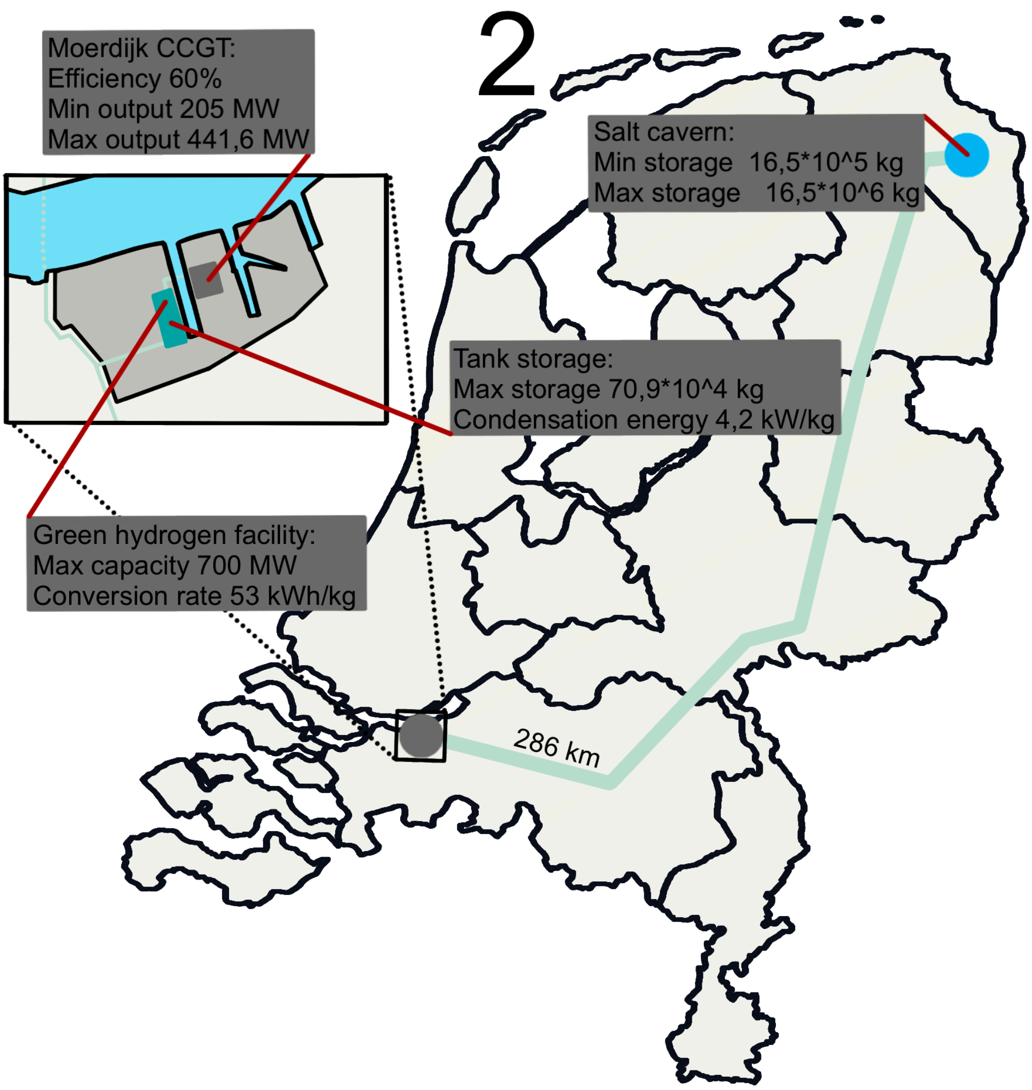

dende (2020) a PEM electrolyzer plant with a GigaWatt (GW) scale approximately takes 80000m$^2$. Giving the location, the theoretical ability to place a green hydrogen facility with a capacity of more than one GW of capacity is possible. However, the electricity plant in Moerdijk only has a grid capacity capable of 700MW (RWE, n.d.). Therefore it is decided to implement a green hydrogen facility that can, at a maximum, have a total capacity of 700MW. This alternative assumes that RWEG invests in a green hydrogen facility at the location in Moerdijk, thereby having the production of hydrogen under own control.

Due to the limit on grid capacity, and to not consume electricity when the CCGT is running, the green hydrogen facility is only able to produce hydrogen when the CCGT is not running. The production of hydrogen can therefore vary between 0 and the maximum capacity of the facility per hour. Because of this, the hydrogen must be stored. This can be done in salt caverns near Veendam as is mentioned before in subsection 4.4.1. However, based on the findings described in subsection 3.2.3, this alternative also has the option to store hydrogen in its liquid form in a tank located at the hydrogen facility. These liquid hydrogen tanks can have a storage volume of up to 10000$m^3$ (Kawasaki, 2020).

Again the hydrogen is transported via the hydrogen backbone provided by Hynetwork, to and from the storage facilities, the CCGT and the green hydrogen facility. The transport of hydrogen uses a combination of both new hydrogen pipelines and retrofitted natural gas pipelines as described in subsection 3.2.2.

A visualisation of this alternative can be seen in Figure 4.3

**Figure 4.3:** Visualisation alternative Green hydrogen

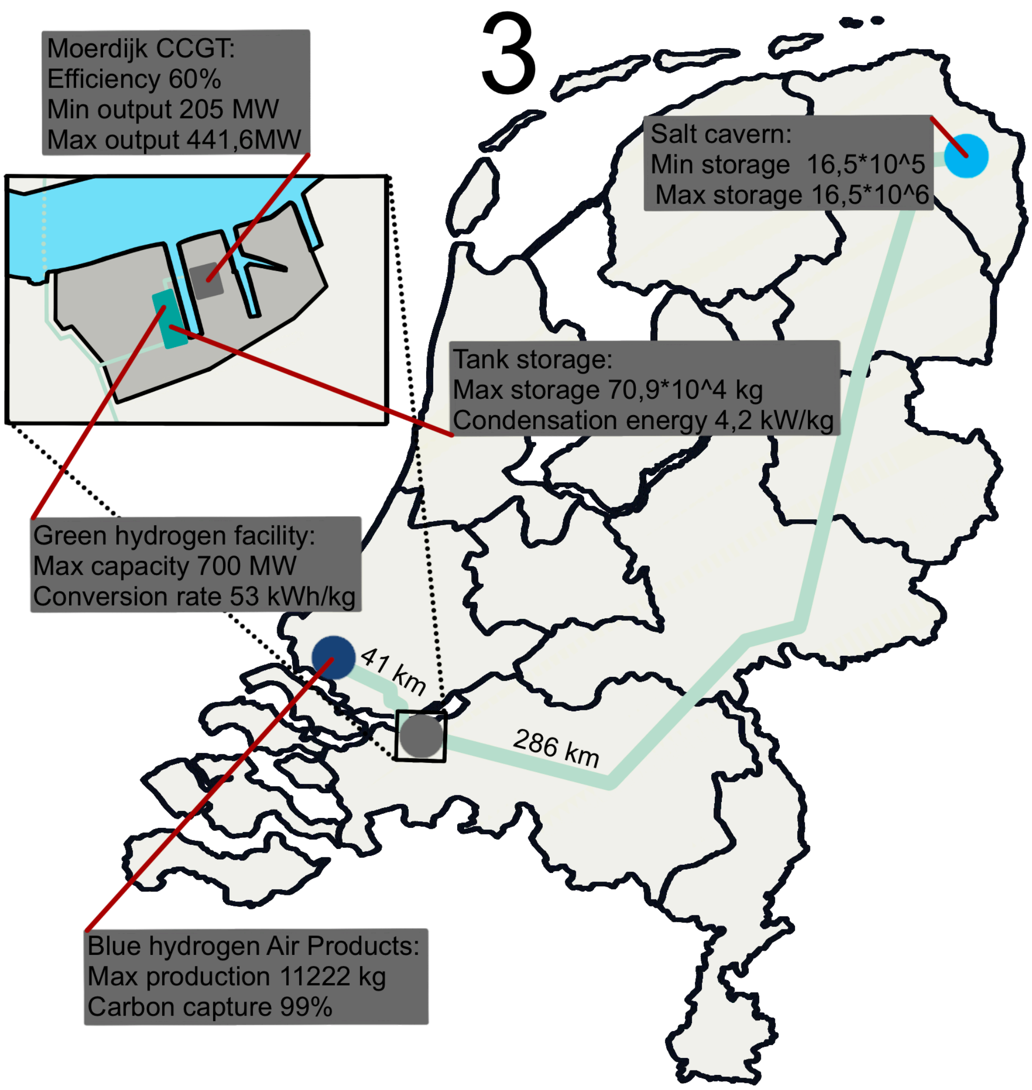



## 4.4.3. Mixing Blue and Green Hydrogen

The third alternative is used to mix both of the previous mentioned alternatives. It therefore relies on a steady inflow of blue hydrogen and the installation of electrolyzers in Moerdijk for a variable supply of green hydrogen. Just as the alternatives on blue and green hydrogen, it is able to use both storage in salt caverns near Veendam, use a local liquid hydrogen tank for storage, or use both options. This alternative, just as the previous alternatives, uses the hydrogen backbone provided by Hynetwork for the transport of hydrogen throughout the different facilities.

A visualisation of this alternative can be seen in Figure 4.4

**Figure 4.4:** Visualisation alternative Mix hydrogen




## 4.4.4. Current alternative on Natural Gas

These alternatives are tested against the current situation on natural gas. This alternative makes use of the supply of natural gas via the infrastructure of GasUnie. There is no need for storage, as the total natural gas in the system can act as a buffer. Besides this, enough natural gas can be supplied every hour to run the CCGT at full capacity for the hour.

### 4.4.5. Parameters used for the alternatives

In order to later calculate results for the quantitative criteria and to get more detailed information about the limitations of the scenarios. Different parameters and assumptions are established for these alternatives and the technologies that are used. The parameters are found via a variety of sources. This can range from different literature sources, statements by companies about their respective work on technologies, forecast data provided by Aurora Energy Research (2024), or information directly supplied by RWEG. An overview of these parameters and the limitations for the alternatives can be seen in Table A.3.

### 4.4.6. Parameters to Optimise

Not all parameters for each alternative are directly available or can be found in literature for the specific alternatives, as they largely depend on the cost minimisation of energy production. Each alternative is optimised in order to have the lowest possible yearly cost. In order to achieve this, there are several parameters that are seen as variables. These parameters are:

- The capacity of the salt cavern storage
- The capacity of the liquid hydrogen tank storage
- The capacity of the green hydrogen electrolyzer facility
- The steady hourly rate of blue hydrogen that is delivered
- The flow and state of hydrogen at each hour through the various locations

These parameters are thus not equal throughout all alternatives and the different forecast, but vary in order to provide the lowest annual cost.

# 5
# Phase 2: Scoring of the Criteria

The second phase of the multi-criteria analysis focuses on collecting the needed information to score the alternatives on the different criteria. To gather this needed information and data, the sub-research questions: *What are the implications for the adaptability, longevity and dependability of the implementation of each alternative for expected infrastructure in 2040?* and *What is the total annual cost in 2040 of flexible produced energy associated with the implication of hydrogen in the Moerdijk plant for each alternative?* are answered in this phase. Once the data is gathered, the different scores are normalised and added to the analysis. Phase two thus provides everything needed for step 5 of the multi-criteria analysis that can be seen in chapter 2.
In order to score the previously mentioned criteria, they are divided into different research methods as mentioned before in section 4.3. Some criteria are based on quantitative data, while other criteria are based on qualitative data.

## 5.1. Quantitative Research

First, the quantitative criteria are evaluated to answer the sub-research question: *What is the total annual cost of flexible energy production associated with implementing hydrogen at the Moerdijk plant for each alternative?*

Each alternative, mentioned before in section 4.4, is optimised to minimise the total annual operation costs using Pyomo, a Python-based open-source optimisation modelling language. This approach focuses on achieving the lowest annual running costs. It is chosen to optimise towards the minimal total annual operation costs, as this helps to maintain competitive energy prices and provide insights into the minimal costs of flexible energy production through hydrogen combustion in CCGT's.

To optimise each alternative, the central running profile is used in the optimisation code. This running profile is used thus throughout all optimisations. This choice is based on the fact that the three different running profiles mentioned in subsection 4.1.1, are nearly identical. The optimisation purely on the central running profile helps to limit any variation in the results due to the small variations in the different running profiles.

It is chosen to optimise the alternatives with the central running profile for the three different forecasts provided by Aurora Energy Research (2024). These are the low, central and high forecasts for the Netherlands in the year 2040. These forecasts have an effect the following parameters:

- Natural gas price
- Blue Hydrogen price
- Electricity price
- Green electricity price
- Electricity $CO_2$ emissions
- Installed capacity of renewable energy

Due to the changing electricity prices and emissions in the different forecasts, the following parameters also change. Reason being that they are directly based on the electricity prices and emissions. These are:

- Variable OPEX electrolyzers
- Variable OPEX tank storage
- $CO_2$ emissions for tank storage
- $CO_2$ emissions for salt cavern storage

The variable OPEX for the electrolyzers is based on the cost and consumption of purified water and the cost of green electricity. The variable OPEX for tank storage is based on multiplying the electricity cost and the electricity that is needed for the liquefaction of hydrogen. The same applies for the $CO_2$ emissions of storing hydrogen in a tank or in salt caverns. The emissions are based on the multiplication of the electricity needs for storing the hydrogen, and the emissions related to the electricity.

The values of these parameters can be seen in **Confidential appendix**.

An overview of the alternatives and varying parameters that are used over the different forecast can be seen in Table A.2

### 5.1.1. Parameters

For the optimisation of the different alternatives several parameters are used. These parameters are established with the design of the alternatives in section 4.4 and can be seen in Table A.3. Most of the parameters are based on different sources ranging from claims by companies, to scientific articles. However a part of these parameters must be specifically calculated or is estimated for the purpose of this research.

#### Professional Estimates

Some of the parameters that are essential for the optimisation are specific for this research and could not be calculated or found via companies or research, especially for the year 2040. These parameters are therefore estimated in consultation with professionals in the sector. These consultations lead to the estimates and their corresponding parameters that can be seen in Table 5.1, which are equal throughout the different alternatives.

**Table 5.1:** Estimated parameters

| **Estimated parameters** | | |
|---|---|---|
| Construction time CCGT conversion | years | 1 |
| Direct $CO_2$ emissions hydrogen combustion | $kgCO_2/kgH2$ | 0 |
| Construction time green hydrogen facility | Years | 4 |
| Carbon Capture rate SMR | % | 99 |
| OPEX Fixed Tank storage | % of CAPEX | 3 |
| Expected life CCGT | Years | 30 |
| Construction time Tank storage | Years | 1 |
| OPEX Fixed salt cavern storage | % of CAPEX | 3 |
| Construction time salt cavern storage | Years | 2 |
| Storage temperature salt cavern storage | K | 293 |
| Transport pipe temperature | K | 293 |

### Calculations

Besides the parameters that are estimated or taken from scientific sources and company claims, some parameters must be calculated. An important part of these parameters that must be calculated are the parameters with respect to the annual cost of capital. These are calculated as it is important to know the annual cost of each capital investment over its expected lifetime. This is a part of the total annual cost and thus has an influence on the cost of electricity.

Besides the annual cost of capital the density of hydrogen is calculated for different pressures. The density at 50 bar helps to estimate the maximum flow rate, while the density at 200 bar helps to estimate the storage capacity of salt caverns in kilograms.

In order to calculate the annual cost of capital for each capital investment, the Capital Recovery Factor (CRF) is used. According to Chauhan and Saini (2016), the CRF converts the initial cost of a capital investment into a series of equal annual cash flows over the project lifetime. Spreading the cost of the capital investment over the lifetime of the project. This is done while taking into account a specified discount rate, the construction time, the investment cost, and the expected life time of the project.

To calculate the CRF the formula as described in Chauhan and Saini (2016) is used.

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{5.1}$$

Where:

$i$ : Discount rate

$N$ : Expected project life in years

In the case that a company plans to use a large amount of its assets to finance a project, it is important to use the correct discount rate. Therefore it is chosen to use the Weighted Average Cost of Capital (WACC), as the WACC gives a great representation of use of both dept and equity and the associated risks for financing a project (Franc-Dabrowska et al., 2021). For the purpose of this research a WACC of 7,36% is used based on the findings by Franc-Dabrowska et al. (2021). The calculated CRF of each possible capital investment with the corresponding WACC and the expected lifetime of the project can be seen in Table A.4.

After the CRF is established, the annual cost of capital can be calculated. Normally this is done by multiplying the CRF with the total capital investment of the corresponding project. This method assumes that the cost is spread over the lifetime of the project directly after the initial investment is made. This might lead to a problem, as this is not the case for the projects. Each project takes time to be constructed before it is in operation. The initial investment is therefore made before the project starts it lifetime. To combat this problem, not only the total capital investment for the project is taken into account, but also the cost that is associated with the construction time. To do this, the interest costs over the construction time should also be calculated. This is done by multiplying the initial investment cost with the WACC and the construction period. Including these costs to calculate the Annual Cost of Capital which is referred to as ACC gives:

$$ACC = (X * i_{WACC} * N_{con} + X) * CRF \tag{5.2}$$

Where:

$i_{WACC}$ : WACC of company
$N_{con}$ : Construction time years
$X$ : Investment cost for project

The calculated annualised cost of capital can be seen in Table A.5.

Besides the annualised cost of capital, the density of hydrogen at 50 and 200 bar is calculated to determine the maximum hydrogen flow rate per hour and the storage capacity in kilograms in the salt caverns. To calculate the densities of hydrogen at these different pressures, the ideal gas law is used. The ideal gas law is chosen for its simplicity and practicality in establishing the density of hydrogen under specific pressures. To calculate the density of hydrogen the ideal gas law as mentioned by Moran et al. (2017) is used. The equation is used to calculate the density of hydrogen depending on the pressure and temperature and can be seen in Equation 5.3. The results for both 50 and 200 bar are shown in Table A.6.

$$\rho = \frac{m}{V} = \frac{PM}{RT} \tag{5.3}$$

Where:

$\rho$ : Density of gas
$m$ : Mass of the gas
$V$ : Volume
$P$ : Pressure in Pascal
$R$ : Universal gas constant
$T$ : temperature in Kelvin

At last, the maximum flow rate for hydrogen transport via pipelines has to be calculated in order to limit the model to not exceed the transportation limits of the hydrogen pipeline network. To calculate the maximum flow rate of hydrogen in kg per hour, the hydrogen density at the specific pressure is multiplied by the cross-section area of the pipe and the maximum velocity of the gas. This leads to the formula:

$$\text{Flow rate} = \rho_{50bar} * \pi * (\frac{d}{2})^2 * v \tag{5.4}$$

Where:

$d$ : Diameter of the pipe
$v$ : Velocity of the gas

The maximum flow rate of hydrogen in kg per hour can be seen in Table A.7. The results of all the previously mentioned calculated parameters can be seen in Table 5.2.

**Table 5.2:** Calculated parameters

| Calculated Parameters | Unit | Value | Formula |
|---|---|---|---|
| CRF Electrolyzers | % | 9,7 | Equation 5.1 |
| CRF CCGT | % | 8,4 | Equation 5.1 |
| CRF Tank Storage | % | 8,4 | Equation 5.1 |
| CRF Salt Cavern Storage | % | 7,6 | Equation 5.1 |
| annual cost of capital Electrolyzer | EUR/kW | 37,69 | Equation 5.2 |
| annual cost of capital CCGT | EUR/kW | 20,89 | Equation 5.2 |
| annual cost of capital Salt Storage | EUR/kg | 0,074 | Equation 5.2 |
| annual cost of capital Tank Storage | EUR/kg | 26,36 | Equation 5.2 |
| H2 density 50 bar | kg/m3 | 4,14 | Equation 5.3 |
| H2 density 200 bar | kg/m3 | 16,55 | Equation 5.3 |
| Max Flow rate | kg/hour | 87069,28 | Equation 5.4 |

### 5.1.2. Pyomo Optimisation Model

In order to estimate the results for the quantitative criteria mentioned in section 4.3, an optimisation model is made using the the Pyomo Python-based open-source optimisation modelling language. This code helps to find the optimum balance between the hydrogen storage capacities, the hydrogen production facilities, and times when to produce and store the hydrogen. It does this while being constraint by the limits set in the alternatives that are mentioned in section 4.4 and can be seen in Table A.3. To find the optimum balance, it strives to find the minimal annual cost for conforming to the running profile for the CCGT in Moerdijk. This gives an answer to the sub-research question: *What is the total annual cost in 2040 of flexible produced energy associated with the implication of hydrogen in the Moerdijk plant for each alternative?*

The final results from the optimisation models is filtered to the show the total capital expenditure, total operational expenditure, the total $CO_2$ emissions and the total efficiency of the alternative. These results are filtered out from the final results of each alternative, as they give the ability to score the different criteria. The optimisation model gathers more results compared to the previously mentioned 4, but the other results are used to understand how the alternatives change compared to each other, across the different forecasts, and to check the code for possible mistakes in the optimisation process.

Each optimisation model is different depending on the alternative and can be seen in section A.4, but follows the same layout principles. In the beginning of the code, the needed model data is loaded into the model. This is the hourly data for the running profiles for the CCGT in Moerdijk. This helps the model to understand the location, time, and quantity of hydrogen that is needed. In the case that green hydrogen is used, also an energy multiplier is added to the code. This energy multiplier is based on the excessive amount of renewable energy for each forecast. This is data that is gathered in order to establish the running profiles mentioned in subsection 4.1.1. However, in this case it helps to establish two different electricity prices for green hydrogen. In the case that there is an excessive amount of renewable energy in the grid, the price for green hydrogen is low.

After the needed data is loaded in the model, all parameters are defined that are needed for the model and that can be seen in Table A.3.

Next the variables in the model are defined. These are the variables that the model optimises. These can be time dependent variables which change every time step, or it can be non-time dependent variables which are equal throughout all time steps in the model.

After this, the optimisation formula is defined. The model tries to optimise this formula to a minimum. Therefore this formula tries calculate the total annual cost and consists of variables, which the model optimises, and parameters. This consist of the annual cost of capital, the fixed operational costs, the costs of hydrogen (production), the $CO_2$ costs, the costs of storing hydrogen, and the cost of transporting hydrogen.

After the model is defined to minimise this formula, the constraints have to be set. These constraints can be interpreted as the flow of hydrogen and the limitations that are associated with this. These constraints for instance limit that the hydrogen used and hydrogen stored, does not exceed the hydrogen produced at that point of time. Or it constraints the variables with specified parameters, for instance making sure that green hydrogen supplied at a point in time does not exceed the limits of the maximum electrolyzer capacity.

After all constraints are set, the model is solved. This can results in two different outcomes. If the solver has found an optimal solution. Meaning that there is an optimal value for the optimisable parameters mentioned in subsection 4.4.6, and the results are printed. This include the constant variables over time, but also the variables that vary over time. Showcasing the flow of hydrogen through the model. This is used to check if the model behaves realistic and without any problems. If the solver does not find a solution, it mentions that there is no solution found. This indicates that the specific alternative with the constrains is not able to follow the provided running profile. Therefore, if an alternative shows results, it is able to satisfy the criteria: running profile conformance.

## 5.2. Quantitative Results

The Pyomo model provides results for the different alternatives on hydrogen and the various forecasts. The final results that are used to score the quantitative criteria can be seen in Figure 5.1, Figure 5.2, Figure 5.3, and Figure 5.4. The criteria that can not be directly seen in these graphs can be concluded from them. The fact that all alternatives have a solution for each forecast shows the ability to conform to the running profile, as is mentioned in subsection 5.1.2. The criteria operational expenditure stability can be concluded by looking at the variance between the operational expenditure for each forecast in Figure 5.1.

### 5.2.1. Blue Hydrogen

The code that is used to gather the results for the alternative on blue hydrogen can be seen in subsection A.4.1. Running this code resulted in an overview of the overall performance of the system. Giving insights in the total costs and how these are composed from different aspects such as the variable operational costs, or annual cost of capital. The results from the code provide numbers with great accuracy, resulting in numbers with many decimal places. Because the purpose of the code is to estimate the total costs associated with hydrogen combustion in Moerdijk, and as the running profile is also an estimation, it is decided to round the values that are larger than a million to the nearest thousand. Due to the estimation of the running profile, it would not be possible to get exact values with the precision of a hundredth, but it gives a great indication of the magnitude of the value.

In Table A.8 the results of the implementation of blue hydrogen can be seen. The table shows the results of three different blue hydrogen alternatives. All alternatives conform to the central running profile estimated in subsection 4.1.1, but differ on the data provided by the forecasts of Aurora Energy Research (2024).

Noticeable from the results is that nearly all variables stay the same, independent of the forecast. Only with the exception of variable (and thus) total OPEX, blue hydrogen price, and the total annual costs. This all has to do with the price of the blue hydrogen. This price strongly dependent on the costs of natural gas. In the case that the cost of natural gas increases over the forecasts, this results in an increase in cost for blue hydrogen. The need for hydrogen is equal across the different forecasts, as they all conform to the same running profile of the CCGT. Therefore resulting in the increase in operational costs.

### 5.2.2. Green Hydrogen

In order to get the results for the alternative on green hydrogen to code has to be altered to suit the needs and limitations of an electrolyzer facility near Moerdijk and to also include an extra hydrogen storage facility. The new code can be seen in subsection A.4.2.

The results of the green hydrogen alternatives can be seen in Table A.9. Again the table shows the results of three different green hydrogen alternatives. All alternatives conform to the central running profile estimated in subsection 4.1.1, but differ on the data provided by the forecasts of Aurora Energy Research (2024).

Noticeable from these results is that the contrary to the results of the alternative on blue hydrogen, the total annual cost decreases from the low to the high and central forecast. This has to do with the pricing strategy of green hydrogen and the penetration of renewable energy in the market. The price of green hydrogen is for a large part dependent on the cost of electricity. The cost of electricity and the green hydrogen price can be seen in **confidential appendix**. The price of electricity and thus the price of green hydrogen decreases when there is more renewable energy production than there is total energy demand. The excess amount of energy in the grid, results in a decreased cost of electricity. Therefore the pricing of green hydrogen has two states. When there is an excessive amount of renewable energy in the grid, the price of green hydrogen is cheap. When there is a shortage of renewable energy in the grid, the price of green hydrogen is more expensive. Starting with the low forecast to the high forecast, the total amount of installed renewable energy capacity increases. More installed renewable capacity results in a higher chance of a larger amount of renewable energy generation. Therefore the higher forecasts have more periods when there is an excessive amount of renewable energy in the grid, and thus a lower green hydrogen price. The code is, because of these price differences, incentivised to produce green hydrogen when the price is low. Therefore it finds the optimum solution and balance between hydrogen production and hydrogen storage. The increase in the availability of lower cost hydrogen production, results in a decrease in total annual cost of the central and high forecast compared to the low forecast alternative.

The central and high forecast alternative are closer to each other compared to the total annual cost of 2040. Although the price for cheaper green hydrogen occurs more often in the high forecast compared to the central forecast, the general electricity price also increased with the high forecast. This results in a higher price for green hydrogen when there is not an excessive amount of renewable energy in the grid for the higher forecast. The extra annual cost of capital due to the increased need for hydrogen storage capacity, together with the increased cost of green hydrogen for when there is no excess amount of renewable energy, does not outweigh the benefits of the increased amount of periods when green hydrogen is cheap. This leads to a relatively small increase in total annual cost for the high forecast alternative compared to the central forecast alternative.

### 5.2.3. Mix of Blue and Green Hydrogen

Next the results of the alternative where both green and blue hydrogen are mixed are established. Again the code has to be altered compared to the green hydrogen alternative to also include the possibility to have blue hydrogen at a steady rate. This results in combining the code from the blue hydrogen case, together with the code from the green hydrogen case. This results in the code that can be seen in subsection A.4.3.

The results of the alternative where blue and green hydrogen are mixed, can be seen in Table A.9. Again the table shows the results of three different mix hydrogen alternatives. All alternatives conform to the central running profile estimated in subsection 4.1.1, but differ on the data provided by the forecasts of Aurora Energy Research

(2024)

Noticeable from the results of the alternative where green and blue hydrogen are mixed, is that the results rests on the strengths of both hydrogen sources in providing energy for the lowest annual cost. From the results it can be seen that the higher the forecast, and thus the installed capacity of renewable energy in the grid, the lower the dependency on blue hydrogen. This is the result from the increase in periods where there is an excessive amount of renewable energy in the grid, resulting in lower green hydrogen prices. This can also be seen in the total electrolyzer facility capacity. This capacity increases as the amount of installed capacity of renewables in the grid also increases. Mixing blue and green hydrogen gives the alternative the benefit to use the cheapest form of hydrogen for the specific case. Noticeable is therefore also the total operational expenditure. The ability to balance the hydrogen costs, results in a relatively stable variable operational cost. This is again the result of the balancing of the hydrogen costs, resulting in an average hydrogen cost that does not significantly change depending on the forecast.

