Renewable Hydrogen in the Dutch Built Environment and the Impact on Energy Security

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Preface

Dear reader,

This thesis is the result of months of hard but delightful work. Together with my supervisors, I have been working on a topic that I am deeply interested in and reflecting on this final product is very rewarding. This would have never been possible without the tremendous support of my supervisors. To my first supervisor, Daniel Scholten, thank you for guiding me throughout the process and especially redirecting me when I was overwhelmed by the different possible perspectives this topic brings. To my second supervisor, Zofia Lukszo, I would like to thank you for your structured feedback during the midterm and for connecting your thesis students. I had some interesting discussions with other students after this catch-up meeting. Last but certainly not least, I would like to thank my supervisors from Accenture. Jorien and Laura, thank you for your unconditional support throughout the process, the discussions and help with connecting me to important stakeholders for my interviews. You have been extremely valuable to me.

Moreover, I cannot move on without thanking my family and friends for their support and trust in me during these challenging times, covid-19 introduced an extra dimension to this graduation process, which has not been too easy at all times. Thank you, mom and dad, for keeping my head up and my girlfriend Ottoline to ease my mind in times of need. Without you all I would not have been able to complete this thesis. Furthermore, of course, I would like to thank my dearest son, Guus. Even though he cannot read yet or discuss my thesis's complexities with me, his unconditional love supported me in every possible way.

The original idea was to carry out this project at the Accenture office. Unfortunately, due to covid-19, this office was replaced with the basement at home. Luckily, my roommates were bound to work from home as well, so at least we had each other during these lonely times. Still, the process was enjoyable and an incredible learning experience.

The thesis topic has been formulated mainly by myself, with the help of my first supervisor. For this reason, the start was quite challenging and required extensive reading of background information and literature. However, I formulated a topic and research question that is very close to my heart and resulted in this thesis you are about to read.

Executive summary

Energy security of countries is shaped by existing characteristics of traditional fossil fuel-based energy systems. However, more renewables are integrated into energy systems every year to decarbonize energy supply to meet climate goals. The traditional fossil fuel-based energy systems make room for a renewable and more diversified energy system. Traditional fuels are replaced with renewable energy carriers, of which electricity is seen as the panacea to the energy challenges decarbonization brings along. Electricity is a versatile energy carrier, easily stored, and is applicable to be integrated into multiple sectors. However, some sectors prove to be less easily electrified, like the metal industry that requires sources of high-temperature heat. Literature is confident of electricity's role in future renewable energy systems but realizes that some form of renewable molecules is paramount to the energy transition. The role of hydrogen in the built environment remains ambiguous; hence, the connection between hydrogen and energy security is underdeveloped. Hydrogen was subject to several upliftings in the last two decades but never managed to find a prominent place in the energy system. With decreasing costs for renewable energy and promising hydrogen technology development, hydrogen has once again hit the headlines in literature, and maybe this time for good. Current developments in the hydrogen field increasingly provide hopeful business cases for the energy carrier to conquer the energy system. Whereas most business cases consider decarbonizing hard to abate industries, there is a progressive trend towards utilizing hydrogen in the transport sector or built environment. Combining these developments with increasing challenges regarding grid expansion for the energy system's electrification increases its appeal in large scale integration in decarbonization efforts.

From these knowledge gaps, the following research question is formulated:

"How will decarbonization of the Dutch built environment through hydrogen affect national energy security in the long-term?"

This research aims to explore how hydrogen as an energy carrier affects Dutch energy security when decarbonizing the Dutch built environment. The differences between the two hydrogen scenarios are compared and reflected on the results from the reference case. Here, the geotechnical characteristics of hydrogen aid in understanding how hydrogen changes aspects of national energy security.

The results from analyzing the reference case and two scenarios through applying the energy security framework give implications on an academic and practical level. Reflecting on the results helps to establish critical takeaways. In general, hydrogen in the built environment significantly improves Dutch energy security performance in multiple dimensions. The existing Dutch gas infrastructure gives the Netherlands a good starting position concerning a frontrunner position in developing a hydrogen supply chain. This can abate the investment challenge for specific sectors like the industry or the built environment. However, hydrogen prices depend on the levelized costs for electricity. This availability of cheap renewable electricity can become a crucial determinant of where to produce hydrogen. Hydrogen in the built environment enforces reutilizing the existing gas grid making this possible. Next, hydrogen in the built environment significantly diversifies the energy system when utilized in hybrid