### 5.2.4. Natural Gas

The last alternative to asses is to assume the continuation of the use of natural gas for the CCGT. To gather the needed results for the alternative on natural gas, Microsoft Excel is used compared to the previous alternatives which relied on Pyomo. Excel is used as there is no need for any optimisation when continuing to run on natural gas. According to professionals from the plant in Moerdijk, the main variable cost would only consider the price of natural gas. There is no need for storage, as the whole natural gas infrastructure functions as a gas buffer. The calculations for the results on natural gas can be seen in **confidential appendix**. The prices of natural gas are based on the pricing provided by Aurora Energy Research (2024). The price of natural gas starts with 20 EUR/MWh for the low forecast alternative and increase with 15 EUR/MWh for each forecast. These prices are plausible and inline with the Dutch TTF (Intercontinental Exchange, 2024). The results of this alternative can be seen in Table A.11.

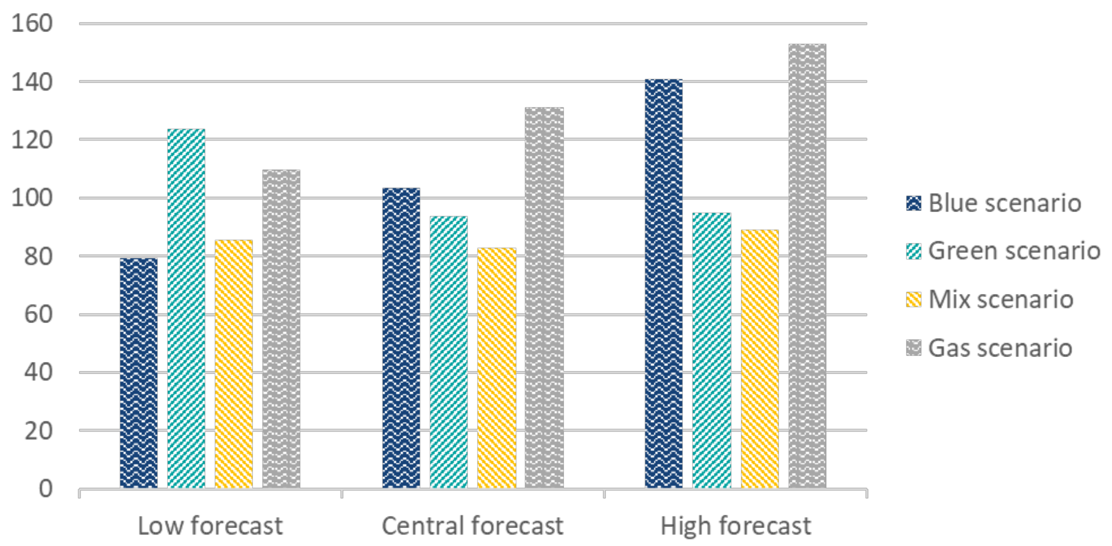
Noticeable from these results is the lack of capital investments. The infrastructure and equipment is already in place and running. Therefore there is no need for new capital investments. Also there are no annual costs of capital. Under the assumption that there are no defects to the CCGT and the correct maintenance is performed, the CCGT is past it's economic life. Resulting in no annual capital investment payments that would be needed to pay back for the initial investment of the CCGT.

Besides the lack of capital investment what can also be noted is the fact that the variable operational expenditure increases as the forecast also increases. The increase in installed capacity of energy is associated with a higher cost for natural gas according to Aurora Energy Research (2024). This increase in cost of natural gas leads to an increase in variable operational expenditure.

### 5.2.5. Final Results Operational Expenditure

Figure 5.1 illustrates the final results used to evaluate the operational expenditure criteria. These results, based on the previous sections, show the performance across the forecasts. The increase in forecast results in an large increase in operational expenditure for both the blue hydrogen and the natural gas alternative. Showcasing that although the operational costs of blue hydrogen are lower compared to natural gas, the operational expenditure increases almost equally as the cost of natural gas increases towards the higher forecast. Figure 5.1 also shows the strength of the mixed blue and green hydrogen alternative. Unlike other alternatives where operational expenditure varies significantly over the forecasts, the mixed alternative maintains relatively consistent operational expenditure.

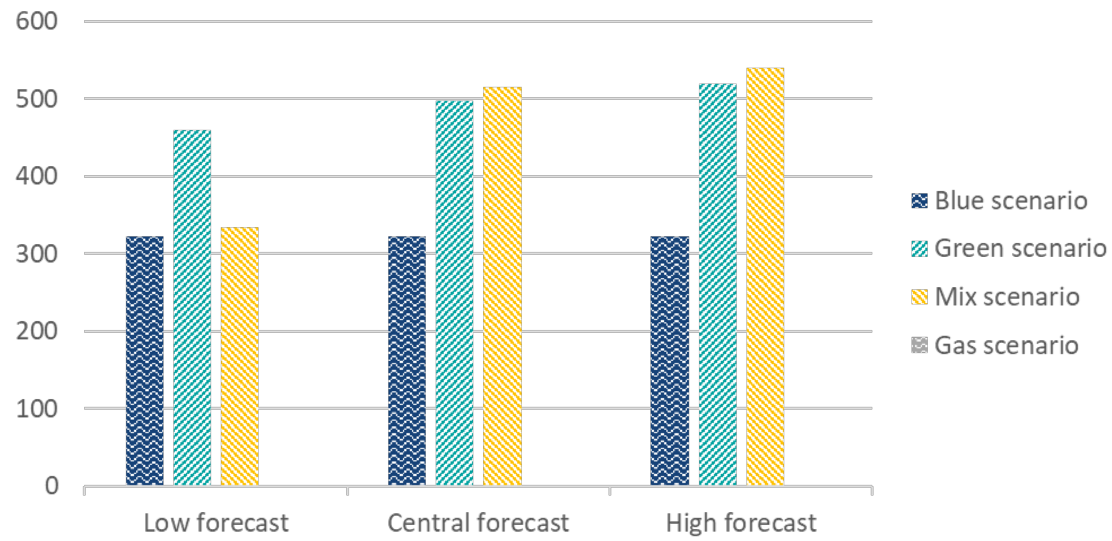
**Figure 5.1:** Total operational expenditure in million euros




### 5.2.6. Final Results Capital Expenditure

Figure 5.2 illustrates the final results used to score the capital expenditure expenditure. The results show that the capital investment of the alternatives is relatively constant throughout the different forecast, except for the alternative mixing blue and green hydrogen. The mix alternative shows a large jump in capital expenditure going from the low to the central forecast. In the low forecast alternative, there is not enough renewable energy surplus to validate the investment in large electrolyzer facilities. Therefore, in the low forecast, the mix alternative mainly relies on blue hydrogen with a small green hydrogen facility, resulting in capital expenditure comparable to the blue hydrogen alternative in the low forecast.

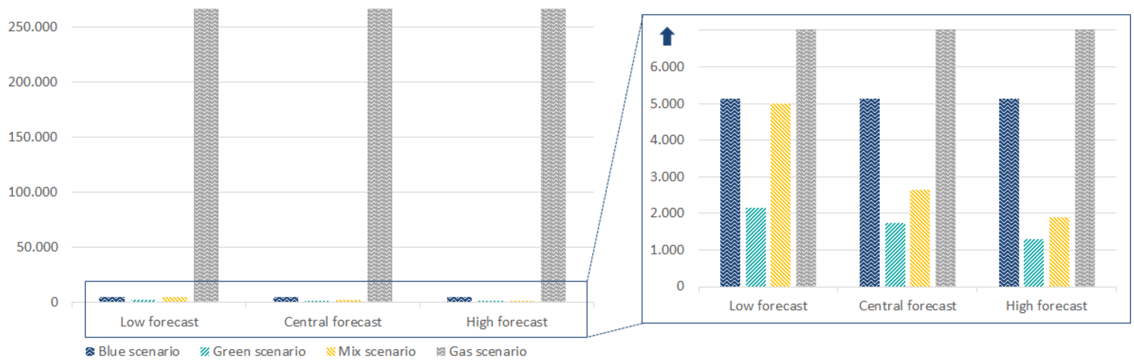
**Figure 5.2:** Total capital expenditure in million euros




### 5.2.7. Final Results Total $CO_2$ Emissions

Figure 5.3 shows the final results used to score the criteria: emission reduction. Illustrated in this figure is the large difference in $CO_2$ emissions between the alternative running on natural gas and the alternatives on hydrogen. While the variations in $CO_2$ emissions among the different alternatives on hydrogen are substantial in relation to their own $CO_2$ emissions, comparing these alternatives to the emissions generated by operating the CCGT on natural gas shows the general strength of hydrogen in reducing $CO_2$ emissions.

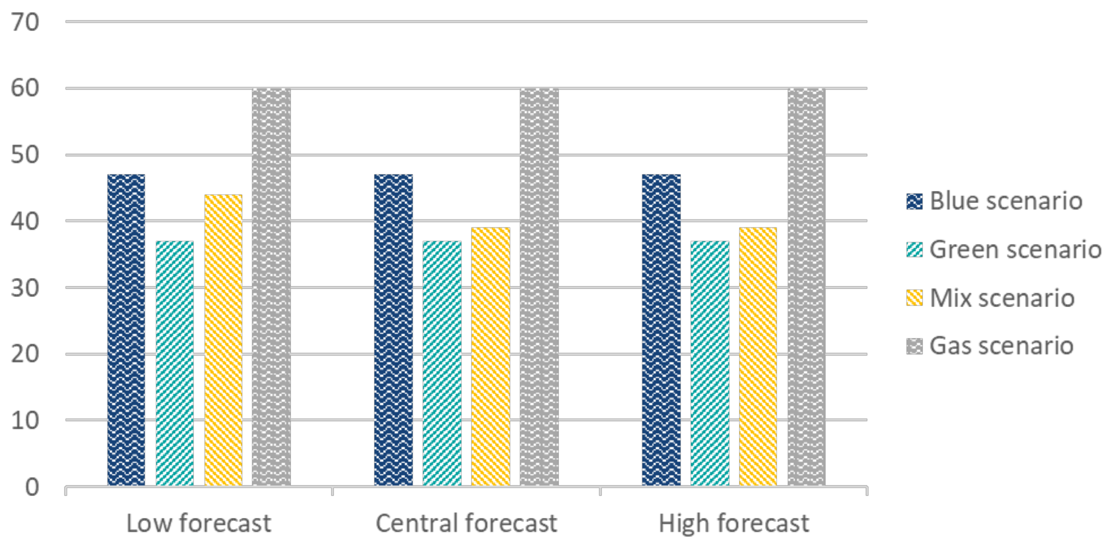
**Figure 5.3:** Total $CO_2$ emissions in tons




### 5.2.8. Final Results Total System Efficiency

Figure 5.4 illustrates the final results used to score the overall system efficiency criteria. The results are based on the sections above. All alternatives have relative stable overall system efficiencies across the different forecast, with a small decrease in efficiency for the green and mix hydrogen alternatives as the electrolyzer facility capacity increases. However, the alternative on natural gas shows a great lead in overall system efficiency compared to the other alternatives due to the lack in conversion technologies and storing needs.

**Figure 5.4:** Total efficiency of the alternative in %




## 5.3. Qualitative Research

In order to get a better understanding of the criteria that are to be assessed by qualitative measures, interviews with professionals in the energy sector are conducted. These interviews help to get a deeper understanding on the technical and infrastructural adaptability, the operational longevity, and the dependability of each alternative. Answering the sub-research question: *What are the implications for the adaptability, longevity and dependability of the implementation of each alternative for expected infrastructure in 2040?*

In order to answer this sub-research question, semi-structured interviews are used. The reason for choosing semi-structured interviews is that this gives the participant the flexibility to answer the question in depth, while also allowing for more interaction with the participant if an interesting concept is mentioned. Each participant is a professional in its own field, giving a detailed answer from their own professional opinion. The semi-structured interviews therefore give the opportunity to go into deeper detail about the technical expertise of the participant.

The interviews provide valuable insights into various opportunities or problems that are related to the implementation of the different alternatives.
The amount of distinct problems and opportunities are counted for each criteria, along with an assessment of the significance of these problems and opportunities.
Subsequently, the problems and opportunities are associated to the alternatives they might affect. This gives the different alternatives a corresponding number of problems and opportunities, helping to score the different qualitative criteria by combining the scores indicating the significance of the associated problems.

Besides giving these valuable insights into the different qualitative criteria, the participants are also be asked to rank both quantitative and qualitative criteria on what they think is most important, to what they think is the least important criteria. The different opinions of the participants on the ranking of all criteria help to give a final weight to the criteria for the multi-criteria analysis.

In order to get insights into the criteria from different perspectives, a simplified way of stratified sampling is used. All participants should be professionals working in the energy sector, but should have different job functions. Basing the sampling strategy on the stratified sampling strategy ensures that all participants have different job functions inside the energy sector. This strategy led to a total of 6 professionals willing to participate in the interviews. A list of the job functions of the participants can be seen in Table 5.3. The job functions are kept to a higher level in order to keep the participants anonymous.

**Table 5.3:** Participant number and their corresponding job function

| Participant number | Job function |
|---|---|
| 1 | Support engineer |
| 2 | Hydrogen system engineer |
| 3 | Energy transition engineer |
| 4 | Development manager |
| 5 | Project engineer |
| 6 | Production engineer |

### 5.3.1. Problem and Opportunity Identification

In order to establish the problems and opportunities to score the alternatives to the 10 different criteria, different steps are taken.

The interviews took place on-site or via Microsoft teams. At the beginning of the interview, the participants were explained the purpose and topic of the research, as well as what is expected from them in this interview. All interviews started with the same question, asking the participant what they think is the biggest problems or obstacles in the switch from natural gas combustion to hydrogen combustion in gas fired power plants. Depending on the answer that they gave, different questions followed. These questions were related to specific topics that were mentioned in the answer, making use of the possibilities of the semi-structured interview. A list of possible questions was prepared beforehand. This list helped to ask questions that are relevant to the criteria, to steer the interview in the correct direction if the answers drifted away from the purpose of the interviews, or to provide questions to ask in the case of answer that lead to a dead end. This list with questions can be seen in subsection A.6.2.

After the interviews are taken, the interview results are summarised combined with possible quotations. These summaries are reviewed by the corresponding participant and asked for conformation before publishing them in this report. This gives the participant the ability to come back to an answer they gave, and make sure that the answers they gave are interpreted how they wanted them to. This is done before drawing conclusions from their answers, as this helps to acquire accurate results. Final summaries of the interviews can be seen in section A.6.

From these interviews, the answers are analysed. This is done by assigning codes to different pieces of the answers from the interviews. These codes are related to the underlying meaning of the sentence, and can therefore make the meaning of the interviews more clear. For this research inductive coding is used. The codes are derived with inductive coding while reading and analysing the interviews. The codes are not decided on before processing the interviews (Dovetail Editorial Team, 2023). Inductive coding is chosen for this research as it gives an overall more complete set of codes. Inductive coding later helps to identify all the problems and opportunities mentioned in the interviews.

The codes also give a great idea of the main problems and opportunities and the significance of them. In order to get a better understanding if the code relates to a problem or an opportunity, the attitude of specific answers from the interviews related to these codes is determined. If a quote related to a specific code mentions a problem or gives a negative opinion about the topic, it is assigned with -1. If the quotes related to a specific code mentions an opportunity or a positive opinion, it is assigned with +1. There might also be the case that an participant didn't really have a positive or negative opinion or might mentioned a problem, but refuted it directly afterwards. In these cases the the quote was assigned a 0.
Doing this for all quotes gives each code a total attitude score, showcasing the overall attitude from all interviews for each code.
This approach is selected to gain a better understanding into the significance of these problems and opportunities. Problems frequently mentioned with a negative attitude across multiple participants are considered more substantial and critical, whereas problems raised infrequently or by a single participant are considered less significant. For example, in the case that a code is mentioned often with a negative attitude would result in a high negative score. Showcasing the higher significance of this problem, as it is addressed often and by multiple participants. If professionals contradict each other, have less of an opinion about a code, or is only mentioned by a single participant, would lead to a more neutral score. Leading to a less significant problem or opportunity. This way the attitude towards a code is tried to quantify, giving a value to the significance of the problem or opportunity. An overview of the first order codes, an example statement, and the final attitude score can be seen in Table 5.4.

**Table 5.4:** Overview of first order codes and the attitude score associated with these codes

| **First order codes** | **Example statements** | **Attitude score** |
|---|---|---|
| Hydrogen technology knowledge | *The combustion technology and hydrogen technology are not really a problem, we are almost there already.* | -3 |
| Dependability on Natural Gas | *Being dependent on natural gas is a risk. There is enough gas, but the problem are conflicts.* | -5 |
| Hydrogen production partnerships | *Proper partnerships need to be formed in order to solve the hydrogen supply problem.* | 2 |
| Congestion problems hydrogen production | *It is not sure if we can solve the congestion problem in the future. This might be a challenge for the building of green hydrogen facilities.* | -4 |
| Green hydrogen development | *The Independence of renewable energy helps to accelerate the development of them.* | 1 |
| Blue hydrogen development | *Based on market criteria, blue hydrogen will be a winner.* | -2 |
| Green hydrogen future perspective | *A reason for going for green hydrogen in the future has to do with the fact that green hydrogen can provide a large amount of production capacity.* | 2 |
| Blue hydrogen future perspective | *The expectation is that blue hydrogen will play a larger part in the future.* | 0 |
| Hydrogen safety concerns | *Hydrogen burns faster and hotter, while the flame is also more difficult to control.* | 0 |
| Hydrogen storage | *People will always be against the storing of hydrogen if it happens near them.* | -2 |
| Hydrogen transport | *Receiving the hydrogen may be somewhat more difficult, especially with regard to measuring the offtake in hydrogen.* | 0 |
| Value of hydrogen usage | *There are other efforts in "hard to abate" industries where the impact of hydrogen is much greater to reduce $CO_2$ emissions.* | -1 |
| CCS technical perspective | *It will cost a lot of power and investment, all while the efficiency is quite low.* | -3 |
| CCS attitude | *You are just pushing away the problem.* | -4 |
| Carbon storage | *The storage for CCS is huge, there is plenty of space available. Of course it is limited, but it will take a long time to fill all the available storage.* | 1 |
| Emission costs | *It is the goals and incentives such as emission cost that drive the conversion to hydrogen combustion.* | 2 |

Next the problems and opportunities are identified based on these codes and their total attitude score. Negative scores relate to a problem, where positive scores relate to an opportunity. In the case that the attitude score is 0, it is not taken as neither a problem nor opportunity and therefore has no positive or negative effect on the alternatives. The magnitude of the attitude score is also taken as an indication of the significance of the problem or opportunity. This leads to the following problems and opportunities based on the codes and scores that can be seen in Table 5.4. The problems and opportunities are ranked from the problem with the most negative significance and attitude score, to the opportunity with the most positive significance and attitude score.

- **Dependability on natural gas**:

  - The dependability on natural gas poses a challenge for energy prices and fuel availability.

Participants mentioned that especially conflicts (like the recent war) can cause problems with the supply or pricing of natural gas. The dependency on natural gas makes the off takers of natural gas vulnerable to the effects of the price and availability of natural gas.

- **Congestion problems hydrogen production**:
  - The placement of green hydrogen facilities can be hindered in areas where there is already a high electricity demand, leading to a possible congested electricity grid.

During the interviews it is mentioned that the placement of hydrogen facilities must be done strategically and can cause problems related to the grid connections. The placement of green hydrogen facilities can add pressure on the electrical infrastructure as in many places the grid is full. Although it is also mentioned that hydrogen facilities can help balance the grid in the case of an excessive amount of energy, the problems occur when hydrogen is needed, but there is not an excessive amount on energy in the grid.

- **CCS attitude**:
  - There is scepticism towards CCS due to its association with $CO_2$ and the perception that it delays sustainability rather than addressing it directly.

Participants mentioned a possible fear of people towards $CO_2$ what causes a negative attitude towards CCS. Besides some participants believed in a future for CCS, it was often mentioned that CCS feels like a temporary solution to the carbon emission problems.

- **Hydrogen technology knowledge**
  - The lack of technical knowledge and experience in burning hydrogen leads to problems for the implementation of hydrogen in gas turbines.

Most participants mentioned that there are still technical obstacles to when trying to convert to 100% hydrogen combustion. It is a relative new technology and to get there is not impossible, but takes time and effort.

- **CCS technical perspective**:
  - CCS technology requires a lot of (sound) space and energy whilst lowering the efficiency.

During the interviews, participants mentioned the substantial area required by the technology, but they primarily focused on issues related to the low efficiency and high energy consumption of CCS.

- **Blue hydrogen development**:
  - The usage of carbon capture technology and the dependability on natural gas can cause resistance from the public in the development and utilisation

of blue hydrogen.

Participants mainly mentioned that the problem for the development of blue hydrogen would be possible resistance by the public. One problem mentioned by a participant was the fact that people do not want to have a blue hydrogen facility near them.

- **Hydrogen storage**:
  - The storage of hydrogen can lead to resistance from the public due to the public not wanting the associated risks and construction to happen near them.

Participants mentioned the main problem is not the storing of the hydrogen itself, but the resistance it might get from the public. People do not want to be located near a large scale hydrogen storage facility.

- **Value of hydrogen usage**:
  - The limited supply of hydrogen might have greater value being used in other industries.

During the interviews it is mentioned that hydrogen should be better used in hard to abate industries. However, the use of hydrogen instead of natural gas does also free up natural gas for other important industries.

- **Green hydrogen development**:
  - The development of green hydrogen facilities is driven by government incentives and the reduction of dependence on fossil fuel energy sources.

Participants mentioned that the development of green hydrogen facilities is driven by the government and the independence on non renewable energy sources. However, the participants also mentioned the problem that the Netherlands is not necessarily equipped for green hydrogen production and that the production of green hydrogen is better suited to be off-shore. It might also take time and development in order to get the price of green hydrogen down.

- **Carbon storage**:
  - There is enough carbon storage capacity available for the future energy needs.

Participants mentioned that there is no real worry for the possibility of carbon storage. There is a large amount of storage capacity available for the future to come. However, it is also mentioned that this storage is not infinite.

- **Hydrogen production partnerships**:
  - Partnering with other companies can increase the total hydrogen supply and lower the hydrogen cost by leveraging each companies strengths.

During the interviews, it is mentioned that forming partnerships with other companies is a great benefit in order to overcome hydrogen supply problems. Companies should leverage their own strengths. Although participants also mentioned that having everything under own control can be beneficial in some cases, there are no real risk in establishing partnerships for hydrogen production.

- **Green hydrogen future perspective**:
  - Green hydrogen facilities can produce large quantities of hydrogen, be located near hydrogen off-takers or renewable energy sources, thereby also freeing up natural gas for other essential processes.

The participants mentioned an overall positive future perspective. The main reasons mentioned are that green hydrogen facilities have a relative small footprint and can be scaled to a large amounts of production capacity. However, it is also mentioned that obtaining a sufficient amount of green hydrogen production takes a long time.

- **Emission costs**:
  - The emission cost incentives the development of cleaner energy generation.

The participants mention that the emission cost in general can be seen as something positive as it provides an incentive towards more sustainable fuels such as hydrogen. However, it is also mentioned that in the end, the emission costs are just added to the energy pricing.

## 5.4. Division of Problems and Opportunities across Alternatives

The goal of identifying these problems and opportunities is to score the qualitative criteria mentioned in section 4.3. Based on the problem or the opportunity as they are mentioned above, they are divided across the qualitative criteria. These problems and opportunities are linked to the different alternatives described in section 4.4. These problems and opportunities also give an answer to the sub-research question: *What are the implications for the adaptability, longevity and dependability of the implementation of each alternative for expected infrastructure in 2040?* This is done by looking if the problems and opportunities affect at least on of the aspects from the alternatives. An overview of each alternative and the problems that are related to them can be seen in Table 5.5

### Technical Adaptability

This criteria relates to the technical aspects about the implementation of hydrogen into the CCGT. Therefore the problems and opportunities related to the technological development have effect on this criteria. For instance problems related to technologies that are used, or are in development for the alternatives. These problems and opportunities are:

- *Hydrogen technology knowledge.* This problem affects all alternatives that use hydrogen as a fuel.
- *Green hydrogen development.* This opportunity is related to the alternative on

green hydrogen, but also the alternative on a mixture of blue and green hydrogen.

- *Blue hydrogen development.* This problem mainly affects the use of the alternative on blue hydrogen, but also the alternative on a mixture of blue and green hydrogen.
- *CCS technical perspective.* This problem is related to alternatives using blue hydrogen. These are the alternatives on blue hydrogen and on a mixture of hydrogen.

### Infrastructural Adaptability

This criteria relates to the infrastructural aspects and the changes that have to be made to the infrastructure. Therefore the problems and opportunities that are related to the infrastructure are linked to this criteria. These are for instance related to the storage of certain materials, or to the gas or electricity infrastructure. These problems and opportunities are:

- *Congestion problems hydrogen production.* This problem is related to the placement of green hydrogen facilities. Therefore the alternatives related to green hydrogen production are effected by this problem. Therefore the alternatives on green hydrogen, and a mixture of hydrogen are effected.
- *Hydrogen storage.* Storing of hydrogen is needed for all alternatives that use hydrogen as a fuel. The alternatives effected by hydrogen storage problems are the alternative on green, blue and a mixture of blue and green hydrogen.
- *Carbon storage.* This opportunity affects the alternatives that store carbon. This in related to the use of blue hydrogen, and therefore affects the blue hydrogen and mix hydrogen alternatives.

### Operational Longevity

For the operational longevity criteria, the same is done as for the previous criteria. However, the problems and opportunities should now have an effect on the future state of certain technologies. The problems and opportunities that have an effect on the operational longevity are:

- *Green hydrogen future perspective.* This opportunity affects the alternatives that use green hydrogen. These are the alternative on green hydrogen, and the alternative on a mix of blue and green hydrogen.
- *CCS attitude.* This problem affects the alternatives that use CCS. CCS is used in this research for the production of blue hydrogen. Thus the alternative on blue hydrogen, and a mix of blue and green hydrogen are affected.
- Emission costs. Emission costs affect all alternatives that emit carbon. Although each alternative emits a different amount of carbon, all alternatives emit at least some carbon.

### Dependability

The last criteria relates to the dependability of the alternatives. Therefore the problems and opportunities that are relate to partnerships, or the dependency on specific materials. The problems and opportunities that are related to the dependability are:

- *Dependability on natural gas.* This problem has an effect on the alternatives that use natural gas. These are the alternatives on blue hydrogen and on natural gas.
- *Hydrogen production partnerships.* This opportunity affects the alternatives that form a partnership for the hydrogen production. In this research, the alternatives that use blue hydrogen form a partnership. These are the alternatives on blue hydrogen and a mixture of blue and green hydrogen.
- *Value of hydrogen usage.* The last problem affects all alternatives that use hydrogen as a fuel for the CCGT. These are the alternatives on blue hydrogen, green hydrogen, and a mixture of blue and green hydrogen.

One important aspect to mention is that the alternative on a mixture of blue and green hydrogen is basically a combination of the problems and opportunities mentioned for the previous two alternatives. However, it must be known that although each forecast for the alternative on a mixture of blue and green hydrogen uses both hydrogen sources, and is thus affected by the problems and opportunities associated with both blue and green hydrogen. There is a difference in the balance between blue and green hydrogen for each forecast. The differences between the forecasts can be seen by looking at the blue hydrogen plant rate and the total electrolyzer facility capacity in Table A.10. This results in slight differences for the final results between the different forecast.

## 5.5. Qualitative Results

The last step of the qualitative research is the scoring of the different qualitative criteria mentioned in section 4.3. This is done by looking how significant the problems and opportunities are for each criteria and alternative specifically. Deciding if this results in the criteria being an opportunity for the specific alternative, or if it causes problems for the alternative. This brings up one problem that has to do with the alternative that combines both blue and green hydrogen. Mentioned before in section 5.4, there is a variance in the dependency on blue or green hydrogen depending on the forecast. The mix alternative with low forecasts depends greatly on blue hydrogen, having a blue hydrogen plant rate almost equal to just running on blue hydrogen alone. While the central and high forecasts for the mix alternative rely more on green hydrogen, having a total electrolyzer facility capacity (almost) equal to the alternative fully on green hydrogen. To achieve a balanced consideration of both the problems and opportunities in the mixed alternative for all forecasts, while still recognising issues associated with the non-dominant form of hydrogen production, the attitude score for the problems and opportunities of the non-dominant production method is halved in these specific instances.

### Technical Adaptability

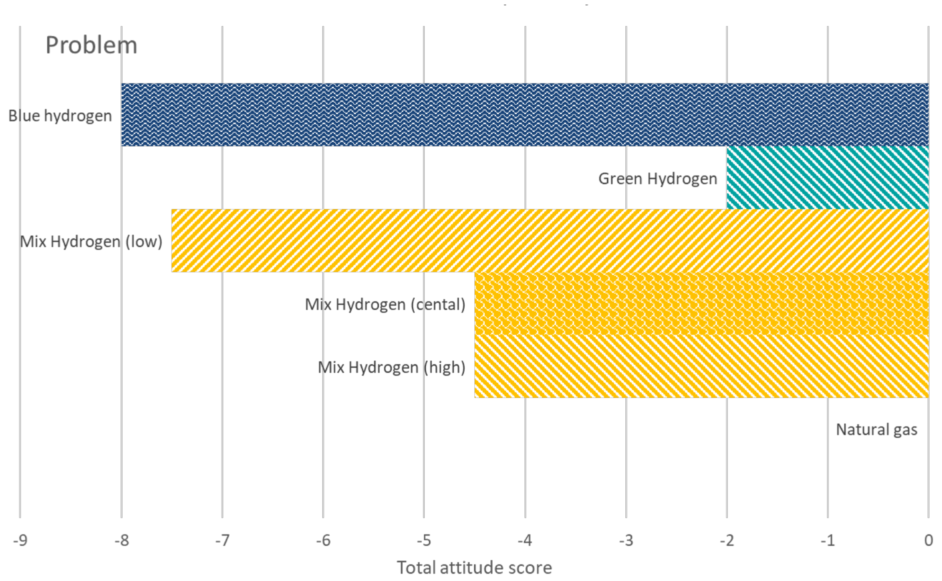
In Figure 5.5 the final results for each alternative can be seen for the technical adaptability criteria. Noticeable for this criteria is that the alternative for natural gas is not shown in this graph. This is because running the CCGT on natural gas poses no problems or opportunities. The technology has been in use for many years, establishing it

**Table 5.5:** Different alternatives and their respective problems and opportunities

| | **Blue hydrogen** | | **Green hydrogen** | | **Mix hydrogen** | | **Natural gas** | |
|---|---|---|---|---|---|---|---|---|
| **Technical adaptability** | Hydrogen technology knowledge | -3 | Hydrogen technology knowledge | -3 | Hydrogen technology knowledge | -3 | | |
| | Blue hydrogen development | -2 | Green hydrogen development | 1 | Blue hydrogen development | -2 | | |
| | CCS technical perspective | -3 | | | CCS technical perspective | -3 | | |
| | | | | | Green hydrogen development | 1 | | |
| **Infrastructural adaptability** | Carbon storage | 1 | Congestion problems hydrogen production | -4 | Congestion problems hydrogen production | -4 | | |
| | Hydrogen storage | -2 | Hydrogen storage | -2 | Hydrogen storage | -2 | | |
| | | | | | Carbon storage | 1 | | |
| **Operational longevity** | CCS attitude | -3 | Green hydrogen future perspective | 2 | CCS attitude | -3 | Emission costs | -2 |
| | Emission costs | 2 | Emission costs | 2 | Green hydrogen future perspective | 2 | | |
| | | | | | Emission costs | 2 | | |
| **Dependability** | Dependability on natural gas | -5 | Value of hydrogen usage | -1 | Dependability on natural gas | -5 | Dependability on natural gas | -5 |
| | Hydrogen production partnerships | 2 | | | Hydrogen production partnerships | 2 | | |
| | Value of hydrogen usage | -1 | | | Value of hydrogen usage | -1 | | |

as a mature and stable option without significant technical problems. The large difference between blue and green hydrogen is mainly the result of blue hydrogen needing carbon capture technology, what has some large problems associated with it.

**Figure 5.5:** The significance of technical adaptability




### Infrastructural Adaptability

The same holds true for the infrastructural adaptability. Here the final results for each alternative can be seen in Figure 5.6. Again, just as for the technical adaptability, there is no visible result for natural gas shown. This is just as mentioned before that running the CCGT on natural gas poses no problems or opportunities. Running on natural gas is a mature option that requires no major changes to the infrastructure in the future. In contrary to the technical adaptability, green hydrogen has larger problems associated with infrastructural adaptability. The main reason has to do with the problems that can hinder the placement of green hydrogen electrolyzer facilities due to the congested electricity grid. Blue hydrogen is less affected by this problem as it relies on natural gas for the production of hydrogen.

### Operational Longevity

The results for the each alternative for the operational longevity can be seen in Figure 5.7. For this criteria natural gas does have a negative score. This is due to the fact that the increase in emission costs pushes the development and use of more sustainable energy sources. Therefore the hydrogen sources are less problematic compared to the alternative on natural gas. Green hydrogen even offers some great opportunities for the operational longevity, due to the fact that can produce large quantities of hydrogen with a relatively small footprint located at strategic locations. All while freeing up natural gas for other essential processes.

**Figure 5.6:** The significance of infrastructural adaptability

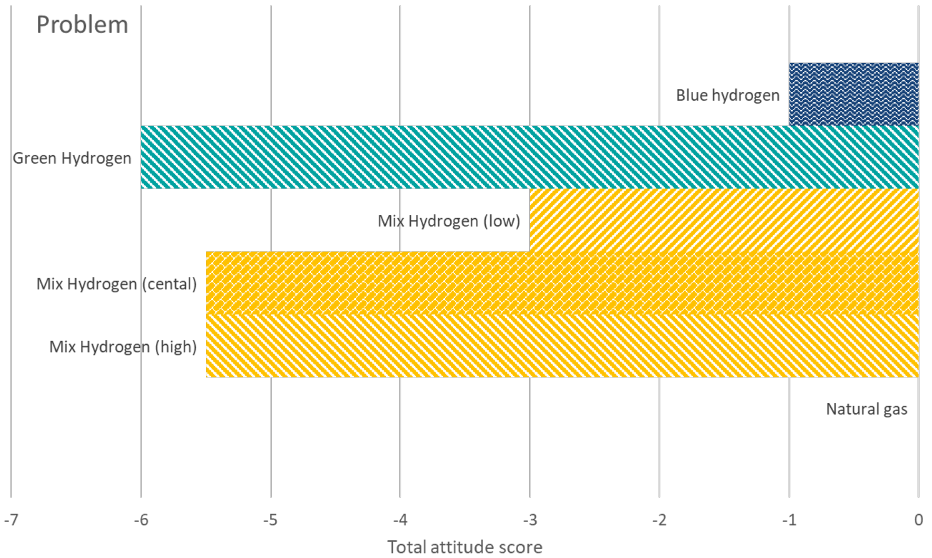
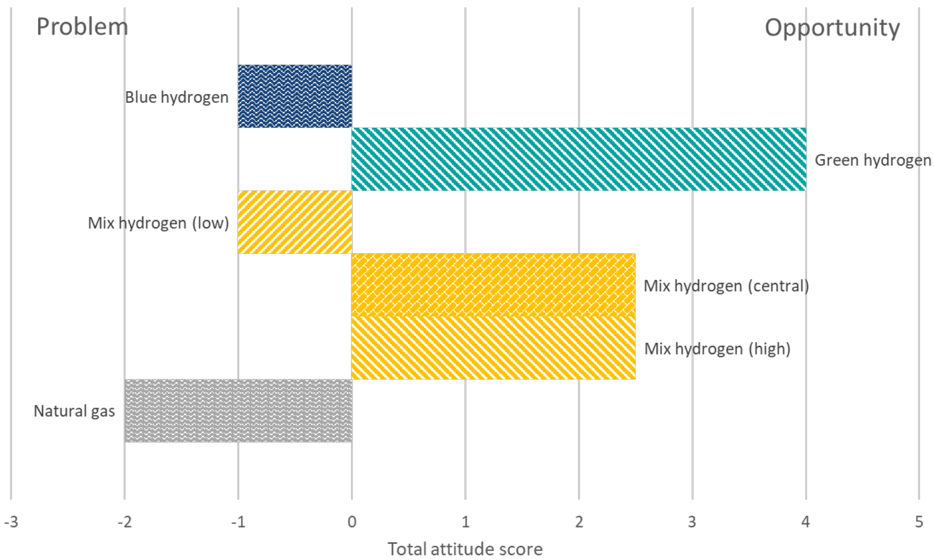



**Figure 5.7:** The significance of operational longevity




## Dependability

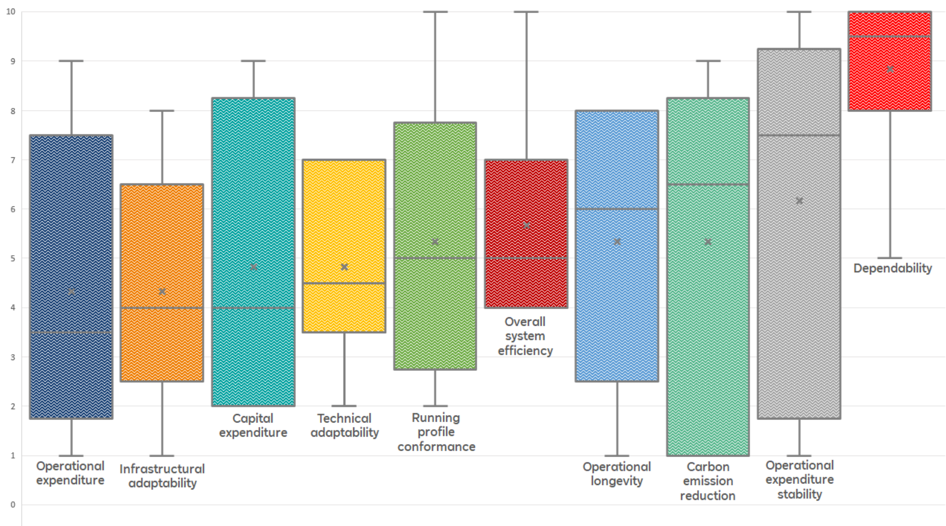
The results of the different alternatives for the last qualitative criteria can be seen in Figure 5.8. The results show that especially natural gas, closely followed by alternatives using blue hydrogen relate to dependability problems. The main reason for this is the dependability on natural gas poses risks and challenges related to energy prices and fuel availability. Mentioned before in subsection 3.2.1, blue hydrogen also depends on the availability and price of natural gas. The benefit that blue hydrogen alternative has compared to the alternative on natural gas, is the fact that the blue hydrogen alternative depends hydrogen partnerships. This is an opportunity as partnering with other companies can increase the total hydrogen supply and lower the hydrogen cost by leveraging each companies strengths.

**Figure 5.8:** The significance of dependability


## 5.5.1. Criteria Ranking Results

During the interviews, the participants were also asked to rank the different criteria established in section 4.3. They scored the criteria which they found most important with a 1 and the criteria that they found least important with a 10. Each score can only be given once, establishing an order of most important to least important for each participant. The results of these rankings can be seen in Table A.12 and are illustrated in Figure 5.9.

**Figure 5.9:** Ranking of the criteria by the participants visualised in a box-plot




These six rankings have to be formed into one single final ranking of the criteria, based on which have been found to be the most important to the least important by the participants. This is done by ranking the criteria based on the median of the 6 scores for each criteria. Ranking based on the median is chosen because it helps to prevent disproportional scoring of a criteria due to single outliers. The median representing the centre value of the scores for each criteria, giving a great indication of the overall importance of the criteria. In the case that two criteria have the same median, another decision has to be made in order to decide which criteria is more important. This decision is than based on the average of each criteria. Where for the criteria that have the same median, the criteria with the lowest average is seen as more important. This is done as in the cases where the median was equal, the criteria had major outliers that would prevent the averages to compare with each other.

This leads to the final ranking that can be seen in Table 5.6

**Table 5.6:** The final ranking of the criteria

| Ranking | Criteria |
|---|---|
| 1 | Operational expenditure |
| 2 | Infrastructural adaptability |
| 3 | Capital expenditure |
| 4 | Technical adaptability |
| 5 | Running profile conformance |
| 6 | Overall system efficiency |
| 7 | Operational longevity |
| 8 | Carbon emission reduction |
| 9 | Operational expenditure stability |
| 10 | Dependability |

## 5.6. Limitations and Validations of Results

Although best efforts are taken into account to produce as accurate results as possible, there are some limitations concerning the results.

### 5.6.1. Quantitative Results

For the qualitative results there are some limitations that should be taken into consideration when interpreting the results. The main limitation has to due with the assumptions and estimations of the parameters used to calculate the total annual cost for 2040. Utter care is taken into finding, estimating, and calculating the parameters. However, although the results are in line with expectations of energy pricing, there might be slight differentiation in the actual numbers. This can be due to many different reasons, but one reason is the fact that it is very difficult to predict the future. It might be that estimations for certain parameters that are set at the time of writing this research, are different in the future. This also relates to the forecasts used that are provided by Aurora Energy Research (2024). These forecasts provide valuable information for the prediction of the energy demand and the total annual cost for energy production in 2040. These forecasts get updates regularly. Newer forecasts can be assumed to be more accurate for the future perspective.

Lastly, there are also limitations in the way that the total annual cost for energy generation is calculated. The annual cost is calculated using Pyomo, a Python-based open-source optimisation modelling language. Although there is previous experience in coding and the Pyomo modelling language, it is not the purpose of this research to develop an optimisation tool. Pyomo is used as a tool in order to calculate the minimal annual cost of energy generation. In this code the running profile established in subsection 4.1.1 are used. Using this running profile indirectly results into the limitations of the running profile as well. The limitations of which can be seen in subsection 4.1.2. Again utter care is taken to provided as accurate results as possible, but the limitations are also taken into consideration by rounding the values above the million to the nearest thousand.

### 5.6.2. Qualitative Results

One of the first limitations of the qualitative research has to do with the fact that only a limited number of interviews is performed. The limit in total amount of interviews has several reasons. One reason for the limited amount of interviews is the time constraint of this research. A longer research period would have given the ability to interview more professionals inside the energy sector. Besides this, another reason would be the difficulty to recruit willing professionals with different job functions to participate in an interview. All participants happily and voluntarily participated in the interviews, but the problem arises as there was no real incentive for them to participate. The only benefit for the participants would be to get access to the final results of this research. This makes the recruitment of professionals difficult. The last reason for the limited amount of interviews has to do with the diminishing amount of results from extra interviews. After 4 interviews, the main problems and opportunities could already be identified. Extra interviews did not add new insights, but mainly confirmed the already mentioned problems and opportunities.

The usage of 6 interviews can result in a lower generalizability compared to conducting more interviews. The limited amount of interviews might not be representative to the larger population of professionals in the energy sector. Conducting more interviews might result in more different opinions and insights into the problems, what might have changed the problems or opportunities as a total, or change the magnitude of the problem or opportunity. Conducting more interviews might also have revealed extra or new problems or opportunities, even considering the diminishing returns of extra interviews.

Besides the limited amount of interviews, another limitation is the way on how the magnitudes of the problems and opportunities are quantified. This is based on counting the positive or negative attitude of the quotes associated with each code. In the case that the number of interviews is increased, the magnitude of the attitude score also changes. It is expected that an increase in interviews will increase the absolute values of the largest problems and opportunities, while the smaller problems and opportunities would stay relatively the same.

However, since the results are standardised for the multi-criteria analysis, the absolute values of the qualitative criteria are less important for comparing alternatives than the ratios between these values. This ratio between the alternatives stays roughly the same if the interviews would increase. Although, an increase in interviews would make the ratio between the alternatives more accurate. Also increasing the scientific validity of the results.

Another potential limitation might be the presence of bias in the interviews, as all participants are professionals in the energy sector. To limit the possibility of a bias it is made sure that all participants in the interviews have different job functions. In order to even more validate the results, interview questions were asked to people outside the energy sector. This led to answers similar to the results of the interviews with the professionals inside the energy sector.

# 6

# Phase 3: Conducting the Multi-Criteria Analysis

The last phase of the multi-criteria analysis, phase 3, adds the weighing factors to the multi-criteria analysis and concludes with an answer to which alternative is the best strategic choice. This phase includes 3 different sensitivity analyses showcasing the strength of the alternatives in case of variation in the priority order of the criteria. This phase provides steps 6 up to and including step 8 of the multi-criteria analysis and uses the data from the previous steps. Phase 3 gives an answer to the main research question: *What is the most effective way of generating electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective?*

## 6.1. Multi-Criteria Analysis Scoring

To score the multi-criteria analysis, the results for both quantitative and qualitative criteria mentioned in chapter 5 are used. The results depend on 3 different forecasts provided by Aurora Energy Research (2024). These different forecasts lead to variation in the results of some criteria over a specific alternative. It is therefore decided to perform 3 different multi-criteria analyses, varying on their respective forecasts. This results in a multi-criteria analysis for a low forecast, a central, and a high forecast.

In order to perform any multi-criteria analysis, first the weights of the different criteria have to be established. These weights are established by using Equation 2.3 from chapter 2 to convert the final ranking of the criteria, that can be seen in Table 5.6, to specific weights of the criteria. The conversion of this criteria ranking, with a significance level of 2, provides the results displayed in Table 6.1. The results for each criteria are standardised using Equation 2.1 and Equation 2.2. This process assigns a score ranging from 0 to 1 to each alternative for each criteria. How these scores are calculated, the results used, and their respective standardised value can be seen in section A.7.

**Table 6.1:** The final weights of the criteria

| **Ranking** | **Criteria** | Weight |
|---|---|---|
| 1 | Operational expenditure | 0,18 |
| 2 | Infrastructural adaptability | 0,16 |
| 3 | Capital expenditure | 0,15 |
| 4 | Technical adaptability | 0,13 |
| 5 | Running profile conformance | 0,11 |
| 6 | Overall system efficiency | 0,091 |
| 7 | Operational longevity | 0,073 |
| 8 | Carbon emission reduction | 0,055 |
| 9 | Operational expenditure stability | 0,036 |
| 10 | Dependability | 0,018 |

### 6.1.1. Low Forecast Multi-Criteria Analysis

In the case of the low forecast alternatives, the results shown in Table A.13 and Table A.16 indicate the weighted scores of each criteria for each alternative. According to the final score of the low forecast multi-criteria analysis, the alternative where the CCGT runs on natural gas is best suited. The alternative on natural gas is followed by the alternative fully relying on the use of blue hydrogen. However, there is still a significant difference between the alternative on natural gas and the alternatives on hydrogen. This difference is greatly impacted by the criteria: capital expenditure and overall system efficiency. Both of these criteria have a relative heavy weight. Combined with the fact that the alternative on natural gas performs extremely well on these two criteria compared to the alternatives on hydrogen, as can be seen in Table A.13, gives the alternative on natural gas great advantage over the alternatives on hydrogen. Resulting in the continuation of running the CCGT on natural gas to be the top performer for the low forecast future state. A visualisation of the final results of the multi-criteria analysis can be seen in Figure 6.1.

### 6.1.2. Central Forecast Multi-Criteria Analysis

In the central forecast alternatives, the natural gas alternative emerges as the top performer with a significant lead over the other alternatives. The scoring of the multi-criteria analysis can be seen in Table A.14 and Table A.17. Unlike the low forecast alternatives mentioned in subsection 6.1.1, the alternative on a mixture of blue and green hydrogen is the next top performer after the alternative on natural gas. However, the alternatives relying on hydrogen are all very close to each other in their final score. Similar to the multi-criteria analysis for the low forecast alternatives, the natural gas alternative indicates a significant advantage over the other alternatives because of the great performance in the overall efficiency and capital expenditure criteria. A visualisation of the final results for the central forecast can be seen in Figure 6.2.

### 6.1.3. High Forecast Multi-Criteria Analysis

In the high forecast, again the alternative on natural gas is the top performer. Nevertheless, the final results of the alternatives on natural gas, on green hydrogen, and on a mix of blue and green hydrogen are very close. Scoring within a 5% margin of each

**Figure 6.1:** Final results low forecast multi-criteria analysis

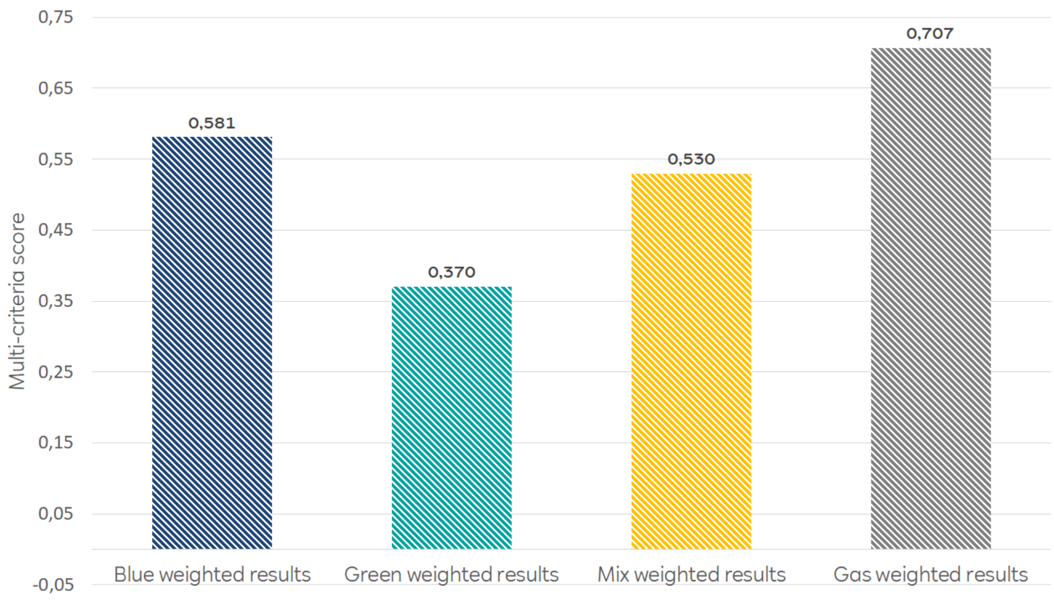
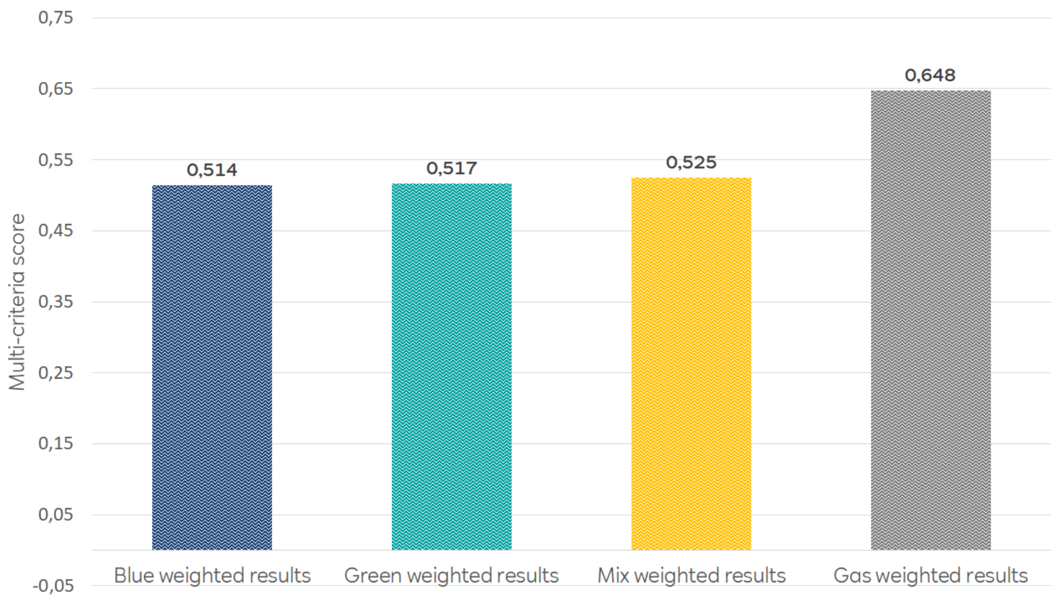
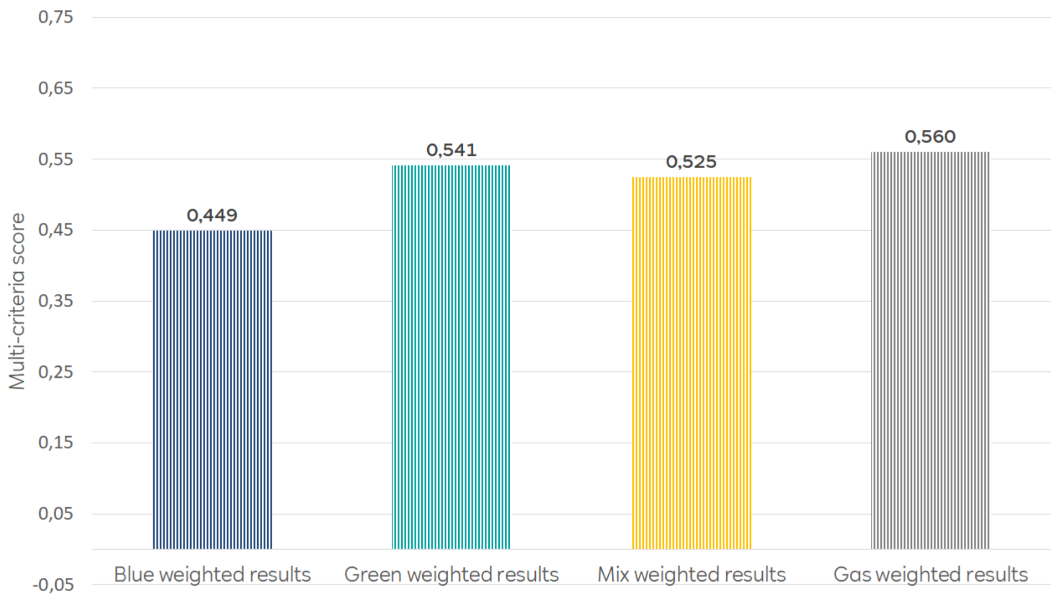



**Figure 6.2:** Final results central forecast multi-criteria analysis




other. The alternative relying fully on blue hydrogen falls behind in the final scores. Similarly to the previous two forecast multi-criteria analyses, the natural gas alternative shows a significant advantage over the other alternatives based on the overall efficiency and the capital expenditure criteria. The scores and weighted results of the multi-criteria analysis for the high forecast alternatives can be seen in Table A.15 and Table A.18. A visualisation of the final results for the high forecast can be seen in Figure 6.3.

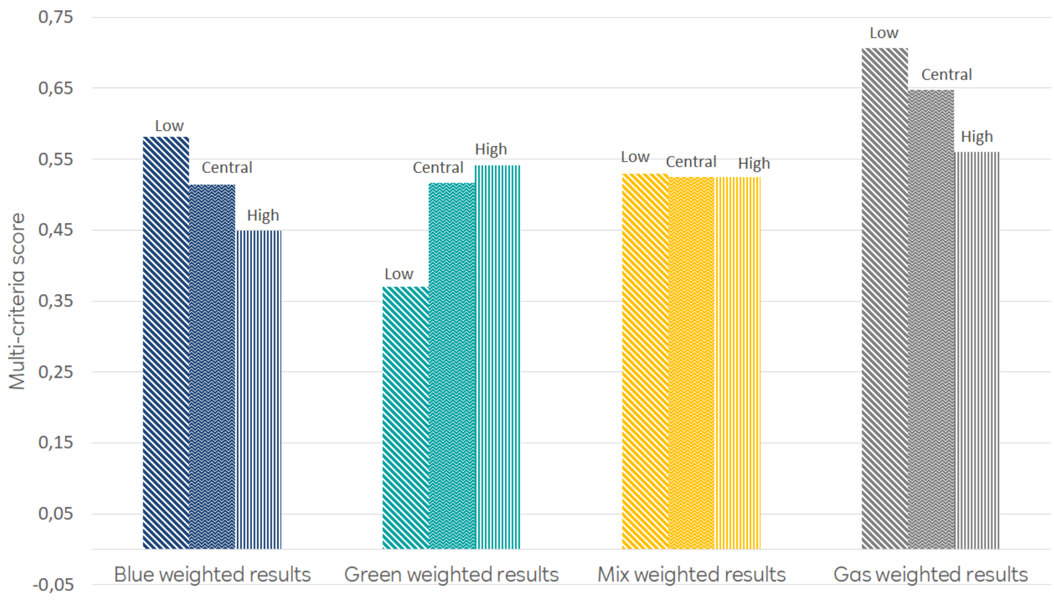
**Figure 6.3:** Final results high forecast multi-criteria analysis




## 6.1.4. Overall Multi-Criteria Analyses Evaluation

There are several interesting findings when evaluating the different multi-criteria analyses. It is important to remember that the different forecasts are related to the installed capacity of renewable energy sources. Higher forecasts have a larger installed capacity of renewable energy compared to the low forecasts. Based on the findings of the previous discussed multi-criteria analysis, it can be noticed that as the forecast increases, the final score of alternatives on blue hydrogen and on natural gas decline. Concluding that an increase in installed capacity of renewable energy leads to a relative decline in performance of alternatives on blue hydrogen and natural gas. On the contrary, the final multi-criteria analysis score of the alternative on green hydrogen increases as the forecasts rise, albeit at a decelerating rate. Concluding that an increase in installed capacity of renewable energy has a positive impact on the usage of green hydrogen in the alternatives. The final multi-criteria analysis score of the alternative mixing blue and green hydrogen remains relatively stable throughout the different forecasts. The main driver for this effect is that the scores of the operational expenditure rise quickly for the green hydrogen alternative, and drops quickly for the alternatives on blue hydrogen and on natural gas. The reason is the increase in the natural gas price, and the increase in excessive amounts of renewable electricity. Both the alternative on natural gas and the blue hydrogen heavily depend on the cost of natural gas, increasing the operational expenditure as the natural gas price increases. Green hydrogen costs depend on the electricity price. The increase in excessive amounts of renewable electricity in higher forecasts result in more times when electricity is cheap, decreasing the operational expenditure. The final results of all the multi-criteria analyses and how they compare to each other can be seen in Figure 6.4.

**Figure 6.4:** Final results of the multi-criteria analyses across the different forecasts




## 6.2. Sensitivity Analysis

A sensitivity analysis is performed over the multi-criteria analyses to test the robustness of the final scores against variations in criteria weights, ensuring the reliability and stability of the chosen alternatives under different conditions. The sensitivity analysis is performed by doing a sensitivity analysis where the criteria ”capital expenditure” is the least important, this is referred to as: sensitivity analysis CAPEX. Afterwards a sensitivity analysis where the criteria ”overall system efficiency” is the least important criteria, referred to as: sensitivity analysis Efficiency. Lastly a sensitivity analysis where the criteria ”carbon emission reduction” is most important, referred to as: Sensitivity analysis CO2 . These criteria are chosen to address in the sensitivity analysis for several reasons. The first reason is that the criteria showed to have a substantial impact on the performance of the natural gas alternative, giving this alternative a great advantage or drawback over the alternatives depending on hydrogen. The initial multi-criteria analysis indicated significant benefits for the continuation of natural gas use in terms of capital expenditure and overall system efficiency, but also showed the drawback related to carbon emission reduction. Another reason is that capital expenditure criteria can loose its significance in the case that the government subsidises all or part of the capital investment (Ministerie van Economische Zaken en Klimaat, 2023). One reason for reducing the weight of the criteria ”overall system efficiency” is that, while conserving energy is crucial, there are situations where prioritising decarbonization efforts may require a sacrifice on efficiency in energy production. The increase of the weight of the carbon emission reduction can be backed by the goals and incentives of the company and government to strive for a more sustainable future and to reach the climate goals. The increase of importance of the criteria ”carbon emission reduction” also adds value to the problem statement to research more sustainable ways of flexible power generation.

To assign new weights for the multi-criteria analysis by changing one of these criteria,

**Table 6.2:** The new rankings for the sensitivity analyses and the corresponding weights

| Ranking | Original | Sensitivity analysis CAPEX | sensitivity analysis Efficiency | sensitivity analysis CO2 | weights |
|---|---|---|---|---|---|
| 1 | Operational expenditure | Operational expenditure | Operational expenditure | Carbon emission reduction | 0,182 |
| 2 | Infrastructural adaptability | Infrastructural adaptability | Infrastructural adaptability | Operational expenditure | 0,164 |
| 3 | Capital expenditure | Technical adaptability | Capital expenditure | Infrastructural adaptability | 0,145 |
| 4 | Technical adaptability | Running profile conformance | Technical adaptability | Capital expenditure | 0,127 |
| 5 | Running profile conformance | Overall system efficiency | Running profile conformance | Technical adaptability | 0,109 |
| 6 | Overall system efficiency | Operational longevity | Operational longevity | Running profile conformance | 0,091 |
| 7 | Operational longevity | Carbon emission reduction | Carbon emission reduction | Overall system efficiency | 0,073 |
| 8 | Carbon emission reduction | Operational expenditure stability | Operational expenditure stability | Operational longevity | 0,055 |
| 9 | Operational expenditure stability | Dependability | Dependability | Operational expenditure stability | 0,036 |
| 10 | Dependability | Capital expenditure | Overall system efficiency | Dependability | 0,018 |

new rankings are formed. These new rankings for the sensitivity analyses and the new corresponding weights of the criteria can be seen in Table 6.2.

### 6.2.1. Results Sensitivity Analysis

Sensitivity analysis CAPEX shows that with a decreased weight in capital expenditure, the alternative on natural gas is still the top performer for the low forecast. Nevertheless, for the central forecast it is the alternative on a mix of blue and green hydrogen that is the top performer. This alternative is closely followed by the alternative on green hydrogen, which is the top performer for the high forecast.

The results of the sensitivity analysis Efficiency show that in the case that the overall system efficiency has the lowest weight, the alternative on natural gas is still the top performer for the low forecast. The results change in the higher forecasts. In the central forecast natural gas, green hydrogen, and the mixed alternative of blue and green hydrogen have a final score within a 0.5% range of each other. Green hydrogen marginally takes the lead as the top performer among these alternatives. Nevertheless, all alternatives, except for the blue hydrogen alternative, can be expected to have near equal performance for the central forecast. For the high forecast, the green hydrogen alternative takes a substantial lead to be the top performer.

In the sensitivity analysis CO2, the performance of the natural gas alternative drops significantly compared to the original scores of the multi-criteria analysis. A continuation of running on natural gas is, for this sensitivity analysis, not the top performer in any forecast. The top performing alternatives range from the blue hydrogen alternative for the low forecast, to the green hydrogen alternative for the high forecast, and the mix alternative of blue and green hydrogen for the central forecast. The final results of the original multi-criteria analysis and the sensitivity analyses for all forecasts can be seen in Table A.19.

Table Table 6.3 shows an overview of the top performers for the different forecasts over the original multi-criteria and the sensitivity analyses.

**Table 6.3:** Top performers of the multi-criteria analysis and the sensitivity analyses

| | **Low forecast** | **Central forecast** | **High forecast** |
|---|---|---|---|
| **Original** | Natural gas | Natural gas | Natural gas |
| **Sensitivity analysis CAPEX** | Natural gas | Mix hydrogen | Green hydrogen |
| **Sensitivity analysis Efficiency** | Natural gas | Green hydrogen | Green hydrogen |
| **Sensitivity analysis CO2** | Blue hydrogen | Mix hydrogen | Green hydrogen |

In the analyses focusing only on alternatives compared to natural gas, the top performers are shown in Table 6.4.

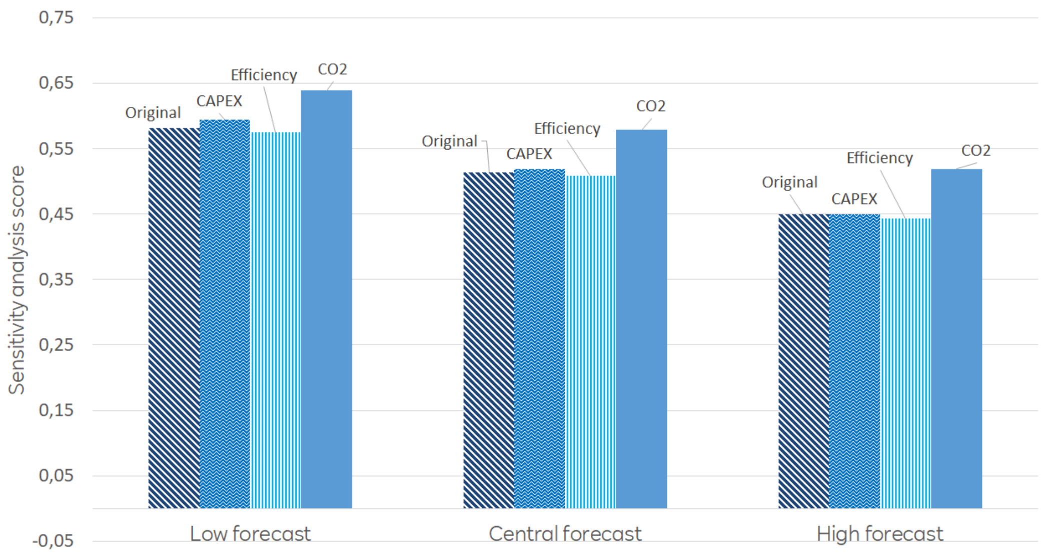
**Table 6.4:** Top performers of the multi-criteria analysis and the sensitivity analyses without natural gas alternative

| | **Low forecast** | **Central forecast** | **High forecast** |
|---|---|---|---|
| **Original** | Blue hydrogen | Mix hydrogen | Green hydrogen |
| **Sensitivity analysis CAPEX** | Blue hydrogen | Mix hydrogen | Green hydrogen |
| **Sensitivity analysis Efficiency** | Blue hydrogen | Green hydrogen | Green hydrogen |
| **Sensitivity analysis CO2** | Blue hydrogen | Mix hydrogen | Green hydrogen |

### Blue Hydrogen

It is important to see how the different sensitivity analyses impact the performance of the specific blue hydrogen alternative. This helps to give an understanding of the overall magnitude of an impact that the change in weight of the specific criteria has on the overall scoring of the alternative. The results in Figure 6.5 indicate that the overall performance of the blue hydrogen alternative declines as the forecasts increase, including the sensitivity analyses. The results also indicate that a decrease of the weight of the capital expenditure in sensitivity analysis CAPEX and of the weight of the overall system efficiency in sensitivity analysis Efficiency have little effect on the overall final score of the alternative. The decrease in weight of the capital expenditure criteria shows a marginal improvement, showing that the capital expenditure is a relative small weakness for the alternative. The decrease in weight of the overall system efficiency criteria even shows a marginal decrease in the performance across the different forecasts. Revealing that the overall system efficiency is a relative strength for the blue hydrogen alternative. However, the result of increasing the importance of carbon emission reduction has the most impact on the final score. This leads to a large increase in performance of the alternative across the different forecast. Showcasing the strength of the relative importance of carbon emission reduction in the performance of the blue hydrogen forecast.

**Figure 6.5:** Final results of multi-criteria and sensitivity analyses for the blue hydrogen alternative




### Green Hydrogen

In the alternative on green hydrogen the results are completely different. It is noted that the overall performance of the alternative increases as the forecast increase. The results in Figure 6.6 show the weakness that the green hydrogen alternative has related to the criteria: capital expenditure. The decrease in the weight of this criteria in sensitivity analysis CAPEX raises the overall score significantly. In sensitivity analysis Efficiency, adjusting the weight of the overall system efficiency criteria positively influences the overall performance of green hydrogen. However, this impact is less substantial compared to sensitivity analysis CAPEX. Although increasing the importance of carbon emission reduction in sensitivity analysis CO2 has a positive compared to the original performance, it makes less impact on the final score compared to the capital expenditure in sensitivity analysis CAPEX. Showcasing the importance and impact that capital expenditure has on the implementation of the green hydrogen alternative.

### Mix Hydrogen

Figure 6.7 shows the results for the multi-criteria and sensitivity analyses for the alternative relying on a mixture of blue and green hydrogen. These results indicate that the final performance has relative little variance over the different forecast. This alternative mixes both blue and green hydrogen, therefore trying to benefit from the best performing hydrogen source in each forecast. Noticeable is that in the low forecast, the scores and the variance in the final results between the original and sensitivity analyses is almost equal to the low forecast shown in Figure 6.5. The same holds true for the high forecast scores and the results in Figure 6.6. Copying the strengths and weaknesses of the dominant hydrogen source in the mix alternative. This results in consistent performance for the mix of blue and green hydrogen across different forecasts, mirroring the performance of the best-performing blue or green hydrogen alternative for each respective forecast.

**Figure 6.6:** Final results of multi-criteria and sensitivity analyses for the green hydrogen alternative

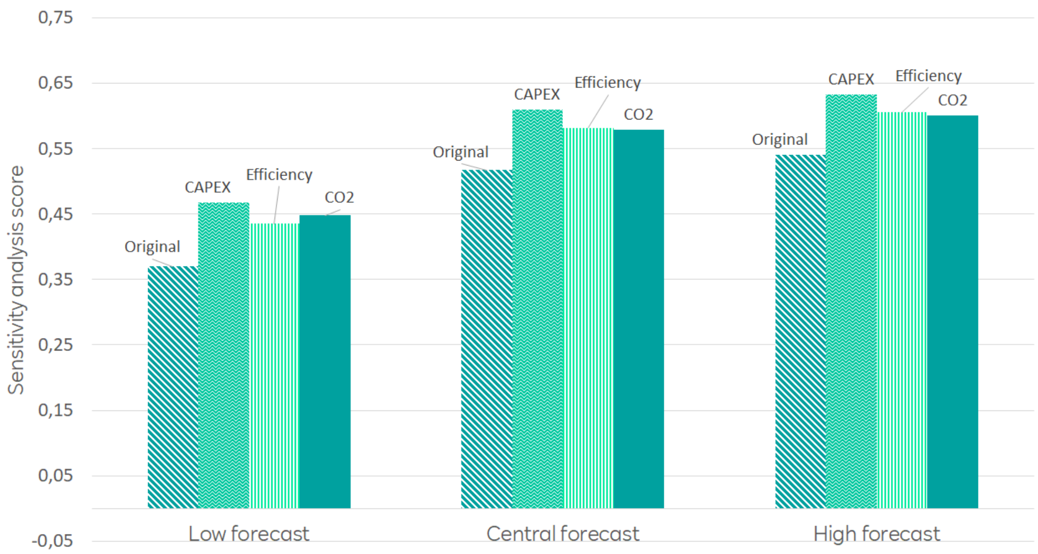
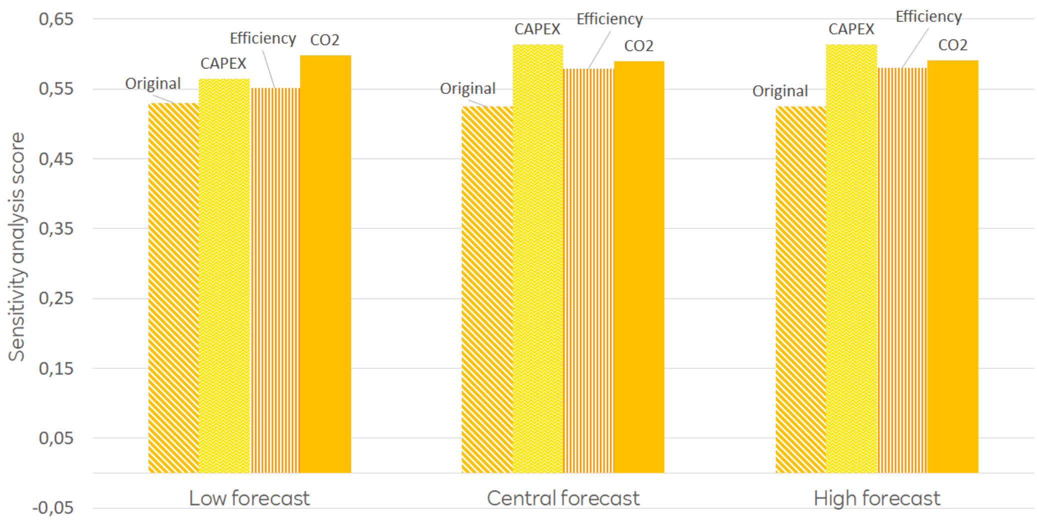


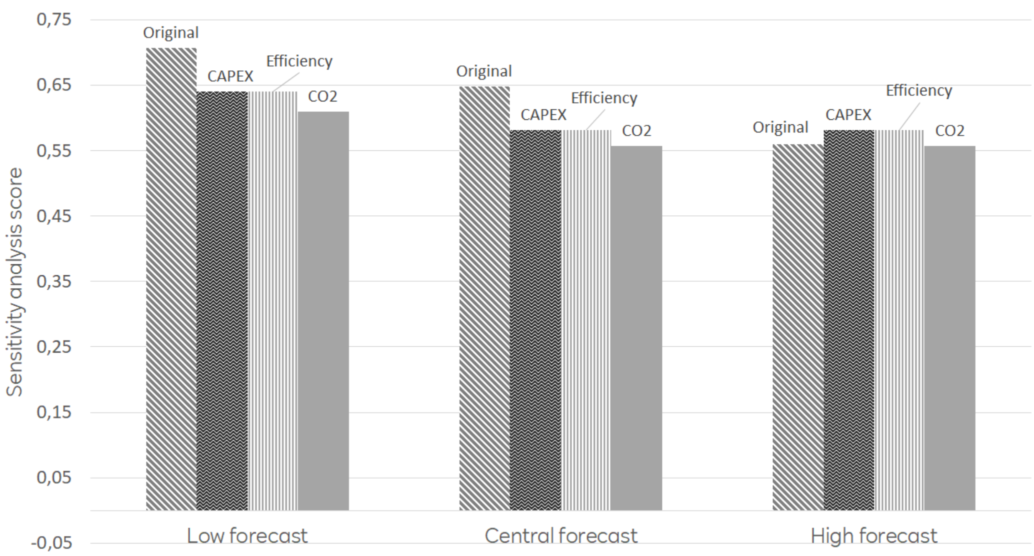

**Figure 6.7:** Final results of multi-criteria and sensitivity analyses for the mix hydrogen alternative




### Natural Gas

The results of the last alternative over the multi-criteria and sensitivity analyses can be seen in Figure 6.8. In the case that the forecast increase, the final score of the alternative decreases. Noticeable is that both sensitivity analyses CAPEX and Efficiency have an equal impact on the final results of the alternative across all forecasts. Relative to each other, the positioning of specific criteria at the bottom of the final ranking of criteria in the sensitivity analyses, results in four criteria having different weights between sensitivity analysis CAPEX and sensitivity analysis Efficiency. The other criteria have equal weights when comparing the sensitivity analyses. However, the 4 criteria where the weights are different, natural gas emerges as the top performer in these specific criteria. Resulting in a relative score of 1 for each of these 4 criteria. All other criteria have equal weights when comparing the sensitivity analyses, means that the sum of the 4 weights is equal for both sensitivity analyses. These 4 criteria having an equal total weight, combined with the fact that the natural gas alternative is the top performer for these 4 criteria, means that there is no difference in the final results between the different sensitivity analyses. The impact per criteria may be different, but the combined sum of the scores of these 4 criteria is equal to each other. Sensitivity analysis CO2 shows a major decrease in performance of the alternative compared to the original multi-criteria analysis. Especially for the low and the high forecast. Showcasing the relative weakness that carbon emissions is on the performance of the alternative, especially when the installed capacity of renewables and natural gas price is low.

**Figure 6.8:** Final results of multi-criteria and sensitivity analyses for the natural gas alternative



# 7 Conclusion

Some interesting findings occurred answering the main research question: *What is the most effective way of generating electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective?*

## 7.1. Conclusion Sub-Research Questions

Whilst answering the first sub-research question: *What is the expected electricity demand profile in Moerdijk in 2040?* it was noted that the if the turbine must be running, it is at maximum capacity. It will only go to minimum capacity if it is needed to cover the time gap between two periods when it runs at maximum capacity. The running profile of the CCGT functions nearly like an on/off switch for the turbine. When the turbine is required to operate, it will do so at full capacity. Even in the forecast with the lowest installed capacity of renewable energy, the demand for dispatchable flexible power generation exceeds what the CCGT in Moerdijk can provide due to its technical limitations, when compared to the total installed capacity of dispatchable flexible power generation. The increase in forecast therefore causes very little difference between the overall running profile for the CCGT across the different forecast provide by Aurora Energy Research (2024), because the running profile was already bound by its limitations for the lowest forecast. These small differences between the running profiles for the CCGT can be seen in Figure 4.1 and Table 4.2, giving an answer to the sub-research question. Showing the expected electricity demand profile in Moerdijk in 2040.

The second research question: *What are possible alternatives for flexible hydrogen-powered energy generation via the gas turbine in Moerdijk?* brought less noticeable findings. The alternatives were based on the research boundaries that can be seen in Figure 1.4. This led to the establishment of three new alternatives. One alternative where blue hydrogen is sourced from an external partner in Rotterdam and having an underground hydrogen salt cavern storage facility near Veendam. Another alternative where green hydrogen is produced at the location in Moerdijk, and having this production under own control. This alternative also has to option to store hydrogen in underground salt caverns, but adds the option to store hydrogen in liquid form in a tank at the CCGT in Moerdijk. The third alternative is a combination of the previous two mentioned alternatives. This alternative relies on a combination producing green hydrogen at the location in Moerdijk, and sourcing blue hydrogen from an external partner in Rotterdam. Having both options for the storage of hydrogen available. The last alternative used in the multi-criteria analysis, is the alternative which the previous mentioned alternatives are compared to. This alternative is the continuation of using natural gas to run the CCGT. This alternative does not require any partner or storage for natural gas, as the gas is taken directly of the natural gas grid that acts as a buffer already. This sub-research question gives a great understanding of the details and limitations, that can be seen in Table A.3, that might occur in the different alternatives.

These details and limitations are also used to calculate the total annual costs of the flexible produced energy. This is done by optimising the variables, mentioned in subsection 4.4.6, from the alternatives to have to lowest annual cost via the Pyomo Python-based open-source optimisation modelling language. The annual cost depended strongly on the forecast that was used. The forecast have effect on several parameters such as natural gas price, the installed capacity of renewable energy, and the electricity price that greatly impacted the final results. Therefore the annual cost for each alternative compared to the annual cost of continuing to run on natural gas, across the three different forecast provided by Aurora Energy Research (2024) is calculated. The costs and how they compare to the cost of natural gas, can be seen in Table 7.1. Answering the sub-research question: *What is the total annual cost in 2040 of flexible produced energy associated with the implication of hydrogen in the Moerdijk plant for each alternative?*

**Table 7.1:** Total annual cost of flexible power generation across the different alternatives

| **Total annual cost** | **Blue hydrogen** | **Green hydrogen** | **Mix hydrogen** | **Natural gas** |
|---|---|---|---|---|
| **Low forecast** | € 107.694.000 (98,3%) | € 172.210.000 (157,2%) | € 117.101.000 (106,9%) | € 109.582.000 (100%) |
| **Central forecast** | € 131.842.000 (100,5%) | € 145.270.000 (110,7%) | € 135.548.000 (103,3%) | € 131.207.000 (100%) |
| **High forecast** | € 168.977.000 (110,6%) | € 148.586.000 (97,2%) | € 144.364.000 (94,4%) | € 152.832.000 (100%) |

The results from these calculations, that can be seen in section 5.2, showed some noteworthy findings. It can for instance be noted that non of the alternatives used the option to store hydrogen in liquid form at the location, but all used the salt cavern hydrogen storage option. This showcased that storing hydrogen in liquid form at the location is not economically feasible. Another remarkable finding is that the total annual cost for the alternative on green hydrogen rises from the central to the high forecast. The increase in forecast results in an increase in installed capacity of renewable energy sources. Because of this increase, surplus of renewable energy relative to energy demand occur more often. This leads to more time periods when the electricity price, which greatly impacts the cost of green hydrogen, is cheap. However, the change from central to high forecast is not just associated with an increase in the installed capacity of renewable energy, it also relates to higher electricity prices during periods without renewable energy surpluses. The results showcase that there is a point when the abundance of renewable energy surplus does not outweigh the increase in green electricity cost. Also noteworthy is that in the alternative of mixing the two hydrogen sources, it can benefit from the strengths of each hydrogen source for each forecast. Having the total annual cost close to the best performer of the green or blue hydrogen alternatives. It does this by adjusting the blue hydrogen delivery rate, or the green hydrogen electrolyzer facility capacity. Because of this balancing between the different hydrogen sources, the mixing alternative has the lowest annual cost in the case of the high forecast. It minimises costs by maximising green hydrogen production during renewable energy surpluses, thereby keeping green hydrogen production costs low. It avoids high-cost green hydrogen production during periods of expensive electricity, relying instead on cheaper blue hydrogen when there are no renewable energy surpluses available.

The last sub-research question: *What are the implications for the adaptability, longevity and dependability of the implementation of each alternative for expected infrastructure in 2040?* identified eight problems and five opportunities by means of interviews with professionals inside the energy sector. The problems span across various topics, encompassing the dependability on natural gas, the application and integration of carbon capture technology, as well as aspects related to hydrogen production and combustion. The opportunities that are identified in the interviews also cover several topics, but mainly concern the development of especially green hydrogen. Dividing the problems and opportunities into the qualitative criteria helps to give a better understanding how the alternatives perform to these criteria. This showed that the alternative on natural gas has a large lead over the hydrogen alternatives in the adaptability scores. This is mainly because running a CCGT on natural gas is a mature technology that would require little to no changes in the future. Nevertheless, the alternative on natural gas lags behind the alternatives on hydrogen when concerning the dependability and operational longevity. This is mainly driven by goals towards a more sustainable future, aiming to phase out carbon-emitting energy sources. There's also a push to reduce dependency on natural gas, as recent conflicts highlighted the risks associated with this dependency. The green hydrogen alternative is the best performing alternative from an operational longevity and dependability point of view. Green hydrogen is produced entirely from renewable energy sources, ensuring independence in the production, as wind and solar energy can be harvested everywhere. Besides hydrogen being produced fully by renewable energy making it independent, it also offers a great future perspective in a more sustainable future. The alternative on green hydrogen also scores, except from the alternative on natural gas, the best on the technical adaptability. This is because, except for the technical problems associated with hydrogen combustion in the CCGT, there are no technical issues related to hydrogen production found in this research. However, the alternative on green hydrogen is the worst performing alternative on infrastructural adaptability due to the problems associated with placing energy-intensive electrolyzers in an already congested electricity grid. The blue hydrogen alternative never ranks as the best nor the worst performer across the criteria, except for technical adaptability, where it is the lowest performing. This is mainly due to the fact that there are technical problems associated with the combustion of hydrogen in the CCGT, as well as technical challenges related to carbon capture and storage and its efficiency. The alternative on a mix of green and blue hydrogen is for all criteria in between the performance of blue and green hydrogen. If it is closer to blue or green hydrogen depends on the dominant hydrogen production method in the mix alternative. All graphs showcasing the problems and opportunities for each alternative can be seen in section 5.5.

## 7.2. Conclusion Research Question

The data from the answers of the sub-research questions is used to answer the main research question: *What is the most effective way of generating electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective?* From the multi-criteria analysis it can be concluded that the alternative of continuing to run the CCGT on natural gas is the most effective. However, in the case that a reduction in carbon emissions is necessary, the top performers can be seen in Table 7.2 .

**Table 7.2:** Most effective alternatives with a decrease in carbon emissions

| | **Low forecast** | **Central forecast** | **High forecast** |
|---|---|---|---|
| **Most effective alternative** | Blue hydrogen | Mix hydrogen | Green hydrogen |

## 7.3. Recommendation for Plant Operators

A recommendation is made for plant operators based on the findings of this research. From the final results of the multi-criteria analysis, it could be concluded to do nothing and continue running on natural gas. However, as the goals of companies and countries strive towards zero emissions in the future, more sustainable alternatives should be taken into consideration. These alternatives might not be the most effective, but they are in line to achieve zero emissions by 2050. Therefore it is recommended to strive for a more sustainable way of generating flexible power. Based on the results of the multi-criteria analysis it is therefore recommended to implement blue hydrogen combustion in the CCGT at first when the natural gas price is still quite low and there is relatively little installed capacity of renewable energy. Depending on the speed that the installed capacity of renewable energy and the natural gas price increases, green hydrogen should slowly be mixed together with the blue hydrogen. This blend of green and blue hydrogen should transition to a larger share of green hydrogen as the installed capacity of renewable energy increases. This should be done so blue hydrogen is steadily fazed out and the system fully relies on green hydrogen for the future. Besides this, it is also recommended to limit the research for liquid hydrogen in storage tanks for large scale hydrogen storage. The results show that it is not an economically feasible solution. Besides this, the liquefaction process of hydrogen costs great amounts of energy. Decreasing the overall system efficiency and emitting more CO2 in the process. It is recommended to increase research towards hydrogen storage in underground salt caverns. This storage method showed great potential for large scale low cost hydrogen storage in combination with flexible power generation.

## 7.4. Limitations

While utmost care has been taken in conducting this research and establishing the most effective way to generate electricity via gas turbines with hydrogen in 2040 from a techno-economic perspective, there are some limitations that should be considered. Some of the limitations regarding the establishment of the running profiles, quantitative and qualitative results are already mentioned and can be seen in subsection 4.1.2 and section 5.6 respectively. However, the establishment of the research boundary can already be seen as a great limitation. This research only focuses on the use of green and blue hydrogen. Broadening this scope beyond these hydrogen sources, or even hydrogen in general, would have resulted in more generalisable research. Due to the time constraints of this research, only blue and green hydrogen are considered.

The second limitation to mention is the method used to conduct this research. This research uses a multi-criteria analysis to answer the research question. A multi-criteria analysis can in itself be a great tool in order to analyse different alternatives to each other. However, the quality of the results depends on the quality of the data input into the analysis. The analysis can in the best case be just as good as the quality of the data. In the case of a multi-criteria analysis this is especially important for weights assigned to the different criteria. If the weights are decided on by the researcher, they are mostly arbitrary. Therefore it is decided to have the participants of the interviews rank the criteria on what they think is most important, and decide the weights based on this combined ranking. Due to the limited amount of interviews conducted in this research, the final ranking on which the weights of the criteria are based can be seen as a limitation. Expanding the number of rankings and interviews would lead to a more definitive final ranking. Strengthening the validity of the weights of the criteria.

Also the generalizability of this research should be considered. The focus of this research is the CCGT in Moerdijk. Limiting the scope of this research to a specific location restricts its broader applicability, resulting in a low generalizability. Nevertheless, the method used to asses the different alternatives can be used for different locations, including the optimisation code. Only the site specific data has to be changed. Also the results for plants located in the Netherlands that are similar in capacity to the plant in Moerdijk would result in similar outcomes, as the main difference would be the transportation cost of hydrogen.

## 7.5. Recommendations for Future Research

There are several limitations to this research with a low generalizability, therefore extended research is recommended. A first recommendation would be to asses the implementation of green and blue hydrogen across different turbine capacities. This provides greater insight into when and how to manage the conversion of various power plants across an entire national system. Another recommendation would be to also include alternatives to hydrogen as a fuel that would require less changes to the turbine itself. It would for instance be interesting to add the use of E-methane or bio-gas to the analysis. This can provide more insight into the challenges associated with converting the turbine versus producing alternative fuels compared to hydrogen.

# References


Agyekum, E., Nutakor, C., Agwa, A., & Kamel, S. (2022). A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation. *Membranes*, *12*(2). https://doi.org/10.3390/membranes12020173

Air Products. (2023, November). Air Products to Build Europe's Largest Blue Hydrogen Plant and Strengthens Long-term Agreement.

Ali Khan, M. H., Daiyan, R., Neal, P., Haque, N., MacGill, I., & Amal, R. (2021). A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage & utilisation. *International Journal of Hydrogen Energy*, *46*(44), 22685–22706. https://doi.org/10.1016/j.ijhydene.2021.04.104

AlZohbi, G. (2024). An Overview of Hydrogen Energy Generation. *ChemEngineering*, *8*(1). https://doi.org/10.3390/chemengineering8010017

Aurora Energy Research. (2024, April). EOS Scenario Explorer.

Benalcazar, P., & Komorowska, A. (2024). Techno-economics of Green Hydrogen: Present Trends and Future Prospects. https://doi.org/10.1007/978-981-97-1339-4{_}23

Carbon Independent. (2023, December). Emissions from home energy use.

Centraal Bureau voor de Statistiek. (2023, September). Bijna helft elektriciteitsproductie uit hernieuwbare bronnen.

Centraal Bureau voor de Statistiek. (2024, March). Renewable electricity; production and capacity.

Chauhan, A., & Saini, R. (2016). Techno-economic feasibility study on Integrated Renewable Energy System for an isolated community of India. *Renewable and Sustainable Energy Reviews*, *59*, 388–405. https://doi.org/10.1016/j.rser.2015.12.290

Cihlar, J., Mavins, D., & van der Leun, K. (2021, June). *Picturing the value of underground gas storage to the European hydrogen system* (tech. rep.). Guidehouse. Utrecht.

Dagdougui, H., Sacile, R., Bersani, C., & Ouammi, A. (2018). Hydrogen Storage and Distribution: Implementation Scenarios. In *Hydrogen infrastructure for energy applications* (pp. 37–52). Elsevier. https://doi.org/10.1016/B978-0-12-812036-1.00004-4

Dean, M. (2022, January). *A Practical Guide to Multi-Criteria Analysis* (tech. rep.). University College London.

de Coning, P., & Swinley, J. (2019). Overview and theory. In *A practical guide to gas analysis by gas chromatography* (pp. 1–43). Elsevier. https://doi.org/10.1016/B978-0-12-818888-0.00001-2

Demanco Hydrogen. (n.d.). The energy density of hydrogen: a unique property.

Dermühl, S., & Riedel, U. (2023). A comparison of the most promising low-carbon hydrogen production technologies. *Fuel*, *340*, 127478. https://doi.org/10.1016/j.fuel.2023.127478

Dovetail Editorial Team. (2023, March). What is inductive coding in qualitative research?

El-Emam, R. S., & Özcan, H. (2019). Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. *Journal of Cleaner Production*, *220*, 593–609. https://doi.org/10.1016/j.jclepro.2019.01.309

ENTSO-E. (2024a). Flexible Generation - ENTSO-E.

ENTSO-E. (2024b, March). Montly Hourly Load Values 2023 Data.

Eradus, D. (2022, January). *the techno-economic feasibility of green hydrogen storage in salt caverns in the dutch north sea* [Doctoral dissertation, Technical University of Delft].

Ershadnia, R., Singh, M., Mahmoodpour, S., Meyal, A., Moeini, F., Hosseini, S. A., Sturmer, D. M., Rasoulzadeh, M., Dai, Z., & Soltanian, M. R. (2023). Impact of geological and operational conditions on underground hydrogen storage. *International Journal of Hydrogen Energy*, *48*(4), 1450–1471. https://doi.org/10.1016/j.ijhydene.2022.09.208

EWI Institute for Energy Economics at the University of Cologne. (2024, May). EWI analyses costs for underground hydrogen storage.

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086

Franc-Dabrowska, J., Madra-Sawicka, M., & Milewska, A. (2021). Energy Sector Risk and Cost of Capital Assessment—Companies and Investors Perspective. *Energies*, *14*(6), 1613. https://doi.org/10.3390/en14061613

Frieling, J., & Madlener, R. (2017). Fueling the US Economy: Energy as a Production Factor from the Great Depression Until Today. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3066173

Galimova, T., Fasihi, M., Bogdanov, D., & Breyer, C. (2023). Impact of international transportation chains on cost of green e-hydrogen: Global cost of hydrogen and consequences for Germany and Finland. *Applied Energy*, *347*, 121369. https://doi.org/10.1016/j.apenergy.2023.121369

Gasunie. (n.d.-a). Delta Rhine Corridor.

Gasunie. (n.d.-b). Hydrogen through natural gas pipelines: safe and sustainable.

Gasunie. (2023, October). Waterstofnetwerk Nederland.

Gasunie & TenneT. (n.d.). Nationaal Energie Dashboard. https://ned.nl/nl

Groenenberg, R., Koornneef, J., Sijm, J., Janssen, G., Espana, M., van Stralen, J., Hernandez-Serna, R., Smekens, K., Juez-Larre, J., Goncalvez, C., Wasch, L., Dijkstra, H., Wassing, B., Orlic, B., Brunner, L., van der Valk, K., van Unen, M., Hajonides van der Meulen, T., Kranenburg-Bruinsma, K., … Duijn, M. (2020, October). *Large-Scale Energy Storage in Salt Caverns and Depleted Fields (LSES) – Project Findings* (tech. rep.). TNO.

Haeseldonckx, D., & Dhaeseleer, W. (2007). The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure. *International*

*Journal of Hydrogen Energy*, *32*(10-11), 1381–1386. https://doi.org/10.1016/j.ijhydene.2006.10.018
Hofstra, J., & van der Leun, K. (2022, January). *Comparing the cost of solar, wind and biomethane on a dispatchable basis* (tech. rep.). Common Futures Energy Transition Specialists B.V. Utrecht.
Hynetwork. (n.d.-a). De waterstofleiding voor de Rotterdamse haven.
Hynetwork. (n.d.-b). Noord-Nederland.
Hynetwork. (2022, April). Shell eerste klant waterstofleiding Rotterdamse haven.
Hynetwork Services. (n.d.). HYDROGEN NETWORK.
Hystock. (2023, July). Succesvolle Open Season: ruime belangstelling voor waterstofopslag eerste zoutcaverne HyStock.
Intercontinental Exchange. (2024, August). Dutch TTF Natural Gas Futures.
Ji, M., & Wang, J. (2021). Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. *International Journal of Hydrogen Energy*, *46*(78), 38612–38635. https://doi.org/10.1016/j.ijhydene.2021.09.142
Jordan, T. (2022). Hydrogen technologies. In *Hydrogen safety for energy applications* (pp. 25–115). Elsevier. https://doi.org/10.1016/B978-0-12-820492-4.00005-1
Katebah, M., Al-Rawashdeh, M., & Linke, P. (2022). Analysis of hydrogen production costs in Steam-Methane Reforming considering integration with electrolysis and CO2 capture. *Cleaner Engineering and Technology*, *10*, 100552. https://doi.org/10.1016/j.clet.2022.100552
Kawasaki. (2020, December). Kawasaki Completes Basic Design for World's Largest Class (11,200-cubic-meter) Spherical Liquefied Hydrogen Storage Tank.
Kennisportaal Klimaatadaptatie. (n.d.). Multicriteria-analyse.
Kiemel, S., Smolinka, T., Lehner, F., Full, J., Sauer, A., & Miehe, R. (2021). Critical materials for water electrolysers at the example of the energy transition in Germany. *International Journal of Energy Research*, *45*(7), 9914–9935. https://doi.org/10.1002/er.6487
Lackey, G., Freeman, G. M., Buscheck, T. A., Haeri, F., White, J. A., Huerta, N., & Goodman, A. (2023). Characterizing Hydrogen Storage Potential in U.S. Underground Gas Storage Facilities. *Geophysical Research Letters*, *50*(3). https://doi.org/10.1029/2022GL101420
Laureys, A., Depraetere, R., Cauwels, M., Depover, T., Hertelé, S., & Verbeken, K. (2022). Use of existing steel pipeline infrastructure for gaseous hydrogen storage and transport: A review of factors affecting hydrogen induced degradation. *Journal of Natural Gas Science and Engineering*, *101*, 104534. https://doi.org/10.1016/j.jngse.2022.104534
Lee, J. M., Lee, S. H., Baik, J. H., & Park, K. (2022). Techno-economic analysis of hydrogen production electrically coupled to a hybrid desalination process. *Desalination*, *539*, 115949. https://doi.org/10.1016/j.desal.2022.115949
Madlener, R. (2020). Sustainable energy transition and increasing complexity: Trade-offs, the economics perspective and policy implications. In *Inequality and energy* (pp. 251–286). Elsevier. https://doi.org/10.1016/B978-0-12-817674-0.00011-4

Martin, P. (2023, November). ’Largest in Europe’ | Air Products announces blue hydrogen plant at Rotterdam linked to Dutch offshore CCS network.

ministere de l enseignement superieur et de la recherche. (2023, July). Advanced materials for hydrogen storage tanks.

Ministerie van Economisch Zaken en Klimaat. (n.d.). Wind op Zee na 2030.

Ministerie van Economische Zaken en Klimaat. (2023, June). Kabinet investeert fors in opschaling waterstof.

Ministery of Economic Affairs and Climate Policy. (2020, January). Climate policy.

Ministry of Economic Affairs and Climate Policy. (n.d.). Stimulating the growth of solar energy.

Moran, M., Shapiro, H., Boettner, D., & Bailey, M. (2017). *Moran’s principles of engineering thermodynamics* (9th ed.). Wiley.

Muhammed, N. S., Haq, B., Al Shehri, D., Al-Ahmed, A., Rahman, M. M., & Zaman, E. (2022). A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook. *Energy Reports*, *8*, 461–499. https://doi.org/10.1016/j.egyr.2021.12.002

Murthy Konda, N., Shah, N., & Brandon, N. P. (2011). Optimal transition towards a large-scale hydrogen infrastructure for the transport sector: The case for the Netherlands. *International Journal of Hydrogen Energy*, *36*(8), 4619–4635. https://doi.org/10.1016/j.ijhydene.2011.01.104

Nationaal Klimaat Platform. (n.d.). Energieopwek.nl Inzicht in de actuele opwekking van hernieuwbare energie.

Nelson, J., & Wisland, L. (2015, August). *Achieving 50 Percent Renewable Electricity in California: The Role of Non-Fossil Flexibility in a Cleaner Electricity Grid* (tech. rep.). Union of Concerned Scientists.

Nemitallah, M. A., Alnazha, A. A., Ahmed, U., El-Adawy, M., & Habib, M. A. (2024). Review on techno-economics of hydrogen production using current and emerging processes: Status and perspectives. *Results in Engineering*, *21*, 101890. https://doi.org/10.1016/j.rineng.2024.101890

Nowotny, J., & Veziroglu, T. N. (2011). Impact of hydrogen on the environment. *International Journal of Hydrogen Energy*, *36*(20), 13218–13224. https://doi.org/10.1016/j.ijhydene.2011.07.071

Öberg, S., Odenberger, M., & Johnsson, F. (2022a). The value of flexible fuel mixing in hydrogen-fueled gas turbines – A techno-economic study. *International Journal of Hydrogen Energy*, *47*(74), 31684–31702. https://doi.org/10.1016/j.ijhydene.2022.07.075

Öberg, S., Odenberger, M., & Johnsson, F. (2022b). Exploring the competitiveness of hydrogen-fueled gas turbines in future energy systems. *International Journal of Hydrogen Energy*, *47*(1), 624–644. https://doi.org/10.1016/j.ijhydene.2021.10.035

Panda, S., Mohanty, S., Rout, P. K., Sahu, B. K., Parida, S. M., Samanta, I. S., Bajaj, M., Piecha, M., Blazek, V., & Prokop, L. (2023). A comprehensive review on demand side management and market design for renewable energy support and integration. *Energy Reports*, *10*, 2228–2250. https://doi.org/10.1016/j.egyr.2023.09.049

Parkinson, B., Tabatabaei, M., Upham, D. C., Ballinger, B., Greig, C., Smart, S., & McFarland, E. (2018). Hydrogen production using methane: Techno-economics of decarbonizing fuels and chemicals. *International Journal of Hydrogen Energy*, *43*(5), 2540–2555. https://doi.org/10.1016/j.ijhydene.2017.12.081

Pena, J. C., Nápoles, G., & Salgueiro, Y. (2022). Normalization method for quantitative and qualitative attributes in multiple attribute decision-making problems. *Expert Systems with Applications*, *198*, 116821. https://doi.org/10.1016/j.eswa.2022.116821

Petrii, O. (2009). CHEMISTRY, ELECTROCHEMISTRY, AND ELECTROCHEMICAL APPLICATIONS | Hydrogen. In *Encyclopedia of electrochemical power sources* (pp. 751–761). Elsevier. https://doi.org/10.1016/B978-044452745-5.00868-6

Ratan, S., Baade, B., & Patel, N. (2010). Driving Hydrogen Efficiency with an Eye on the Environment. *Hydrocarbonengineering*.

Reksten, A. H., Thomassen, M. S., Møller-Holst, S., & Sundseth, K. (2022). Projecting the future cost of PEM and alkaline water electrolysers; a CAPEX model including electrolyser plant size and technology development. *International Journal of Hydrogen Energy*, *47*(90), 38106–38113. https://doi.org/10.1016/j.ijhydene.2022.08.306

Rijksoverheid. (2019, June). *Klimaatakkoord* (tech. rep.). Rijksoverheid.

Ripson, P., & van ’t Noordende, H. (2020, June). *ntegration of gigawatt scale electrolyser in five industrial clusters* (tech. rep.). Institute for Sustainable Process Technology.

RWE. (n.d.). Moerdijkcentrale.

RWE. (2021, October). RWE CO2-neutraal in 2040.

Sainz-Garcia, A., Abarca, E., Rubi, V., & Grandia, F. (2017). Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer. *International Journal of Hydrogen Energy*, *42*(26), 16657–16666. https://doi.org/10.1016/j.ijhydene.2017.05.076

Siemens-Energy. (n.d.). Leipziger Stadtwerke, Germany: 100% hydrogen-ready CHP plant.

Sikiru, S., Oladosu, T., Amosa, T., Olutoki, J., Ansari, M., Abioye, K., Rehman, Z., & Soleimani, H. (2024). Hydrogen-powered horizons: Transformative technologies in clean energy generation, distribution, and storage for sustainable innovation. *International Journal of Hydrogen Energy*, *56*, 1152–1182. https://doi.org/10.1016/j.ijhydene.2023.12.186

Simoes, S. G., Catarino, J., Picado, A., Lopes, T. F., di Berardino, S., Amorim, F., Gírio, F., Rangel, C., & Ponce de Leão, T. (2021). Water availability and water usage solutions for electrolysis in hydrogen production. *Journal of Cleaner Production*, *315*, 128124. https://doi.org/10.1016/j.jclepro.2021.128124

SMIT, R., WEEDA, M., & DEGROOT, A. (2007). Hydrogen infrastructure development in The Netherlands. *International Journal of Hydrogen Energy*, *32*(10-11), 1387–1395. https://doi.org/10.1016/j.ijhydene.2006.10.044

Tezel, G., & Hensgens, R. (2021, June). *waterstoftransport via het bestaande gasnetwerk?* (Tech. rep.). HyWay27.

Thawani, B., Hazael, R., & Critchley, R. (2023). Assessing the pressure losses during hydrogen transport in the current natural gas infrastructure using numerical modelling. *International Journal of Hydrogen Energy*, *48*(88), 34463–34475. https://doi.org/10.1016/j.ijhydene.2023.05.208

TKI Energie en Industrie, TNO, DNV, & MSG Sustainable Strategies. (2024, October). *Elektrificatie: cruciaal voor een duurzame industrie* (tech. rep.).

TNO. (n.d.). 15 dingen die je moet weten over waterstof.

Trattner, A., Höglinger, M., Macherhammer, M.-G., & Sartory, M. (2021). Renewable Hydrogen: Modular Concepts from Production over Storage to the Consumer. *Chemie Ingenieur Technik*, *93*(4), 706–716. https://doi.org/10.1002/cite.202000197

United Nations. (n.d.). Causes and effects of climate change | United Nations.

van Roekel, J. (2022, June). *How to evaluate the cost of the green hydrogen business case?* (Tech. rep.). KPMG Advisory N.V.

Vendrik, J., Groenewege, H., & Rooijers, F. (2023, February). *Nut en noodzaak extra wind op land in 2030 en 2050* (tech. rep.). CE Delft. Delft.

Werther, M., van Hooff, W., Colijn, K., & Blokdijk, R. (2020). *Next-generation solar power Dutch technology for the solar energy revolution* (tech. rep.). RVO, FME, TKI Urban Energy, Top Sector Energy.

www.dieselgasturbine.com. (2021). Diesel and Gas Turbine Worldwide. *A KHL Group Publication*, 44–46.

Zhang, F., Zhao, P., Niu, M., & Maddy, J. (2016). The survey of key technologies in hydrogen energy storage. *International Journal of Hydrogen Energy*, *41*(33), 14535–14552. https://doi.org/10.1016/j.ijhydene.2016.05.293

# A

# Appendix

# A.1. Literature Study Overview

**Table A.1:** Sources used in the background literature study, their main focus, and the related key concept it provides information for

| Source | Title | Related Key Concepts |
|---|---|---|
| (Agyekum et al., 2022) | A Critical Review of Renewable Hydrogen Production Methods: Factors Affecting Their Scale-Up and Its Role in Future Energy Generation | Hydrogen Production |
| (Ali Khan et al., 2021) | A framework for assessing economics of blue hydrogen production from steam methane reforming using carbon capture storage and utilisation | Hydrogen Production |
| (AlZohbi, 2024) | An Overview of Hydrogen Energy Generation | Hydrogen Production |
| (Benalcazar & Komorowska, 2024) | Techno-economics of Green Hydrogen: Present Trends and Future Prospects | Hydrogen economics |
| (El-Emam & Özcan, 2019) | Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production | Hydrogen economics |
| (Ershadnia et al., 2023) | Impact of geological and operational conditions on underground hydrogen storage | Hydrogen storage |
| (Frieling & Madlener, 2017) | Fueling the US Economy: Energy as a Production Factor from the Great Depression Until Today | Hydrogen economics |
| (Gasunie, n.d.-b) | Hydrogen through natural gas pipelines: safe and sustainable | Hydrogen transport |
| (Gasunie, 2023) | Waterstofnetwerk Nederland | Hydrogen transport |
| (Haeseldonckx & Dhaeseleer, 2007) | The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure | Hydrogen transport |
| (Ji & Wang, 2021) | Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators | Hydrogen Production |
| (Lackey et al., 2023) | Characterizing Hydrogen Storage Potential in U.S. Underground Gas Storage Facilities | Hydrogen storage, Hydrogen transport |
| (Laureys et al., 2022) | Use of existing steel pipeline infrastructure for gaseous hydrogen storage and transport: A review of factors affecting hydrogen induced degradation | Hydrogen transport |
| (Madlener, 2020) | Sustainable energy transition and increasing complexity: Trade-offs, the economics perspective and policy implications | Hydrogen economics |
| (Muhammed et al., 2022) | A review on underground hydrogen storage: Insight into geological sites, influencing factors and future outlook | Hydrogen storage |
| (Murthy Konda et al., 2011) | Optimal transition towards a large-scale hydrogen infrastructure for the transport sector: The case for the Netherlands | Hydrogen Turbine electricity generation, Hydrogen storage, Hydrogen transport, Hydrogen Production |
| (Nemitallah et al., 2024) | Review on techno-economics of hydrogen production using current and emerging processes: Status and perspectives | Hydrogen economics |
| (Nowotny & Veziroglu, 2011) | Impact of hydrogen on the environment | Hydrogen Production |
| (Öberg et al., 2022a) | The value of flexible fuel mixing in hydrogen-fueled gas turbines – A techno-economic study | Hydrogen Turbine electricity generation |
| (Parkinson et al., 2018) | Hydrogen production using methane: Techno-economics of decarbonizing fuels and chemicals | Hydrogen economics |
| (Sainz-Garcia et al., 2017) | Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer | Hydrogen storage |
| (Siemens-Energy, n.d.) | 100% hydrogen-ready CHP plant | Hydrogen Turbine electricity generation |
| (Sikiru et al., 2024) | Hydrogen-powered horizons: Transformative technologies in clean energy generation, distribution, and storage for sustainable innovation | Hydrogen storage, Hydrogen Production |
| (SMIT et al., 2007) | Hydrogen infrastructure development in The Netherlands | Hydrogen transport |
| (Tezel & Hensgens, 2021) | waterstoftransport via het bestaande gasnetwerk | Hydrogen transport |
| (Thawani et al., 2023) | Assessing the pressure losses during hydrogen transport in the current natural gas infrastructure using numerical modelling | Hydrogen storage, Hydrogen transport |
| (www.dieselgasturbine.com, 2021) | Diesel and Gas Turbine Worldwide | Hydrogen Turbine electricity generation |
| (Trattner et al., 2021) | Renewable Hydrogen: Modular Concepts from Production over Storage to the Consumer | Hydrogen Production |
| (Zhang et al., 2016) | The survey of key technologies in hydrogen energy storage | Hydrogen storage, Hydrogen Production |

## A.2. Parameters and alternatives

This section provides of which forecasts are used for forecast specific data, and an overview of all parameters.

**Table A.2:** The different alternatives and which forecast is used for the different parameters specific to the forecast

| | | Running profile | Natural gas price; Blue hydrogen price; Electricity price; Electricity CO2 emissions; Installed capacity of renewable energy sources |
|---|---|---|---|
| 1 | **Low forecast Blue hydrogen alternative** | Central forecast | Low forecast |
| 2 | **Central forecast Blue hydrogen alternative** | Central forecast | Central forecast |
| 3 | **High forecast Blue hydrogen alternative** | Central forecast | High forecast |
| 4 | **Low forecast Mix hydrogen alternative** | Central forecast | Low forecast |
| 5 | **Central forecast Mix hydrogen alternative** | Central forecast | Central forecast |
| 6 | **High forecast Mix hydrogen alternative** | Central forecast | High forecast |
| 7 | **Low forecast Green hydrogen alternative** | Central forecast | Low forecast |
| 8 | **Central forecast Green hydrogen alternative** | Central forecast | Central forecast |
| 9 | **High forecast Green hydrogen alternative** | Central forecast | High forecast |
| 10 | **Low forecast Natural gas alternative** | Central forecast | Low forecast |
| 11 | **Central forecast Natural gas alternative** | Central forecast | Central forecast |
| 12 | **High forecast Natural gas alternative** | Central forecast | High forecast |

**Table A.3:** Parameters used in the different scenarios

| General parameters | Unit | Values | Source |
|---|---|---|---|
| CO2 emission cost | EUR/ton | 277,21 | |
| El baseload price | EUR/MWh | Confidential | N.a. |
| El green price | EUR/MWh | Confidential | N.a. |
| NG price | EUR/MWh | Confidential | N.a. |
| WACC Energy and Industry | % | 7,36 | (Franc-Dabrowska et al., 2021) |
| H2 density atm | kg/m3 | 0,08375 | (Demanco Hydrogen, n.d.) |
| H2 density 50 bar | kg/m3 | 4,137927637 | Table 5.1.1 |
| H2 density 200 bar | kg/m3 | 16,55171055 | Table 5.1.1 |
| H2 density liquid | kg/m3 | 70,9 | (Demanco Hydrogen, n.d.) |
| El co2 emissions | kg/MWh | Confidential | N.a. |
| H2 energy density | MJ/kg | 120 | (TNO, n.d.) |
| Available space at Moerdijk | m3 | 99000 | Google-Maps (2024) |
| CO2 emissions natural gas | kg/kWh | 0,185 | (Carbon Independent, 2023) |
| Molar Mass | kg/mol | 0,002016 | (Petrii, 2009) |
| Ideal gas constant R | J/Kmol | 8,314 | (de Coning & Swinley, 2019) |
| **CCGT** | | | |
| Efficiency | % | 60 | (RWE, n.d.) |
| OPEX fixed | % of CAPEX | 1,5 | (Hofstra & van der Leun, 2022) |
| Start cost | EUR/MW | Confidential | N.a. |
| Conversion CAPEX | EUR/kW | 233 | (Öberg et al., 2022b) |
| annual cost of capital | EUR/kW | 20,89 | Table 5.1.1 |
| Min output | MW | 205 | RWE (2024) |
| Max output | MW | 441,6 | (RWE, n.d.) |
| CRF CCGT | % | 8 | Table 5.1.1 |
| Expected life | years | 30 | subsection 5.1.1 |
| Construction time CCGT conversion | years | 1 | subsection 5.1.1 |
| Direct co2 emissions hydrogen combustion | kgCO2/kgH2 | 0 | subsection 5.1.1 |
| **Electrolyzers** | | | |
| Conversion consumption | kwh/kg | 53 | (Reksten et al., 2022) |

| | | | |
|---|---|---|---|
| Electrolyzer CAPEX | EUR/kw cap | 300 | (Reksten et al., 2022) |
| annual cost of capital | EUR/kw cap | 37,69 | Table 5.1.1 |
| OPEX Fixed | % of CAPEX | 4 | (van Roekel, 2022) |
| CRF Electrolyzers | % | 10 | Table 5.1.1 |
| H2 price - dis (RE surplus) | EUR/kg | Confidential | N.a. |
| H2 price + dis (no RE surplus) | EUR/kg | Confidential | N.a. |
| Max capacity size limited | GW | 1,25 | Google-maps (2024) |
| Max grid capacity | MW | 700 | (RWE, n.d.) |
| Expected life | Years | 20 | (Kiemel et al., 2021) |
| Construction time | Years | 4 | subsection 5.1.1 |
| Water consumption | L/kg(h2) | 15 | (Simoes et al., 2021) |
| Water cost | EUR/ton | 1,29 | (Lee et al., 2022) |
| CO2 emissions | kgCO2/kgH2 | 0 | N.a. |
| **SMR** | | | |
| Cost Blue H2 | EUR/kg | Confidential | N.a. |
| Min production rate m3 | m3 | 0 | N.a. |
| Max production rate m3 | m3 | 134000 | (Ratan et al., 2010) |
| T&S cost CO2 | EUR/ton(co2) | 50 | (Fasihi et al., 2019) |
| CO2 production | kgCO2/kgH2 | 8,47 | (Katebah et al., 2022) |
| Carbon capture rate | % | 99 | subsection 5.1.1 |
| CO2 emissions | kgCO2/kgH2 | 0,0847 | Table 5.1.1 |
| **Tank Storage** | | | |
| Min storage cap | m3 | 0 | N.a. |
| Max storage cap | m3 | 10000 | (Kawasaki, 2020) |
| Liquification energy | MWh/kgH2 | 0,004194444 | (Jordan, 2022) |
| OPEX Var | EUR/kg | Confidential | N.a. |
| CAPEX | EUR/kg cap | 294 | (ministere de l enseignement superieur et de la recherche, 2023) |
| annual cost of capital | EUR/kg cap | 26,36 | Table 5.1.1 |
| CRF Tank Storage | % | 8 | Table 5.1.1 |
| OPEX Fixed | % of CAPEX | 3 | subsection 5.1.1 |

| | | | |
|---|---|---|---|
| Expected life | Years | 30 | subsection 5.1.1 |
| Construction time | Years | 1 | subsection 5.1.1 |
| CO2 emissions | kgCO2/kgH2 | Confidential | N.a. |
| **Salt Cavern Storage** | | | |
| Min storage cap m3 | m3 | 100000 | (Groenenberg et al., 2020) |
| Max storage cap m3 | m3 | 1000000 | (Groenenberg et al., 2020) |
| OPEX Var | EUR/kg | 0,2 | (EWI Institute for Energy Economics at the University of Cologne, 2024) |
| CAPEX | EUR/kg | 29 | (Cihlar et al., 2021) |
| CRF Salt Cavern Storage | % | 8 | Table 5.1.1 |
| annual cost of capital | EUR/kg | 2,52 | Table 5.1.1 |
| OPEX Fixed | % of CAPEX | 3 | subsection 5.1.1 |
| Expected life | Years | 50 | (Eradus, 2022) |
| Construction time | Years | 2 | subsection 5.1.1 |
| Storage temperature | K | 293 | subsection 5.1.1 |
| Compression energy | MWh/kgH2 | 0,0007 | (Dagdougui et al., 2018) |
| CO2 emissions | kgCO2/kgH2 | Confidential | N.a. |
| **Transport** | | | |
| Distance Green hydrogen to CCGT | km | 1 | Google-Maps (2024) |
| Distance Green hydrogen to Tank | km | 0 | Google-Maps (2024) |
| Distance Green hydrogen to Salt cavern | km | 287 | Google-Maps (2024) |
| Distance Tank storage to CCGT | km | 1 | Google-Maps (2024) |
| Distance Salt cavern to CCGT | km | 286 | Google-Maps (2024) |
| Distance Blue hydrogen to CCGT | km | 41 | Google-Maps (2024) |
| Distance Blue hydrogen to Salt cavern | km | 328 | Google-Maps (2024) |
| Distance Blue hydrogen to Tank storage | km | 40 | Google-Maps (2024) |
| Variable cost | EUR/kg/km | 0,00016 | (Galimova et al., 2023) |

| | | | |
|---|---|---|---|
| Pipeline diameter | meter | 0,61 | (Hynetwork, 2022) |
| Operating pressure | bar | 50 | (Hynetwork Services, n.d.) |
| Max flow rate | kg/hour | 87069,27724 | Table 5.1.1 |
| Pipe temperature | K | 293 | N.a. |

# A.3. Calculations

This section provides the results and parameters used for the calculations needed for the research.

## A.3.1. CRF

**Table A.4:** CRF results

| | **CCGT conversion** | **Electrolyzer facility** | **Tank storage** | **Salt cavern storage** |
|---|---|---|---|---|
| WACC (*i*) | 7,36% | 7,36% | 7,36% | 7,36% |
| Expected projected life in years (*N*) | 30 | 20 | 30 | 50 |
| CRF | 8,4% | 9,7% | 8,35% | 7,6% |

## A.3.2. ACC

**Table A.5:** ACC results

| | **CCGT conversion** | **Electrolyzer facility** | **Tank storage** | **Salt cavern storage** |
|---|---|---|---|---|
| WACC (*i*) | 7,36% | 7,36% | 7,36% | 7,36% |
| Construction time in years (*N*) | 1 | 4 | 1 | 2 |
| Investment cost for project (X) | 233 €/kW (Öberg et al., 2022b) | 300 €/kW (Reksten et al., 2022) | 294 €/kg (ministere de l enseignement superieur et de la recherche, 2023) | 29 €/kg (Cihlar et al., 2021) |
| Annualised cost of capital | 20,89 €/kW | 37,69 €/kW | 26,36 €/kg | 2,52 €/kg |

### A.3.3. Density

**Table A.6:** Hydrogen density at different pressures

| | Unit | Value | Value | Reference |
|---|---|---|---|---|
| Pressure | Bar | 50 | 200 | Table A.3 |
| Molar mass | kg/mol | 0,002016 | 0,002016 | (Moran et al., 2017) |
| Universal gas constant | J/(Kmol) | 8,314 | 8,314 | (Moran et al., 2017) |
| Temperature | K | 293 | 293 | Table A.3 |
| Density | $kg/m^3$ | 4,14 | 16,55 | Equation 5.3 |

### A.3.4. Hydrogen flow rate

**Table A.7:** Maximum flow rate of hydrogen via pipelines per hour

| Diameter of the pipe | Velocity of the gas | Density of gas at 50 bar | Flow rate |
|---|---|---|---|
| 0,61 m | 20 m/s | 4,14 $kg/m^3$ | 87069 kg/h |

## A.4. Pyomo Code

This section provides the code used for the cost optimisation of the scenarios

### A.4.1. Blue Hydrogen Code

```
import pyomo.environ as pyo
import pandas as pd
import math as mt

print("Script started")

# Load energy demand
demand_energy = pd.read_csv('MED_demand_profile_2040.csv').squeeze('
    columns')

#here all model parameters mentioned in Table A.1

# Model setup
model = pyo.ConcreteModel()

# Time index
time = range(len(adjusted_demand))

# Variables
model.blue_constant = pyo.Var(domain=pyo.NonNegativeReals)
model.salt_storage_state = pyo.Var(time, domain=pyo.NonNegativeReals)
model.max_salt_storage = pyo.Var(domain=pyo.NonNegativeReals)
model.hydrogen_AIR_MD = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Salt_MD = pyo.Var(time, domain=pyo.NonNegativeReals)

model.hydrogen_AIR_Salt = pyo.Var(time, domain=pyo.NonNegativeReals) #is
    zelfde als model.hydrogen_AIR_Salt

def total_cost(model):
```

```
    return (model.max_salt_storage * annual_CAPEX_Salt +
            (CCGT_max_gen * annual_CAPEX_CCGT) +
            (OPEX_fix_CCGT * CCGT_max_gen) +
            (model.max_salt_storage * OPEX_fix_Salt) +
            #co2 costs
            sum(model.hydrogen_AIR_MD[t] * CO2_Cost *
                Emissions_kg_Blue_low for t in time) +
            sum(model.hydrogen_AIR_Salt[t] * CO2_Cost *
                Emissions_kg_Blue_low for t in time) +
            sum(model.hydrogen_AIR_Salt[t] * CO2_Cost *
                Emissions_kg_Salt_low for t in time) +
            #h2 cost
            sum(model.hydrogen_AIR_MD[t] * Cost_blue_h2_low for t in time)
                 +
            sum(model.hydrogen_AIR_Salt[t] * Cost_blue_h2_low for t in
                time) +
            #variable costs
            (Starts * Start_cost * CCGT_max_gen) +
            sum(model.hydrogen_AIR_Salt[t] * OPEX_Var for t in time) +
            #transport costs
            sum(model.hydrogen_AIR_MD[t] * Dis_AIR_MD *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_AIR_Salt[t] * Dis_AIR_Salt *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Salt_MD[t] * Dis_Salt_MD *
                Transport_cost_kg_km for t in time))
model.cost = pyo.Objective(rule=total_cost, sense=pyo.minimize)

# Constraints
model.blue_low = pyo.Constraint(expr=model.blue_constant >=
    Min_production_rate_kg)
model.blue_high = pyo.Constraint(expr=model.blue_constant <=
    Max_production_rate_kg)

def salt_storage_state_max_rule(model, t):
    return model.salt_storage_state[t] <= Max_storage_cap_kg
model.salt_storage_state_max = pyo.Constraint(time, rule=
    salt_storage_state_max_rule)

def salt_storage_state_min_rule(model, t):
    return model.salt_storage_state[t] >= Min_storage_cap_kg
model.salt_storage_state_min = pyo.Constraint(time, rule=
    salt_storage_state_min_rule)

def plant_balance_rule(model, t):
    return model.hydrogen_AIR_MD[t] + model.hydrogen_AIR_Salt[t] == model.
        blue_constant
model.plant_balance = pyo.Constraint(time, rule=plant_balance_rule)

# def demand_fulfillment_rule(model, t):
#     return model.hydrogen_AIR_MD[t] <= adjusted_demand[t]
# model.demand_fulfillment = pyo.Constraint(time, rule=
    demand_fulfillment_rule)

def demand_balance_rule(model, t):
```

```
    return model.hydrogen_AIR_MD[t] + model.hydrogen_Salt_MD[t] ==
        adjusted_demand[t]
model.demand_balance = pyo.Constraint(time, rule=demand_balance_rule)

def storage_dynamics_rule(model, t):
    if t == 0:
        return model.salt_storage_state[t] == initial_storage + model.
            hydrogen_AIR_Salt[t] - model.hydrogen_Salt_MD[t]
    else:
        return (model.salt_storage_state[t] == model.salt_storage_state[t
            -1] +
                model.hydrogen_AIR_Salt[t] - model.hydrogen_Salt_MD[t])
model.storage_dynamics = pyo.Constraint(time, rule=storage_dynamics_rule)

def storage_outflow_rule(model, t):
    return model.hydrogen_Salt_MD[t] <= model.salt_storage_state[t]
model.storage_outflow = pyo.Constraint(time, rule=storage_outflow_rule)

def storage_capacity_rule(model, t):
    return model.salt_storage_state[t] <= model.max_salt_storage
model.storage_capacity = pyo.Constraint(time, rule=storage_capacity_rule)

def max_storage_salt_rule(model, t):
    return model.max_salt_storage >= model.salt_storage_state[t]
model.max_storage_salt = pyo.Constraint(time, rule=max_storage_salt_rule)

def final_storage_min_rule(model):
    final_t = max(time)
    return (model.salt_storage_state[final_t] >= 1 * initial_storage)
model.final_storage_min_constraint = pyo.Constraint(rule=
    final_storage_min_rule)

# def final_storage_max_rule(model):
#     final_t = max(time)
#     return (model.salt_storage_state[final_t] <= 1.01 * initial_storage)
# model.final_storage_max_constraint = pyo.Constraint(rule=
    final_storage_max_rule)

# Solve the model
solver = pyo.SolverFactory('glpk')
result = solver.solve(model)

total_cost_value = pyo.value(model.cost)
# Check solver results
if result.solver.status == pyo.SolverStatus.ok and result.solver.
    termination_condition == pyo.TerminationCondition.optimal:
    print(f" Total annual cost: {(pyo.value(model.cost))}")
    # CAPEX
    print(f" Total capex CCGT conversion: {CCGT_max_gen *
        CCGT_conversion_cost}")
    print(f" Total capex Storage: {model.max_salt_storage.value *
        CAPEX_Salt}")
    print(f" Total hydrogen in initial storage cost: {initial_storage *
        Cost_blue_h2_low}")
    # OPEX Fix
    print(f" OPEX Fix CCGT: {CCGT_max_gen * OPEX_fix_CCGT}")
```

```
    print(f" OPEX Fix Salt: {model.max_salt_storage.value * OPEX_fix_Salt}")
    # OPEX Var
    print(f" OPEX VAR: {pyo.value(model.cost) - (model.max_salt_storage.value * annual_CAPEX_Salt) - (CCGT_max_gen * annual_CAPEX_CCGT) - (CCGT_max_gen * OPEX_fix_CCGT) - (model.max_salt_storage.value * OPEX_fix_Salt)}")
    # CO2
    print(f" Total h2 kg from plant {model.blue_constant.value * len(adjusted_demand)}")
    print(f" Total h2 kg put in storage {sum(model.hydrogen_AIR_Salt[t].value for t in time)}")
    print(f" Total h2 kg put in CCGT {(sum(model.hydrogen_AIR_MD[t].value for t in time)) +  (sum(model.hydrogen_Salt_MD[t].value for t in time)) }")
    print(f" CO2 from blue h2 plant {(model.blue_constant.value * len(adjusted_demand)) * Emissions_kg_Blue_low}")
    print(f" CO2 from Salt storage facility {(sum(model.hydrogen_AIR_Salt[t].value for t in time)) * Emissions_kg_Salt_low}")
    print(f" Total h2 kg put in CCGT {sum((model.hydrogen_AIR_MD[t].value + model.hydrogen_Salt_MD[t].value) for t in time)}")
    # Capacities
    print(f" Constant value blue: {model.blue_constant.value}")
    print(f" Salt storage capacity needed: {model.max_salt_storage.value}")
    for t in time:
        try:
            print(f"Time {t}")
            # print(f"Time {t}, adjusted demand: {adjusted_demand[t]}, AIR-MD {model.hydrogen_AIR_MD[t].value}, Salt-MD {model.hydrogen_Salt_MD[t].value}, AIR-Salt {model.hydrogen_AIR_Salt[t].value}, Storage state {model.salt_storage_state[t].value}")
        except Exception as e:
            print(f"Error printing values for time {t}: {str(e)}")
else:
    print("No optimal solution found or solver did not run correctly.")
    print("Solver status:", result.solver.status)
    print("Solver termination condition:", result.solver.termination_condition)
```

### A.4.2. Green Hydrogen Code

```
import pyomo.environ as pyo
import pandas as pd
import math as mt

print("Script started")

# Load energy demand
demand_energy = pd.read_csv('MED_demand_profile_2040.csv').squeeze('columns')
Green_energy_price_multiplier = pd.read_csv('Green_energy_multiplier_HIGH.csv').squeeze('columns')

# Model setup
```

```
model = pyo.ConcreteModel()

# Time index
time = range(len(adjusted_demand))

# Variables
model.green_h2_production = pyo.Var(time, domain=pyo.NonNegativeReals)
model.salt_storage_state = pyo.Var(time, domain=pyo.NonNegativeReals)
model.max_salt_storage = pyo.Var(domain=pyo.NonNegativeReals)
model.max_green_h2_production = pyo.Var(domain=pyo.NonNegativeReals)

model.hydrogen_Green_MD = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Salt_MD = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Green_Salt = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Green_Tank = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Tank_MD = pyo.Var(time, domain=pyo.NonNegativeReals)

model.tank_storage_state = pyo.Var(time, domain=pyo.NonNegativeReals)
model.max_tank_storage = pyo.Var(domain=pyo.NonNegativeReals)

model.Green_energy_price_multiplier = pyo.Param(time, initialize=Green_energy_price_multiplier.to_dict())
model.adjusted_demand = pyo.Param(time, initialize=adjusted_demand.to_dict())

# vergeet OPEX tank, and starts niet aan te passen en ook de h2 prijs voor initial storage cost enzo
def total_cost(model):
    return ((model.max_salt_storage * annual_CAPEX_Salt) +
            (model.max_tank_storage * annual_CAPEX_Tank) +
            (model.max_green_h2_production * Electrolyzer_conversion * annual_CAPEX_electrolyzer) +
            (CCGT_max_gen * annual_CAPEX_CCGT) +
            # Fixed OPEX
            (OPEX_fix_CCGT * CCGT_max_gen) +
            (model.max_green_h2_production * Electrolyzer_conversion * OPEX_fix_electrolyzer) +
            (model.max_tank_storage * OPEX_fix_tank) +
            (model.max_salt_storage * OPEX_fix_salt) +
            # hydrogen costs
            sum((model.hydrogen_Green_MD[t]   * OPEX_var_positive_high_electrolyzer if model.Green_energy_price_multiplier[t] == 1 else model.hydrogen_Green_MD[t] * OPEX_var_negative_high_electrolyzer) for t in time) +
            sum((model.hydrogen_Green_Salt[t] * OPEX_var_positive_high_electrolyzer if model.Green_energy_price_multiplier[t] == 1 else model.hydrogen_Green_Salt[t] * OPEX_var_negative_high_electrolyzer) for t in time) +
            sum((model.hydrogen_Green_Tank[t] * OPEX_var_positive_high_electrolyzer if model.Green_energy_price_multiplier[t] == 1 else model.hydrogen_Green_Tank[t] * OPEX_var_negative_high_electrolyzer) for t in time) +
            # Variable costs
```

```
            (Starts * Start_cost * CCGT_max_gen) +
            sum(model.hydrogen_Green_Salt[t] * OPEX_Var_Salt for t in time) +
            sum(model.hydrogen_Green_Tank[t] * OPEX_var_tank_high for t in time) +
            # CO2 cost
            sum(model.hydrogen_Green_Salt[t] * CO2_Cost * Emissions_kg_Salt_high for t in time) +
            sum(model.hydrogen_Green_Tank[t] * CO2_Cost * Emissions_kg_Tank_high for t in time) +
            # transport cost
            sum(model.hydrogen_Green_MD[t] * Dis_Green_MD * Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Green_Salt[t] * Dis_Green_Salt * Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Green_Tank[t] * Dis_Green_Tank * Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Tank_MD[t] * Dis_Tank_MD * Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Salt_MD[t] * Dis_Salt_MD * Transport_cost_kg_km for t in time))
model.cost = pyo.Objective(rule=total_cost, sense=pyo.minimize)

# Constraints
model.green_production_limits = pyo.ConstraintList()
for t in time:
    model.green_production_limits.add(model.green_h2_production[t] >= Min_electrolyzer_cap_kg)
    model.green_production_limits.add(model.green_h2_production[t] <= Max_electrolyzer_cap_kg)

def max_green_h2_production_rule(model, t):
    return model.green_h2_production[t] <= model.max_green_h2_production
model.max_green_h2_production_constraint = pyo.Constraint(time, rule=max_green_h2_production_rule)

def salt_storage_state_max_rule(model, t):
    return model.salt_storage_state[t] <= Max_storage_cap_kg
model.salt_storage_state_max = pyo.Constraint(time, rule=salt_storage_state_max_rule)

def salt_storage_state_min_rule(model, t):
    return model.salt_storage_state[t] >= Min_storage_cap_kg
model.salt_storage_state_min = pyo.Constraint(time, rule=salt_storage_state_min_rule)

def tank_storage_state_max_rule(model, t):
    return model.tank_storage_state[t] <= Max_tank_storage_cap_kg
model.tank_storage_state_max = pyo.Constraint(time, rule=tank_storage_state_max_rule)

def tank_storage_state_min_rule(model, t):
    return model.tank_storage_state[t] >= Min_tank_storage_cap_kg
model.tank_storage_state_min = pyo.Constraint(time, rule=tank_storage_state_min_rule)

```

```
def plant_balance_rule(model, t):
    return model.hydrogen_Green_MD[t] + model.hydrogen_Green_Salt[t] + model.hydrogen_Green_Tank[t] == model.green_h2_production[t]
model.plant_balance = pyo.Constraint(time, rule=plant_balance_rule)

# def demand_fulfillment_rule(model, t):
#     return model.hydrogen_Green_MD[t] <= adjusted_demand[t]
# model.demand_fulfillment = pyo.Constraint(time, rule=demand_fulfillment_rule)

def green_h2_production_rule(model, t):
    if model.adjusted_demand[t] > 0:
        return model.green_h2_production[t] == 0
    else:
        return pyo.Constraint.Skip
model.green_h2_production_constraint = pyo.Constraint(time, rule=green_h2_production_rule)

def demand_balance_rule(model, t):
    return model.hydrogen_Green_MD[t] + model.hydrogen_Salt_MD[t] + model.hydrogen_Tank_MD[t] == adjusted_demand[t]
model.demand_balance = pyo.Constraint(time, rule=demand_balance_rule)

def storage_dynamics_rule(model, t):
    if t == 0:
        return model.salt_storage_state[t] == initial_storage + model.hydrogen_Green_Salt[t] - model.hydrogen_Salt_MD[t]
    else:
        return (model.salt_storage_state[t] == model.salt_storage_state[t-1] +
                model.hydrogen_Green_Salt[t] - model.hydrogen_Salt_MD[t])
model.storage_dynamics = pyo.Constraint(time, rule=storage_dynamics_rule)

def tank_storage_dynamics_rule(model, t):
    if t == 0:
        return model.tank_storage_state[t] == initial_tank_storage + model.hydrogen_Green_Tank[t] - model.hydrogen_Tank_MD[t]
    else:
        return (model.tank_storage_state[t] == model.tank_storage_state[t-1] +
                model.hydrogen_Green_Tank[t] - model.hydrogen_Tank_MD[t])
model.tank_storage_dynamics = pyo.Constraint(time, rule=tank_storage_dynamics_rule)

def storage_outflow_rule(model, t):
    return model.hydrogen_Salt_MD[t] <= model.salt_storage_state[t]
model.storage_outflow = pyo.Constraint(time, rule=storage_outflow_rule)

def tank_storage_outflow_rule(model, t):
    return model.hydrogen_Tank_MD[t] <= model.tank_storage_state[t]
model.tank_storage_outflow = pyo.Constraint(time, rule=tank_storage_outflow_rule)

def storage_capacity_rule(model, t):
    return model.salt_storage_state[t] <= model.max_salt_storage
model.storage_capacity = pyo.Constraint(time, rule=storage_capacity_rule)
```

```python

def tank_storage_capacity_rule(model, t):
    return model.tank_storage_state[t] <= model.max_tank_storage
model.tank_storage_capacity = pyo.Constraint(time, rule=tank_storage_capacity_rule)

def max_storage_salt_rule(model, t):
    return model.max_salt_storage >= model.salt_storage_state[t]
model.max_storage_salt = pyo.Constraint(time, rule=max_storage_salt_rule)

def max_storage_tank_rule(model, t):
    return model.max_tank_storage >= model.tank_storage_state[t]
model.max_storage_tank = pyo.Constraint(time, rule=max_storage_tank_rule)

#these two only for the salt storage, tank does not matter as starts at 0
def final_storage_min_rule(model):
    final_t = max(time)
    return (model.salt_storage_state[final_t] >= 0.99 * initial_storage)
model.final_storage_min_constraint = pyo.Constraint(rule=final_storage_min_rule)

# def final_storage_max_rule(model):
#     final_t = max(time)
#     return (model.salt_storage_state[final_t] <= 1.01 * initial_storage)
# model.final_storage_max_constraint = pyo.Constraint(rule=final_storage_max_rule)

# Solve the model
solver = pyo.SolverFactory('glpk')
result = solver.solve(model)

total_cost_value = pyo.value(model.cost)
Total_annualised_cost = (model.max_salt_storage.value * annual_CAPEX_Salt) + (model.max_tank_storage.value * annual_CAPEX_Tank) + (model.max_green_h2_production.value * Electrolyzer_conversion * annual_CAPEX_electrolyzer) + (CCGT_max_gen * annual_CAPEX_CCGT)
Total_Fix_OPEX = (OPEX_fix_CCGT * CCGT_max_gen) + (model.max_green_h2_production.value * Electrolyzer_conversion * OPEX_fix_electrolyzer) + (model.max_tank_storage.value * OPEX_fix_tank) + (model.max_salt_storage.value * OPEX_fix_salt)

# Check solver results
if result.solver.status == pyo.SolverStatus.ok and result.solver.termination_condition == pyo.TerminationCondition.optimal:
    print(f" Total annual cost: {(pyo.value(model.cost))}")
    # CAPEX
    print(f" Total capex CCGT conversion: {CCGT_max_gen * CCGT_conversion_cost}")
    print(f" Total capex Salt Storage: {model.max_salt_storage.value * CAPEX_Salt}")
    print(f" Total capex Tank Storage: {model.max_tank_storage.value * CAPEX_Salt}")
    print(f" Total capex Electrolyzer: {model.max_green_h2_production.value * Electrolyzer_conversion * CAPEX_electrolyzer}")
    print(f" Total annualized CAPEX: {Total_annualised_cost}")
    # OPEX FIX
```

```
    print(f" OPEX Fix CCGT: {(OPEX_fix_CCGT * CCGT_max_gen)}")
    print(f" OPEX Fix electrolyzer: {(model.max_green_h2_production.value
        * Electrolyzer_conversion * OPEX_fix_electrolyzer)}")
    print(f" OPEX Fix Tank: {(model.max_tank_storage.value * OPEX_fix_tank
        )}")
    print(f" OPEX Fix salt: {(model.max_salt_storage.value * OPEX_fix_salt
        )}")
    print(f" Total fixed OPEX: {Total_Fix_OPEX}")
    #  OPEX Var
    print(f" Total OPEX Var: {pyo.value(model.cost) -
        Total_annualised_cost - Total_Fix_OPEX}")
    # CO2
    # print(f" Total h2 kg from green h2 plant {sum((model.
        hydrogen_Green_MD[t].value + model.hydrogen_Green_Salt[t].value +
        model.hydrogen_Green_Tank[t].value) for t in time)}")
    print(f" Total h2 kg put in storage Salt {sum(model.
        hydrogen_Green_Salt[t].value for t in time)}")
    print(f" Total h2 kg put in storage Tank {sum(model.
        hydrogen_Green_Tank[t].value for t in time)}")
    print(f" CO2 salt storage {(sum(model.hydrogen_Green_Salt[t].value for
         t in time)) * Emissions_kg_Salt_high}")
    print(f" CO2 tank storage {(sum(model.hydrogen_Green_Tank[t].value for
         t in time)) * Emissions_kg_Tank_high}")
    print(f" Total h2 kg put in CCGT {sum((model.hydrogen_Green_MD[t].
        value + model.hydrogen_Salt_MD[t].value + model.hydrogen_Tank_MD[t
        ].value) for t in time)}")
    # capacities
    print(f" Max Salt storage capacity {model.max_salt_storage.value}")
    print(f" Max Tank storage capacity {model.max_tank_storage.value}")
    print(f" max green h2 production {model.max_green_h2_production.value
        * Electrolyzer_conversion}")

    for t in time:
        try:
          print(f"Time:{t}")
            # print(f"Time:{t},production plant:{model.green_h2_production
                [t].value} MD demand:{adjusted_demand[t]}, Green-MD:{model.
                hydrogen_Green_MD[t].value}, Green-Salt:{model.
                hydrogen_Green_Salt[t].value}, Green-tank:{model.
                hydrogen_Green_Tank[t].value}, Salt-MD:{model.
                hydrogen_Salt_MD[t].value}, Tank-MD:{model.hydrogen_Tank_MD
                [t].value}, Salt-state:{model.salt_storage_state[t].value},
                 Tank-state:{model.tank_storage_state[t].value}")
        except Exception as e:
            print(f"Error printing values for time {t}: {str(e)}")
else:
    print("No optimal solution found or solver did not run correctly.")
    print("Solver status:", result.solver.status)
    print("Solver termination condition:", result.solver.
        termination_condition)
```

### A.4.3. Mix Hydrogen Code

```
import pyomo.environ as pyo
import pandas as pd
import math as mt
```

```python

print("Script started")

# Load energy demand
demand_energy = pd.read_csv('MED_demand_profile_2040.csv').squeeze('
    columns')
Green_energy_price_multiplier = pd.read_csv('Green_energy_multiplier_LOW.
    csv').squeeze('columns')

# Model setup
model = pyo.ConcreteModel()

# Time index
time = range(len(adjusted_demand))

# Variables
model.green_h2_production = pyo.Var(time, domain=pyo.NonNegativeReals)
model.blue_h2_production = pyo.Var(domain=pyo.NonNegativeReals)
model.salt_storage_state = pyo.Var(time, domain=pyo.NonNegativeReals)
model.max_salt_storage = pyo.Var(domain=pyo.NonNegativeReals)
model.max_green_h2_production = pyo.Var(domain=pyo.NonNegativeReals)

model.hydrogen_Green_MD = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Salt_MD = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Green_Salt = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Green_Tank = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_Tank_MD = pyo.Var(time, domain=pyo.NonNegativeReals)

model.hydrogen_AIR_MD = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_AIR_Salt = pyo.Var(time, domain=pyo.NonNegativeReals)
model.hydrogen_AIR_Tank = pyo.Var(time, domain=pyo.NonNegativeReals)

model.tank_storage_state = pyo.Var(time, domain=pyo.NonNegativeReals)
model.max_tank_storage = pyo.Var(domain=pyo.NonNegativeReals)

model.Green_energy_price_multiplier = pyo.Param(time, initialize=
    Green_energy_price_multiplier.to_dict())
model.adjusted_demand = pyo.Param(time, initialize=adjusted_demand.to_dict
    ())

# vergeet OPEX tank, and starts niet aan te passen en ook de h2 prijs voor
     initial storage cost enzo
def total_cost(model):
    return (#annual storage and fixed cost of equipment
            (model.max_salt_storage * annual_CAPEX_Salt) +
            (model.max_tank_storage * annual_CAPEX_Tank) +
            (CCGT_max_gen * annual_CAPEX_CCGT) +
            (model.max_green_h2_production * Electrolyzer_conversion *
                annual_CAPEX_electrolyzer) +
            # OPEX Fix
            (OPEX_fix_CCGT * CCGT_max_gen) +
            (model.max_green_h2_production * Electrolyzer_conversion *
                OPEX_fix_electrolyzer) +
            (model.max_tank_storage * OPEX_fix_tank) +
            (model.max_salt_storage * OPEX_fix_salt) +
            #OPEX VAR
```

```
            sum((model.hydrogen_Green_MD[t]   *
                OPEX_var_positive_low_electrolyzer if model.
                Green_energy_price_multiplier[t] == 1 else model.
                hydrogen_Green_MD[t] * OPEX_var_negative_low_electrolyzer)
                for t in time) +
            sum((model.hydrogen_Green_Salt[t] *
                OPEX_var_positive_low_electrolyzer if model.
                Green_energy_price_multiplier[t] == 1 else model.
                hydrogen_Green_Salt[t] * OPEX_var_negative_low_electrolyzer
                ) for t in time) +
            sum((model.hydrogen_Green_Tank[t] *
                OPEX_var_positive_low_electrolyzer if model.
                Green_energy_price_multiplier[t] == 1 else model.
                hydrogen_Green_Tank[t] * OPEX_var_negative_low_electrolyzer
                ) for t in time) +
            sum(model.hydrogen_AIR_MD[t] * Cost_blue_h2_low for t in time)
                 +
            sum(model.hydrogen_AIR_Salt[t] * Cost_blue_h2_low for t in
                time) +
            sum(model.hydrogen_AIR_Tank[t] * Cost_blue_h2_low for t in
                time) +
            (Starts * Start_cost * CCGT_max_gen) +
            #cost of storing
            sum(model.hydrogen_Green_Salt[t] * OPEX_Var_Salt for t in time
                ) +
            sum(model.hydrogen_Green_Tank[t] * OPEX_var_tank_low for t in
                time) +
            #CO2 cost
            sum((model.hydrogen_Green_Salt[t] + model.hydrogen_AIR_Salt[t
                ]) * CO2_Cost * Emissions_kg_Salt_low for t in time) +
            sum((model.hydrogen_Green_Tank[t] + model.hydrogen_AIR_Tank[t
                ]) * CO2_Cost * Emissions_kg_Tank_low for t in time) +
            model.blue_h2_production * Emissions_kg_Blue_low * len(
                adjusted_demand) +
            #cost of transport
            sum(model.hydrogen_Green_MD[t] * Dis_Green_MD *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Green_Salt[t] * Dis_Green_Salt *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Green_Tank[t] * Dis_Green_Tank *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Tank_MD[t] * Dis_Tank_MD *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_Salt_MD[t] * Dis_Salt_MD *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_AIR_Tank[t] * Dis_AIR_Tank *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_AIR_MD[t] * Dis_AIR_MD *
                Transport_cost_kg_km for t in time) +
            sum(model.hydrogen_AIR_Salt[t] * Dis_AIR_Salt *
                Transport_cost_kg_km for t in time))
model.cost = pyo.Objective(rule=total_cost, sense=pyo.minimize)

# Constraints
model.green_production_limits = pyo.ConstraintList()
for t in time:
```

```
    model.green_production_limits.add(model.green_h2_production[t] >= Min_electrolyzer_cap_kg)
    model.green_production_limits.add(model.green_h2_production[t] <= Max_electrolyzer_cap_kg)

model.blue_h2_production_min = pyo.Constraint(expr=model.blue_h2_production >= 1 * Min_production_rate_kg)
model.blue_h2_production_max = pyo.Constraint(expr=model.blue_h2_production <= 1 * Max_production_rate_kg)

def max_green_h2_production_rule(model, t):
    return model.green_h2_production[t] <= model.max_green_h2_production
model.max_green_h2_production_constraint = pyo.Constraint(time, rule=max_green_h2_production_rule)

def salt_storage_state_max_rule(model, t):
    return model.salt_storage_state[t] <= Max_storage_cap_kg
model.salt_storage_state_max = pyo.Constraint(time, rule=salt_storage_state_max_rule)

def salt_storage_state_min_rule(model, t):
    return model.salt_storage_state[t] >= Min_storage_cap_kg
model.salt_storage_state_min = pyo.Constraint(time, rule=salt_storage_state_min_rule)

def tank_storage_state_max_rule(model, t):
    return model.tank_storage_state[t] <= Max_tank_storage_cap_kg
model.tank_storage_state_max = pyo.Constraint(time, rule=tank_storage_state_max_rule)

def tank_storage_state_min_rule(model, t):
    return model.tank_storage_state[t] >= Min_tank_storage_cap_kg
model.tank_storage_state_min = pyo.Constraint(time, rule=tank_storage_state_min_rule)

def plant_balance_rule(model, t):
    return model.hydrogen_Green_MD[t] + model.hydrogen_Green_Salt[t] + model.hydrogen_Green_Tank[t] == model.green_h2_production[t]
model.plant_balance = pyo.Constraint(time, rule=plant_balance_rule)

def blue_plant_balance_rule(model, t):
    return model.hydrogen_AIR_MD[t] + model.hydrogen_AIR_Salt[t] + model.hydrogen_AIR_Tank[t] == model.blue_h2_production
model.blue_plant_balance = pyo.Constraint(time, rule=blue_plant_balance_rule)

def green_h2_production_rule(model, t):
    if model.adjusted_demand[t] > 0:
        return model.green_h2_production[t] == 0
    else:
        return pyo.Constraint.Skip
model.green_h2_production_constraint = pyo.Constraint(time, rule=green_h2_production_rule)

def demand_balance_rule(model, t):
    return model.hydrogen_Green_MD[t] + model.hydrogen_Salt_MD[t] + model.
```

```
hydrogen_Tank_MD[t] + model.hydrogen_AIR_MD[t]== adjusted_demand[t]
model.demand_balance = pyo.Constraint(time, rule=demand_balance_rule)

def storage_dynamics_rule(model, t):
    if t == 0:
        return model.salt_storage_state[t] == initial_storage + model.hydrogen_Green_Salt[t] + model.hydrogen_AIR_Salt[t] - model.hydrogen_Salt_MD[t]
    else:
        return (model.salt_storage_state[t] == model.salt_storage_state[t-1] +
                model.hydrogen_Green_Salt[t] + model.hydrogen_AIR_Salt[t] - model.hydrogen_Salt_MD[t])
model.storage_dynamics = pyo.Constraint(time, rule=storage_dynamics_rule)

def tank_storage_dynamics_rule(model, t):
    if t == 0:
        return model.tank_storage_state[t] == initial_tank_storage + model.hydrogen_Green_Tank[t] + model.hydrogen_AIR_Tank[t] - model.hydrogen_Tank_MD[t]
    else:
        return (model.tank_storage_state[t] == model.tank_storage_state[t-1] +
                model.hydrogen_Green_Tank[t] + model.hydrogen_AIR_Tank[t]- model.hydrogen_Tank_MD[t])
model.tank_storage_dynamics = pyo.Constraint(time, rule=tank_storage_dynamics_rule)

def storage_outflow_rule(model, t):
    return model.hydrogen_Salt_MD[t] <= model.salt_storage_state[t]
model.storage_outflow = pyo.Constraint(time, rule=storage_outflow_rule)

def tank_storage_outflow_rule(model, t):
    return model.hydrogen_Tank_MD[t] <= model.tank_storage_state[t]
model.tank_storage_outflow = pyo.Constraint(time, rule=tank_storage_outflow_rule)

def storage_capacity_rule(model, t):
    return model.salt_storage_state[t] <= model.max_salt_storage
model.storage_capacity = pyo.Constraint(time, rule=storage_capacity_rule)

def tank_storage_capacity_rule(model, t):
    return model.tank_storage_state[t] <= model.max_tank_storage
model.tank_storage_capacity = pyo.Constraint(time, rule=tank_storage_capacity_rule)

def max_storage_salt_rule(model, t):
    return model.max_salt_storage >= model.salt_storage_state[t]
model.max_storage_salt = pyo.Constraint(time, rule=max_storage_salt_rule)

def max_storage_tank_rule(model, t):
    return model.max_tank_storage >= model.tank_storage_state[t]
model.max_storage_tank = pyo.Constraint(time, rule=max_storage_tank_rule)

#these two only for the salt storage, tank does not matter as starts at 0
def final_storage_min_rule(model):
```

```
    final_t = max(time)
    return (model.salt_storage_state[final_t] >= 0.99 * initial_storage)
model.final_storage_min_constraint = pyo.Constraint(rule=final_storage_min_rule)

# def final_storage_max_rule(model):
#     final_t = max(time)
#     return (model.salt_storage_state[final_t] <= 2 * initial_storage)
# model.final_storage_max_constraint = pyo.Constraint(rule=final_storage_max_rule)

def final_storage_max_rule(model):
    final_t = max(time)
    return (model.salt_storage_state[final_t] <= 0.5 * Max_storage_cap_kg)
model.final_storage_max_constraint = pyo.Constraint(rule=final_storage_max_rule)




# Solve the model
solver = pyo.SolverFactory('glpk')
result = solver.solve(model)

total_cost_value = pyo.value(model.cost)
Total_annualised_cost = (model.max_salt_storage.value * annual_CAPEX_Salt) + (model.max_tank_storage.value * annual_CAPEX_Tank) + (CCGT_max_gen * annual_CAPEX_CCGT) + (model.max_green_h2_production.value * Electrolyzer_conversion * annual_CAPEX_electrolyzer)
Total_OPEX_Fix = (OPEX_fix_CCGT * CCGT_max_gen) + (model.max_green_h2_production.value * Electrolyzer_conversion * OPEX_fix_electrolyzer) + (model.max_tank_storage.value * OPEX_fix_tank) + (model.max_salt_storage.value * OPEX_fix_salt)
# Check solver results
if result.solver.status == pyo.SolverStatus.ok and result.solver.termination_condition == pyo.TerminationCondition.optimal:
    print(f" Total annual cost: {(pyo.value(model.cost))}")
    print(f" Total Annualised CAPEX: {Total_annualised_cost}")
    print(f" Constant Blue h2 rate: {model.blue_h2_production.value}")
    # CAPEX
    print(f" Total capex CCGT conversion: {CCGT_max_gen * CCGT_conversion_cost}")
    print(f" Total capex Salt Storage: {model.max_salt_storage.value * CAPEX_Salt}")
    print(f" Total capex Tank Storage: {model.max_tank_storage.value * CAPEX_Salt}")
    print(f" Total capex electrolyzer: {model.max_green_h2_production.value * Electrolyzer_conversion * CAPEX_electrolyzer}")
    print(f" Total annualized CAPEX: {Total_annualised_cost}")
    # OPEX FIX
    print(f" OPEX Fix CCGT: {(OPEX_fix_CCGT * CCGT_max_gen)}")
    print(f" OPEX Fix electrolyzer: {(model.max_green_h2_production.value * Electrolyzer_conversion * OPEX_fix_electrolyzer)}")
    print(f" OPEX Fix Tank: {(model.max_tank_storage.value * OPEX_fix_tank)}")
    print(f" OPEX Fix salt: {(model.max_salt_storage.value * OPEX_fix_salt
```

```
)}")
    print(f" Total fixed OPEX: {Total_OPEX_Fix}")
    #  OPEX Var
    print(f" Total OPEX Var: {pyo.value(model.cost) - Total_annualised_cost - Total_OPEX_Fix}")
    # CO2
    # print(f" Total h2 kg from green h2 plant {sum((model.hydrogen_Green_MD[t].value + model.hydrogen_Green_Salt[t].value + model.hydrogen_Green_Tank[t].value) for t in time)}")
    print(f" Total h2 kg put in storage Salt {sum((model.hydrogen_Green_Salt[t].value + model.hydrogen_AIR_Salt[t].value) for t in time)}")
    print(f" Total h2 kg put in storage Tank {sum((model.hydrogen_Green_Tank[t].value + model.hydrogen_AIR_Tank[t].value) for t in time)}")
    print(f" CO2 salt storage {(sum((model.hydrogen_Green_Salt[t].value + model.hydrogen_AIR_Salt[t].value) for t in time)) * Emissions_kg_Salt_low}")
    print(f" CO2 tank storage {(sum((model.hydrogen_Green_Tank[t].value + model.hydrogen_AIR_Tank[t].value) for t in time)) * Emissions_kg_Tank_low}")
    print(f" Total h2 kg from electrolyzers {sum((model.hydrogen_Green_Salt[t].value + model.hydrogen_Green_MD[t].value + model.hydrogen_Green_Tank[t].value) for t in time)}")
    print(f" Total h2 kg from AIR {sum((model.hydrogen_AIR_Salt[t].value + model.hydrogen_AIR_MD[t].value + model.hydrogen_AIR_Tank[t].value) for t in time)}")
    print(f" Total h2 kg put in CCGT {sum((model.hydrogen_Green_MD[t].value + model.hydrogen_Salt_MD[t].value + model.hydrogen_Tank_MD[t].value + model.hydrogen_AIR_MD[t].value) for t in time)}")
    # capacities
    print(f" Max Salt storage capacity {model.max_salt_storage.value}")
    print(f" Max Tank storage capacity {model.max_tank_storage.value}")
    print(f" max green h2 production {model.max_green_h2_production.value * Electrolyzer_conversion}")
    for t in time:
        try:
            # print(f"Time: {t} MD demand:{adjusted_demand[t]}, production Green H2 plant:{model.green_h2_production[t].value}, production blue H2 plant {model.blue_h2_production.value}")
            # print(f"Time: {t} Flow from AIR: AIR-MD:{model.hydrogen_AIR_MD[t].value}, AIR-Salt:{model.hydrogen_AIR_Salt[t].value}, AIR-Tank:{model.hydrogen_AIR_Tank[t].value}")
            # print(f"Time: {t} Flow from Green: Green-MD:{model.hydrogen_Green_MD[t].value}, Green-Salt:{model.hydrogen_Green_Salt[t].value}, Green-tank:{model.hydrogen_Green_Tank[t].value}")
            # print(f"Time: {t} Flow from storages: Tank-MD:{model.hydrogen_Tank_MD[t].value}, Salt-MD:{model.hydrogen_Salt_MD[t].value}")
            # print(f"Time: {t} Storage states: Salt-state:{model.salt_storage_state[t].value}, Tank-state:{model.tank_storage_state[t].value}")
            print(f"Time: {t}")
        except Exception as e:
```

```
            print(f"Error printing values for time {t}: {str(e)}")
else:
    print("No optimal solution found or solver did not run correctly.")
    print("Solver status:", result.solver.status)
    print("Solver termination condition:", result.solver.
        termination_condition)
```

# A.5. Quantitative Results

This section provides more detailed results of the quantitative part of the research.

## A.5.1. Quantitative Results Blue Hydrogen Scenario

**Table A.8:** Quantitative results blue hydrogen scenario

| | unit | Blue H2 low forecast | Blue H2 Central forecast | Blue H2 high forecast |
|---|---|---|---|---|
| **Total energy production in 2040** | MWh | 864.990 | 864.990 | 864.990 |
| **Blue H2 price** | € | +- € 1,00 (confidential) | +- € 2,00 (condifential) | +-€ 3,00 (confidential) |
| **Total annual cost of 2040** | € | € 107.694.000 | € 131.842.000 | € 168.977.000 |
| **Annual cost per MWh of 2040** | € | € 125 | € 152 | € 195 |
| **CAPEX CCGT conversion** | € | € 102.893.000 | € 102.893.000 | € 102.893.000 |
| **CAPEX salt cavern storage** | € | € 219.518.000 | € 219.518.000 | € 219.518.000 |
| **CAPEX hydrogen tank storage** | € | n.a. | n.a. | n.a. |
| **CAPEX electrolyzer facility** | € | n.a. | n.a. | n.a. |
| **Total CAPEX** | € | € 322.411.000 | € 322.411.000 | € 322.411.000 |
| **OPEX Var of 2040** | € | € 67.840.000 | € 91.988.000 | € 129.123.000 |
| **OPEX Fix of 2040** | € | € 11.554.000 | € 11.554.000 | € 11.554.000 |
| **Total OPEX of 2040** | € | € 79.393.000 | € 103.542.000 | € 140.676.000 |
| **Total annual cost of capital** | € | € 28.300.000 | € 28.300.000 | € 28.300.000 |
| **Total electrolyzer facility capacity** | MW | n.a. | n.a. | n.a. |
| **Blue hydrogen plant rate** | kg/h | 4.943 | 4.943 | 4.943 |
| **Total Salt cavern storage capacity** | kg | 7.570.000 | 7.570.000 | 7.570.000 |
| **Total hydrogen tank storage capacity** | kg | n.a. | n.a. | n.a. |
| **Total CO2 emissions** | tons | 5.133 | 5.133 | 5.133 |
| **Overall efficiency** | % | 47% | 47% | 47% |

## A.5.2. Quantitative Results Green Hydrogen Scenario

**Table A.9:** Quantitative results Green hydrogen scenario

| | unit | Green H2 Low | Green H2 Central | Green H2 high |
|---|---|---|---|---|
| **Total energy production** | MWh | 864.990 | 864.990 | 864.990 |
| **Blue H2 price** | € | +- € 1,00 (confidential) | +- € 2,00 (condifential) | +-€ 3,00 (confidential) |
| **Total annual cost of 2040** | € | € 172.210.000 | € 145.270.000 | € 148.586.000 |
| **Annual cost per MWh of 2040** | € | € 199 | € 168 | € 172 |
| **CAPEX CCGT conversion** | € | € 102.893.000 | € 102.893.000 | € 102.893.000 |
| **CAPEX salt cavern storage** | € | € 146.619.000 | € 184.945.000 | € 206.394.000 |
| **CAPEX hydrogen tank storage** | € | € 0 | € 0 | € 0 |
| **CAPEX electrolyzer facility** | € | € 210.000.000 | € 210.000.000 | € 210.000.000 |
| **Total CAPEX** | € | € 459.511.000 | € 497.838.000 | € 519.287.000 |
| **OPEX Var of 2040** | € | € 106.095.000 | € 74.674.000 | € 75.483.000 |
| **OPEX Fix of 2040** | € | € 17.767.000 | € 18.916.000 | € 19.560.000 |
| **Total OPEX of 2040** | € | € 123.861.000 | € 93.591.000 | € 95.043.000 |
| **Total annual cost of capital** | € | € 48.349.000 | € 51.679.000 | € 53.543.000 |
| **Total electrolyzer facility capacity** | MW | 700 | 700 | 700 |
| **Blue hydrogen plant rate** | kg/h | n.v.t | n.v.t | n.v.t |
| **Total Salt cavern storage capacity** | kg | 5.056.000 | 6.377.000 | 7.117.000 |
| **Total hydrogen tank storage capacity** | kg | 0 | 0 | 0 |
| **Total CO2 emissions** | tons | 2.164 | 1.732 | 1.299 |
| **Overall efficiency** | % | 37% | 37% | 37% |

## A.5.3. Quantitative Results Mix Hydrogen Scenario

**Table A.10:** Quantitative results of mixed blue and green hydrogen scenario

| | unit | Mix H2 Low | Mix H2 Central | Mix H2 high |
|---|---|---|---|---|
| **Total energy production** | MWh | 864.990 | 864.990 | 864.990 |
| **Blue H2 price** | € | +- € 1,00 (confidential) | +- € 2,00 (condifential) | +-€ 3,00 (confidential) |
| **Total annual cost of 2040** | € | € 117.101.000 | € 135.548.000 | € 144.364.000 |
| **Annual cost per MWh of 2040** | € | € 135 | € 157 | € 167 |
| **CAPEX CCGT conversion** | € | € 102.893.000 | € 102.893.000 | € 102.893.000 |
| **CAPEX salt cavern storage** | € | € 170.133.000 | € 216.778.000 | € 227.220.000 |
| **CAPEX hydrogen tank storage** | € | € 0 | € 0 | € 0 |
| **CAPEX electrolyzer facility** | € | € 60.866.000 | € 195.586.000 | € 210.000.000 |
| **Total CAPEX** | € | € 333.892.000 | € 515.257.000 | € 540.112.000 |
| **OPEX Var of 2040** | € | € 72.938.000 | € 63.619.000 | € 68.827.000 |
| **OPEX Fix of 2040** | € | € 12.507.000 | € 19.295.000 | € 20.185.000 |
| **Total OPEX of 2040** | € | € 85.445.000 | € 82.914.000 | € 89.011.000 |
| **Total annual cost of capital** | € | € 31.656.000 | € 52.634.000 | € 55.353.000 |
| **Total electrolyzer facility capacity** | MW | 203 | 652 | 700 |
| **Blue hydrogen plant rate** | kg/h | 4.571 | 1.422 | 909 |
| **Total Salt cavern storage capacity** | kg | 5.867.000 | 7.732.000 | 7.835.000 |
| **Total hydrogen tank storage capacity** | kg | 0 | 0 | 0 |
| **Total CO2 emissions** | tons | 4.993 | 2.647 | 1.888 |
| **Overall efficiency** | % | 44% | 39% | 39% |

## A.5.4. Quantitative Results Natural Gas Scenario

**Table A.11:** Quantitative results of natural gas scenario

| | unit | Natural Gas Low | Natural Gas Central | Natural Gas High |
|---|---|---|---|---|
| **Total energy production** | MWh | 864.990 | 864.990 | 864.990 |
| **Blue H2 price** | € | n.a. | n.a. | n.a. |
| **Total annual cost of 2040** | € | € 109.582.000 | € 131.207.000 | € 152.832.000 |
| **Annual cost per MWh of 2040** | € | € 127 | € 152 | € 177 |
| **CAPEX CCGT conversion** | € | n.a. | n.a. | n.a. |
| **CAPEX salt cavern storage** | € | n.a. | n.a. | n.a. |
| **CAPEX hydrogen tank storage** | € | n.a. | n.a. | n.a. |
| **CAPEX electrolyzer facility** | € | n.a. | n.a. | n.a. |
| **Total CAPEX** | € | n.a. | n.a. | n.a. |
| **OPEX Var of 2040** | € | € 104.614.000 | € 126.239.000 | € 147.864.000 |
| **OPEX Fix of 2040** | € | € 4.968.000 | € 4.968.000 | € 4.968.000 |
| **Total OPEX of 2040** | € | € 109.582.000 | € 131.207.000 | € 152.832.000 |
| **Total annual cost of capital** | € | n.a. | n.a. | n.a. |
| **Total electrolyzer facility capacity** | MW | n.a. | n.a. | n.a. |
| **Blue hydrogen plant rate** | kg/h | n.a. | n.a. | n.a. |
| **Total Salt cavern storage capacity** | kg | n.a. | n.a. | n.a. |
| **Total hydrogen tank storage capacity** | kg | n.a. | n.a. | n.a. |
| **Total CO2 emissions** | tons | 266.705 | 266.705 | 266.705 |
| **Overall efficiency** | % | 60% | 60% | 60% |

# A.6. Interviews

Next section will provide the list of possible interview questions, the summaries of the interviews used for the qualitative criteria, and the ranking of the criteria.

### A.6.1. Informed Consent Form

# Informed Consent

You are being invited to participate in a research study titled **Implementing hydrogen combustion in Moerdijk for sustainable flexible power generation**. This study is being done by Kane IJdo from the TU Delft in collaboration with RWE.

The purpose of this research study is to investigate the implementation for flexible energy generation by the transition towards hydrogen for gas turbine energy generation, and will take you approximately 30 minutes to complete. The data will be used for judging 4 different criteria on a 7 step semantic differential scale. These criteria are:

- Technical adaptability
- Infrastructural adaptability
- Operational longevity
- Self sufficiency

The results of this semantic differential scale, possible non identifiable anonymized quotes and anonymized interview summaries will be used in a masters thesis. The thesis will be made publicly available at repository.tudelft.nl. You will be asked to not share any information that can be marked as confidential during the interview.

We will be asking you to answer open questions related to these before mentioned 4 criteria, for example: " How do you think hydrogen economy will be changed by the year 2040?" or "How do you think carbon capture will keep up with technologies that do not emit any carbon?"

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. We will minimize any risks by:

Only storing data on a institutionally approved TU Delft onedrive that is password protected and only accessible by the researcher conducting this interview and the supervisory team. Besides this, the only direct personal data that will be collected are: Name, Contact information, general job description. This data will not be used in the Thesis, but only to analyze the results and possibly get in contact in the case of any problems or data removal.

Following the interview, we will produce an anonymous summary of the discussion. That summary will be sent to you as soon as it is ready. You will be welcome to provide feedback or suggest modification. The summary will be made publicly available as supplementary material to the thesis.

The summary will be anonymized by filtering out the Name, Company and Function in the final results in the thesis. Also any personally identifiable research data, opinions and views that can be traced back to you as a participant will be filtered out of the final summary that will be put as supplementary material in the thesis.

The identifiable data will only be stored on the before mentioned institutionally approved TU Delft onedrive, as the data must be able to be identified in the case a participant request the data to be deleted before the end of the project, which is expected to be 23th of August. After the end of the project, any other data than the anonymized summaries will be deleted.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. You can request your data to be deleted by contacting ***private email*** before the 31th of August latest. After this date, any other data than the anonymized summaries will be already be deleted. The data will be deleted within two working weeks after contact.

In case there are any questions or request to remove all or a part of your data, please contact

Kane Ijdo via ***private email***

This informed consent document will be provided before the interview. By participating in the interview, you agree to have read this document and are aware of the risks and measures taken to minimize the risks. Besides this, you are also aware that you have the option to request the deletion of data, or the withdraw from the interview at any time, or omit to answer a question without any reason.

Name:

Date:

Signature:

**Figure A.1:** Informed consent form

### A.6.2. Interview Question List

**Technical adaptability:**

- How difficult is it to alter the power plant to switch from running on natural gas to running on 100% hydrogen?

- Does the switch to hydrogen require more safety aspects to be implemented for both the technical aspects within the generation plant, as well as in the transport and storing of hydrogen.
- What problems might be encountered for the retro fitment of the CCGT's for hydrogen combustion?
- Will there be any safety concerns that need to be tackled for the public when running CCGT's on hydrogen?
- What are the difficulties associated with the build of a large scale (700MW) electrolyzer plant at an industrial area?
- Will there be much resistance from the public in the building of large green hydrogen facilities?

**Infrastructural adaptability:**

- Are there any expectations in hydrogen transport development for the future years?
- Do you think transport via hydrogen pipelines will develop even further in the future or will it stay the same?
- Will there be valuable alternatives for hydrogen transport in the near future?
- What do you think the downsides are of storing hydrogen underground compared to hydrogen in liquid form in tanks?
- Do you think we have enough options and space to store hydrogen in the future?
- Will the production of hydrogen at the location of the power plant result in even more net congestion issues, and if so, can these be fixed?

**Operational longevity:**

- What is your opinion about carbon capture and how do you think it will held up in the future years compared to other decarbonization methods or green energy sources?
- Will there be a problem with storage capacity for the storage of CO2 in the future?
- How do you think hydrogen production will develop in by 2040 and beyond
- Do you think there will be alternatives for flexible energy generation in the future or new solutions to cope with the intermittent renewable energy sources?
- How do you think the emission prices will develop in the years after 2040?
- Do you think blue or green hydrogen will play a larger part in the future, and how do you think the prices will compare in the future?

**Self sufficiency:**

- What do you think will be the benefits of having hydrogen production under your own control?
- What do you think of having the hydrogen supply form external suppliers

- Do you think being dependent on Gasunie soley for the transport of hydrogen might be a threat for the operation of the powerplant
- Do you think being dependent on Natural Gas is a future concern looking at the situation caused by the war between Ukraine and Russia?

### A.6.3. Summary Interviewee 1

What possible problems will there be when switching to hydrogen? Hydrogen is very different from gas, so there may for example also be problems with leaks. The problem is that there is no long-term data and little experience with running on hydrogen. We currently know very little about factors such as wear and tear. So we still have to gain a lot of experience, which may also reveal new problems.

Could dependence on gas possibly become a problem in the future? Natural gas was cheap at first, and then everything went fine. However, due to the war between Ukraine and Russia, we now get it from many different places. Something can just happen at these places as well. This makes the Natural gas system very vulnerable. The closer to home we get it, the better. The dependence on Natural gas can certainly be seen as a risk.

Do you think it might be better to have hydrogen production in your own hands? The market for hydrogen production itself can work well. It is possible that a central controlling/managing party would be useful. There are advantages to getting hydrogen from outside, but it may be wise to aim for an independent system.

Are there risks associated with dependence on external parties? Legally, contracts between companies are well established, so it does not pose any additional risks if you obtain something from an external party. There is a market and there are rights. Of course there are risks, but this can be managed in advance and afterwards. Are there safety risks associated with implementing hydrogen in gas turbines and storing the hydrogen?

It is possible that hydrogen is more risky than natural gas, as the explosion area is wider. This makes it riskier to work with. It is thought that the public does not necessarily see this risk. They compare it with natural gas, which ensures that they will not see any more risks or setbacks compared to natural gas.

How will the public view CO2 storage? However, it is expected that there will be more resistance to the storage of CO2. This is because CO2 is socially seen as a different story, and there is more fear associated with CO2. This is due to the known risks to public health and the negative impact of CO2 in the news. As a result, it is expected that the storage of CO2 will encounter a lot of resistance from society. It is also expected that there may be an end point to CO2 storage, as it is not a sustainable option. Once it is full, CO2 storage becomes problematic.

If it is finite, how will CO2 storage compare in the future? There is also a market for CO2 storage. How much storage there is will therefore also influence the market and possibly also the emission costs. Genuine sustainable energy generation is CO2 free. CO2 storage will not be full overnight, but this will certainly change. Everything will have to become more sustainable.

Could storing hydrogen also possibly lead to problems? Storage for hydrogen is expected to be different from storage of CO2. The storage of hydrogen will behave like a buffer, while the storage of CO2 is permanent. Hydrogen storage is not expected to be a problem in the future. A market will also develop for the storage of hydrogen. This market will find a solution for hydrogen storage and determine what the best and cheapest form of storage will be.

Will the production of green hydrogen possibly place too much burden on the electricity grid? Making hydrogen from green energy can be problematic. This mainly concerns the electricity grid. If you want to use the grid to get the steam to the location of your green hydrogen production, this puts extra pressure on the electricity grid. "Make sure hydrogen is produced directly at the energy source."

Is pipeline transport of hydrogen future-proof? Hydrogen transport via the pipelines will not really be a problem, there is enough capacity for this. It will entail few risks. The current structure of the gas pipelines is also suitable for transporting hydrogen. If there are no pipelines available, it will have to be examined whether it is cheaper to lay new pipelines or to transport energy via the grid.

How do you envision the future of hydrogen? Hydrogen will have a long-term role in the market, but will not be aimed at consumers and small businesses. The future of hydrogen could go in any direction, and we don't know exactly how things will turn out in the future. We are in the middle of the energy transition, everyone is working together.

### A.6.4. Summary Interviewee 2

Hydrogen implementation for gas turbines is seen as difficult, but it is not new. We have been doing it with diffusion combustion for a long time (1̃980s). The current challenge is high vol-% hydrogen with low NOx emissions. The state of the art (F, H, + class gas turbines and Dry Low NOx) make it more challenging. The technical challenges are present, it sounds very exciting, but the GasTurbine industry has been working on more fuel flexibility and low emissions since the turn of the century. It sounds much more exciting than it is.

Receiving the hydrogen may be somewhat more difficult, especially with regard to measuring the offtake in hydrogen. The challenge lies mainly in the economic part of implementing hydrogen in gas power stations. New hardware, higher operating costs and lower margins.

Although a gas turbine is always an ignition source, an OEM will never put something on the market for which the risks cannot be mitigated, an OEM will not risk its reputation. In addition, the EU directives always apply and this guarantees an minimum security. (CE marking) Safety will always play a role, regardless of which fuel you use. When converting an existing gas turbine, proper attention must be paid to this, not just the technical part. Updating the site specific "Risk assessment and Evaluation" is very important.

Hydrogen is a high-quality molecule, the question is whether we should use this valuable substance on gas turbines? We have a significant challenge with the climate, but at the same time we want to maintain our prosperity. As a result, there are other efforts in “hard to abate” industries (e.g. fertilizer, Yara, OCI of Steel, Tatasteel) where the impact of hydrogen is much greater to reduce CO2 emissions.

Making gas-fired power stations more flexible with hydrogen is good, but the investment is interesting if other industries may benefit more from this hydrogen. Is it worth the investment of converting the power stations? Perhaps it is better to accept that these gas-fired power stations will emit some CO2 at times when no wind, sun or Battery energy storage systems (or other sustainable alternatives) are available to support the E-grid.

Maintaining gas-fired power stations is not exciting, discussed, but gas-fired power stations are necessary to prevent grid instabilities. Not only E generation, but also supporting grid stability.

CCS is a possibility. The power density (kW/m2) of gas turbines is high and efficient. The alternatives require much more (sound) space.

CCS requires a lot of surface area and produces extra noise for the environment. It affects the power station’s neighbors.

The question we have to ask ourselves is: Do we want to use our limited public space for CCS, which also produces a lot of noise? This also involves the NIMBY principle. The question is therefore whether CCS is acceptable, especially if you take into account that the efficiency of your process also decreases.

Green hydrogen gives a bit of Fear Of Missing Out (FOMO), everyone wants to participate in case it turns out to be something.

The gas infrastructure is very strong and provides reliable energy. However, the addiction to fossil fuels is also strong. We have the prosperity that we are willing to accept prices and dependence.

Biogas is a good emerging development. This may increase in the future and provide an alternative in the mix. In the future we will use a mix of different fuels. It is difficult to determine what this mix will look like, but there will certainly be a lot of changes in where we get our energy from.

An opinion: hydrogen is a good experiment, but it is really an experiment. Obtaining sufficient hydrogen capacity will take a very long time. This will have to be (even) more stimulated by the government to initiate green hydrogen production and fill the new H2 networks with hydrogen. In the Netherlands we are not necessarily equipped to make green hydrogen possible (lack of space, lack of noise space, high grid connection costs due to an E grid that is well used.

The government will have to make choices about which development contributes most to CO2 reduction. Electrification is very important for large customers and now also for smaller companies. However, the E grid is being challenged considerably. The import of renewables is increasing, BESS is also taking off (although not always in the right places to support the grid). And when the wind is not blowing, the sun is not shining and the batteries are empty, the gas turbine comes in, fueled with natural gas, biogas or hydrogen to support the grid; keep the lights on.

It all really comes down to a balance: prosperity versus climate.

### A.6.5. Summary Interviewee 3

Currently there the technology is not ready to fully run on 100% hydrogen. It might be the case in the future, but this is still uncertain.

If we want to make an impact, we need to go with high volumes of hydrogen blends, above 80%. Getting there is very difficult and takes time.

The value chain of is also a problem, to get the infrastructure ready and have everything connected. This partly also results in a cost of hydrogen that is simply too high. This needs to have better support for hydrogen to work in the future.

Hydrogen will also have some safety concerns, many elements needs to be updated to now suit the hydrogen as a fuel. Hydrogen is a very small molecule, odorless and can react with metals. This leads to the way that how repairs and inspections are performed also needs to change. However, this will not be a great concern.

The main thing is that communication to the public should be important for the implementation and production of hydrogen. The main challenge will be the “not in my backyard”, where people don’t want it happening near them. This is more the fact of the large infrastructure and projects, not really the hydrogen itself.

Looking at today’s grid congestion is a problem, we are almost full everywhere. It is not sure if we can solve the congestion problem in the future. This might be a challenge for the building of green hydrogen facilities. It might only be possible if we bypass the grid and generate directly at the energy source. The grid connection is the real bottle neck for green hydrogen and electrification. If the grid capacity increased faster, we could have done more.

CCS is going to play an important role in the future. We see it as a bridge for now, but it might stay for a longer time. CCS will bring us where we want to be. It is now in a demonstration phase. It will play a substantial role in the future, but there will be more options in the future.

The storage for CCS is huge, there is plenty of space available. Of course it is limited, but it will take a long time to fill all the available storage. By the all CCS storage would be full, CCS would not be needed anymore. Especially taking into account the goals the EU has set for 2050.

The total emission cap will go down by each year. The rate at which it goes down will increase. All emission must be paid for in the future, increasing the demand for ETS. This increase in demand will drive up the price of ETS

Looking at studies and predictions, the expectation is that blue hydrogen will play a larger part in the future. However the role of green hydrogen could be driven by governments, as they can really stimulate the production of green hydrogen. Of course It will become a mixture of hydrogen sources, but the government subsidies will play an important role in what this mixture is exactly. Based on market criteria, blue hydrogen will be a winner. Green will depend more on regulations. It might catch up, but it is difficult.

Being dependent on natural gas is a risk. There is enough gas, but the problem are conflicts. Importing natural gas for blue hydrogen is not a good option. Levering natural gas from more local sources would be better for the production of blue hydrogen. If we want blue hydrogen, we also need to focus on natural gas and the supply of it.

Outsourcing hydrogen production is not a real problem. Companies leverage their own strengths, this could work good together. You can't do everything alone. There could be benefits for having hydrogen production under own control, but there are no downsides in outsourcing hydrogen production. If you have everything under own control, there will be no competition. What can be beneficial in the end.

### A.6.6. Summary Interviewee 4

The main problem for implementing hydrogen in gas turbines is to get the hydrogen supply. Although there are technical obstacles with the conversion from running turbines natural gas to hydrogen, the biggest problem is to get the large supply of hydrogen. There might be less supply then demand in the future. The combustion technology and hydrogen technology are not really a problem, we are almost there already.

In order to solve this problem of hydrogen supply some action have to be taken. This mainly comes down to communication. It is really important to know what others are doing and working on, while communicating about what is needed. Proper partnerships need to be formed in order to solve the hydrogen supply problem.

We would like to think that green hydrogen is the future, but blue hydrogen is a stepping stone towards the hydrogen economy. However, there are many challenges to get hydrogen towards a competitive price.

CCS for the long term is not the problem for blue hydrogen, there is enough storage possibilities for the future to come. Operations will have to be efficient and safe, but there are many people looking in to the future of CO2 storage.

The downside of CCS is the fact that people see CO2 as the enemy and are scared of it. It is important to be careful about communications concerning CCS. The fact that people see CO2 as the enemy can cause resistance towards CCS. However, people are slowly starting to understand that CCS must be used towards a more sustainable future.

Green hydrogen is much easier to explain and show to the public. A reason for going for green hydrogen in the future has to do with the fact that green hydrogen can provide a large amount of production capacity. This combined with the fact that onshore green hydrogen facilities have a smaller footprint compared to blue hydrogen facilities due to the lack CCS facility. Green hydrogen also has the ability to be produced in the proximity of hydrogen demand. This all while natural gas can be used for other more important sources.

The downside of green hydrogen is the added pressure on the electrical infrastructure.

The grid is already quite congested, and that might be a problem for green hydrogen facilities. Technically it would be possible to strengthen the grid, but it would require large investments. It can be done, its nothing new, but it takes a lot of work. It also raises the question: "Who is going to pay for it?"

The storage and burning of hydrogen also raises some safety concerns that must be taken into account. Hydrogen burns faster and hotter, while the flame is also more difficult to control. Besides this, hydrogen is a colorless and odorless gas, so leakages are critical to detect. But these safety risks are easy to mitigate.

Most natural gas currently comes from Norway. We can import natural gas, but the supply complicated by the prices. We are susceptible for the prices set by other countries. The war showed the risk.

The dependency on natural gas helps to sell green hydrogen, as it does not rely on natural gas. The Independence of renewable energy helps to accelerate the development of them.

Producing hydrogen yourself or outsourcing it to an external partner has some complications as well. It might be better to trade hydrogen on the market as this can result in cheaper prices. However, having hydrogen production under own control can be beneficial as it gives you more options. There are no real downsides for outsourcing hydrogen production.

One point to taker into consideration is that the conversion towards hydrogen would not happen in a free market, as it will always be cheaper to directly burn natural gas. It is the goals and incentives such as emission cost that drive the conversion to hydrogen combustion.

### A.6.7. Summary Interviewee 5

The largest problem in the switch to hydrogen combustion might be the technical development of gas turbines. Especially taking into account the capacity that the turbines would have to be. It will probably take some time before this is properly developed.

If there are any safety concerns with the implementation of hydrogen? There might be some safety concerns, but these would be solvable quite easily.

This would also not cause any resistance in the building or placing large green hydrogen facilities, especially if they are located far away from people. Large industrial projects already happen at such places, so the placement of such a green hydrogen facility would not cause any problems.

If the placement of such an hydrogen facility would cause any problems related to the grid congestion's depends on what would be developed first, the strengthening of the grid, or the placement of such an facility. On the other hand, the placement of a green hydrogen facility can also help in balancing the grid by taking energy when needed. But if these large green hydrogen facilities will be placed on land is still a question. It would be better to place them at the source of green electricity off-shore.

Therefore it is also mentioned that transporting hydrogen might be easier compared to transporting electricity. Hydrogen transport via new or retrofitted pipelines does not show any reason for trouble in the future. This will also probably stay the method of transporting hydrogen for the future.

CCS will not have the future. It does not make sense to capture CO2 and store it away. CCS cost a lot of energy, and you are just pushing away the problem. It is not expected that blue hydrogen will therefore have a future.

This is accompanied by the thought that blue hydrogen will also have some resistance by the public because of CCS. Might even have more resistance than burning biomass.

Will hydrogen storage cause any problems? It is expected that this would not be a real problem. Underground in for instance empty gas fields is not expected to cause any trouble. However, it is expected to also cause some resistance of the public. It might give the feeling that they are sitting on a timebomb. But, rather have hydrogen storage compared to CO2 storage.

Being dependent on natural gas can cause some problems, but these are not expected to be very large.

Being dependent on hydrogen production is another question. Having green hydrogen production has some financial benefits. You can decide if you want to use it for own consumption, or if you want to trade the hydrogen.

Emission costs might rise in the future, but the running hours of turbines will go down. Therefore the increase in emission cost might be compensated by the decrease in total running hours of the turbine. But in the end, the emission cost will just be included in the electricity price.

However, the legislation will make everyone switch to hydrogen, and as a company you have to follow what the others are doing.

A great way to switch to hydrogen is to first make realistic plans. Don’t strive to make a very large hydrogen plan at the start, that is too large of a step that might lead to a large amount of technical challenges and too high investment costs and risks. If you want to pioneer, you have to dare to start small at first, and build up from there.

### A.6.8. Summary Interviewee 6

One of the biggest problems might be the infrastructure. Technically everything will be doable, however it is important that the hydrogen is able to get to the turbines. The technical part of hydrogen transport is doable as well, but the hydrogen pipelines must be placed. That is the most important part.

There are some extra risks associated with running on hydrogen, but that will be fine. The large scale storage of hydrogen is seen as a larger risk. Especially if large scale hydrogen is stored above ground. However, it is expected that other companies will find a solution for the storage and the associated risk. A lot of companies will have to switch to hydrogen, so companies will figure out a solution. This will not form a real problem. Outsourcing the hydrogen storage can even be an good idea. Companies should collaborate and use their own and each other’s expertise and strengths.

However, people will always be against the storing of hydrogen if it happens near them. The same holds true for the storing of carbon. However, storing of sea would result in less resistance from public.

CCS is not really seen to have a future perspective. It will cost a lot of power and investment, all while the efficiency if quite low. The question might be if we might save more CO2 emissions by not using CCS and start planting trees, especially in the case where biomass is burned. The logic of CCS is not really seen.

Emissions cost however are a good idea. The emission costs will probably make hydrogen the cheaper fuel in the future. First coal will stop, after that gas will stop, and next we will run on hydrogen. Let the large CO2 emitters decide the price. This way companies will be forced to invest and innovate in more sustainable alternatives. Rather not subsidize, but let the market do its thing. In the end, the consumers will pay for it. Or it will be by higher electricity prices, of via their tax money.

How hydrogen is produced does not matter, via electrolyzers or other sources. Everything is okay, as long as there is hydrogen. The emission costs will decide how this hydrogen will be produced. In the end, the market will decide.

Green hydrogen is not expected to put a large burden on the grid. It could even be used to balance the grid by taking energy and converting it to hydrogen when there is an excess amount of energy. This will also result in very cheap energy.

It is important to be the first in placing electrolyzers, or other comparative technologies and investments. This way the market benefits will be the greatest.

Besides gas turbines, gas motors might also be an interesting solution for future flexible power generation. They have fast startup times and a high efficiency. They give you the ability to really quickly respond to the grid. This will probably also be possible on hydrogen in the future.

How much we depend on natural gas will probably not increase in the future. The dependency we have on natural gas, we made our self. Countries where we get our gas from can become a bit difficult. However, that will probably not really become a problem. We can solve it. But we are more dependent on gas than we are on the sun and wind. Relying on sun and wind does give us more freedom on how to use these energy sources.

### A.6.9. Ranking of the Criteria by Interview Participants

**Table A.12:** Scoring of the criteria by participants

| **Participant:** | **1** | **2** | **3** | **4** | **5** | **6** | Median | Average |
|---|---|---|---|---|---|---|---|---|
| Carbon emission reduction | 6 | 7 | 1 | 8 | 1 | 9 | 6,5 | 5,3 |
| Running profile conformance | 5 | 10 | 7 | 5 | 2 | 3 | 5 | 5,3 |
| Overall system efficiency | 4 | 6 | 4 | 4 | 10 | 6 | 5 | 5,7 |
| Operational expenditure | 9 | 3 | 2 | 1 | 7 | 4 | 3,5 | 4,3 |
| Capital expenditure | 8 | 2 | 3 | 2 | 9 | 5 | 4 | 4,8 |
| Operational expenditure stability | 7 | 1 | 9 | 10 | 8 | 2 | 7,5 | 6,2 |
| Technical adaptability | 2 | 4 | 5 | 7 | 4 | 7 | 4,5 | 4,8 |
| Infrastructural adaptability | 1 | 5 | 6 | 3 | 3 | 8 | 4 | 4,3 |
| Operational longevity | 3 | 8 | 8 | 6 | 6 | 1 | 6 | 5,3 |
| Dependability | 10 | 9 | 10 | 9 | 5 | 10 | 9,5 | 8,8 |

## A.7. Multi-Criteria Analysis

Table A.13, Table A.14, and Table A.15 showcasing the results used for the multi-criteria analysis. The low forecast standardised values between 0 and 1 are based on the results of the qualitative and quantitative research, Equation 2.1, and Equation 2.2. The weighted results and the final outcomes of the multi-criteria analysis can be seen in Figure 6.1 Figure 6.2 Figure 6.3.

**Table A.13:** Low forecast values used for multi criteria analysis

| **Low forecast** | **Weight** | **Blue** | **Green** | **Mix** | **Gas** | **Blue score** | **Green score** | **Mix score** | **Gas score** |
|---|---|---|---|---|---|---|---|---|---|
| **Carbon emission reduction** | 0,055 | 5133 tons | 2164 tons | 4993 tons | 266705 tons | 0,99 | 1,00 | 0,99 | 0,00 |
| **Running profile conformance** | 0,109 | 1 | 1 | 1 | 1 | 1,00 | 1,00 | 1,00 | 1,00 |
| **Overall system efficiency** | 0,091 | 47% | 37% | 44% | 60% | 0,43 | 0,00 | 0,30 | 1,00 |
| **Operational expenditure** | 0,182 | € 79.393.000 | € 123.861.000 | € 85.445.000 | € 109.582.000 | 1,00 | 0,00 | 0,86 | 0,32 |
| **Capital expenditure** | 0,145 | € 322.411.000 | € 459.511.000 | € 333.892.000 | € 0 | 0,30 | 0,00 | 0,27 | 1,00 |
| **Operational expenditure stability** | 0,036 | € 61.283.000 | € 30.270.000 | € 6.097.000 | € 43.250.000 | 0,00 | 0,56 | 1,00 | 0,33 |
| **Technical adaptability** | 0,127 | -8 | -2 | -7,5 | 0 | 0,00 | 0,75 | 0,06 | 1,00 |
| **Infrastructural adaptability** | 0,164 | -1 | -6 | -3,0 | 0 | 0,83 | 0,00 | 0,50 | 1,00 |
| **Operational longevity** | 0,073 | -1 | 4 | -1,0 | -2 | 0,17 | 1,00 | 0,17 | 0,00 |
| **Dependability** | 0,018 | -4 | -1 | -4,0 | -5 | 0,25 | 1,00 | 0,25 | 0,00 |

**Table A.14:** Central forecast values used for multi criteria analysis

| **Central forecast** | **Weight** | **Blue** | **Green** | **Mix** | **Gas** | **Blue score** | **Green score** | **Mix score** | **Gas score** |
|---|---|---|---|---|---|---|---|---|---|
| **Carbon emission reduction** | 0,055 | 5133 tons | 1732 tons | 2647 tons | 266705 tons | 0,99 | 1,00 | 1,00 | 0,00 |
| **Running profile conformance** | 0,109 | 1 | 1 | 1 | 1 | 1,00 | 1,00 | 1,00 | 1,00 |
| **Overall system efficiency** | 0,091 | 47% | 37% | 39% | 60% | 0,43 | 0,00 | 0,09 | 1,00 |
| **Operational expenditure** | 0,182 | € 103.542.000 | € 93.591.000 | € 82.914.000 | € 131.207.000 | 0,57 | 0,78 | 1,00 | 0,00 |
| **Capital expenditure** | 0,145 | € 322.411.000 | € 497.838.000 | € 515.257.000 | € 0 | 0,37 | 0,03 | 0,00 | 1,00 |
| **Operational expenditure stability** | 0,036 | € 61.283.000 | € 30.270.000 | € 6.097.000 | € 43.250.000 | 0,00 | 0,56 | 1,00 | 0,33 |
| **Technical adaptability** | 0,127 | -8 | -2 | -4,5 | 0 | 0,00 | 0,75 | 0,44 | 1,00 |
| **Infrastructural adaptability** | 0,164 | -1 | -6 | -5,5 | 0 | 0,83 | 0,00 | 0,08 | 1,00 |
| **Operational longevity** | 0,073 | -1 | 4 | 2,5 | -2 | 0,17 | 1,00 | 0,75 | 0,00 |
| **Dependability** | 0,018 | -4 | -1 | -2,5 | -5 | 0,25 | 1,00 | 0,63 | 0,00 |

**Table A.15:** High forecast values used for multi criteria analysis

| **High forecast** | **Weight** | **Blue** | **Green** | **Mix** | **Gas** | **Blue score** | **Green score** | **Mix score** | **Gas score** |
|---|---|---|---|---|---|---|---|---|---|
| **Carbon emission reduction** | 0,055 | 5133 tons | 1299 tons | 1888 tons | 266705 tons | 0,99 | 1,00 | 1,00 | 0,00 |
| **Running profile conformance** | 0,109 | 1 | 1 | 1 | 1 | 1,00 | 1,00 | 1,00 | 1,00 |
| **Overall system efficiency** | 0,091 | 47% | 37% | 39% | 60% | 0,43 | 0,00 | 0,09 | 1,00 |
| **Operational expenditure** | 0,182 | € 140.676.000 | € 95.043.000 | € 89.011.000 | € 152.832.000 | 0,19 | 0,91 | 1,00 | 0,00 |
| **Capital expenditure** | 0,145 | € 322.411.000 | € 519.287.000 | € 540.112.000 | € 0 | 0,40 | 0,04 | 0,00 | 1,00 |
| **Operational expenditure stability** | 0,036 | €61.283.000 | € 30.270.000 | € 6.097.000 | € 43.250.000 | 0,00 | 0,56 | 1,00 | 0,33 |
| **Technical adaptability** | 0,127 | -8 | -2 | -4,5 | 0 | 0,00 | 0,75 | 0,44 | 1,00 |
| **Infrastructural adaptability** | 0,164 | -1 | -6 | -5,5 | 0 | 0,83 | 0,00 | 0,08 | 1,00 |
| **Operational longevity** | 0,073 | -1 | 4 | 2,5 | -2 | 0,17 | 1,00 | 0,75 | 0,00 |
| **Dependability** | 0,018 | -4 | -1 | -2,5 | -5 | 0,25 | 1,00 | 0,63 | 0,00 |

**Table A.16:** Low forecast multi criteria analysis with weighted results

| Low forecast | Weight | Blue weighted results | Green weighted results | Mix weighted results | Gas weighted results |
|---|---|---|---|---|---|
| **Carbon emission reduction** | 0,055 | 0,054 | 0,055 | 0,054 | 0,000 |
| **Running profile conformance** | 0,109 | 0,109 | 0,109 | 0,109 | 0,109 |
| **Overall system efficiency** | 0,091 | 0,040 | 0,000 | 0,028 | 0,091 |
| **Operational expenditure** | 0,182 | 0,182 | 0,000 | 0,157 | 0,058 |
| **Capital expenditure** | 0,145 | 0,043 | 0,000 | 0,040 | 0,145 |
| **Operational expenditure stability** | 0,036 | 0,000 | 0,020 | 0,036 | 0,012 |
| **Technical adaptability** | 0,127 | 0,000 | 0,095 | 0,008 | 0,127 |
| **Infrastructural adaptability** | 0,164 | 0,136 | 0,000 | 0,082 | 0,164 |
| **Operational longevity** | 0,073 | 0,012 | 0,073 | 0,012 | 0,000 |
| **Dependability** | 0,018 | 0,005 | 0,018 | 0,005 | 0,000 |
| **Final score** | | 0,581 | 0,370 | 0,530 | 0,707 |

**Table A.17:** Central forecast multi criteria analysis with weighted results

| Central forecast | Weight | Blue weighted results | Green weighted results | Mix weighted results | Gas weighted results |
|---|---|---|---|---|---|
| **Carbon emission reduction** | 0,055 | 0,054 | 0,055 | 0,054 | 0,000 |
| **Running profile conformance** | 0,109 | 0,109 | 0,109 | 0,109 | 0,109 |
| **Overall system efficiency** | 0,091 | 0,040 | 0,000 | 0,008 | 0,091 |
| **Operational expenditure** | 0,182 | 0,104 | 0,142 | 0,182 | 0,000 |
| **Capital expenditure** | 0,145 | 0,054 | 0,005 | 0,000 | 0,145 |
| **Operational expenditure stability** | 0,036 | 0,000 | 0,020 | 0,036 | 0,012 |
| **Technical adaptability** | 0,127 | 0,000 | 0,095 | 0,056 | 0,127 |
| **Infrastructural adaptability** | 0,164 | 0,136 | 0,000 | 0,014 | 0,164 |
| **Operational longevity** | 0,073 | 0,012 | 0,073 | 0,055 | 0,000 |
| **Dependability** | 0,018 | 0,005 | 0,018 | 0,011 | 0,000 |
| **Final score** | | 0,514 | 0,517 | 0,525 | 0,648 |

**Table A.18:** High forecast multi criteria analysis with weighted results

| High forecast | Weight | Blue weighted results | Green weighted results | Mix weighted results | Gas weighted results |
|---|---|---|---|---|---|
| **Carbon emission reduction** | 0,055 | 0,054 | 0,055 | 0,054 | 0,000 |
| **Running profile conformance** | 0,109 | 0,109 | 0,109 | 0,109 | 0,109 |
| **Overall system efficiency** | 0,091 | 0,040 | 0,000 | 0,008 | 0,091 |
| **Operational expenditure** | 0,182 | 0,035 | 0,165 | 0,182 | 0,000 |
| **Capital expenditure** | 0,145 | 0,059 | 0,006 | 0,000 | 0,145 |
| **Operational expenditure stability** | 0,036 | 0,000 | 0,020 | 0,036 | 0,012 |
| **Technical adaptability** | 0,127 | 0,000 | 0,095 | 0,056 | 0,127 |
| **Infrastructural adaptability** | 0,164 | 0,136 | 0,000 | 0,014 | 0,164 |
| **Operational longevity** | 0,073 | 0,012 | 0,073 | 0,055 | 0,000 |
| **Dependability** | 0,018 | 0,005 | 0,018 | 0,011 | 0,000 |
| **Final score** | | 0,449 | 0,541 | 0,525 | 0,560 |

## A.7.1. Sensitivity Analysis

**Table A.19:** Final scores of the original multicriteria analysis and the sensitivity analysis

| Original | Blue weighted results | Green weighted results | Mix weighted results | Gas weighted results |
|---|---|---|---|---|
| Final score low forecast | 0,581 | 0,37 | 0,53 | 0,707 |
| Final score central forecast | 0,514 | 0,517 | 0,525 | 0,648 |
| Final score high forecast | 0,449 | 0,541 | 0,525 | 0,560 |
| **sensitivity analysis CAPEX** | **Blue weighted results** | **Green weighted results** | **Mix weighted results** | **Gas weighted results** |
| Final score low forecast | 0,594 | 0,467 | 0,564 | 0,640 |
| Final score central forecast | 0,518 | 0,609 | 0,614 | 0,581 |
| Final score high forecast | 0,449 | 0,632 | 0,614 | 0,581 |
| **sensitivity analysis Efficiency** | **Blue weighted results** | **Green weighted results** | **Mix weighted results** | **Gas weighted results** |
| Final score low forecast | 0,575 | 0,435 | 0,552 | 0,640 |
| Final score central forecast | 0,508 | 0,582 | 0,580 | 0,581 |
| Final score high forecast | 0,443 | 0,605 | 0,580 | 0,581 |
| **sensitivity analysis CO2** | **Blue weighted results** | **Green weighted results** | **Mix weighted results** | **Gas weighted results** |
| Final score low forecast | 0,639 | 0,448 | 0,599 | 0,610 |
| Final score central forecast | 0,578 | 0,579 | 0,591 | 0,557 |
| Final score high forecast | 0,519 | 0,601 | 0,591 | 0,557 |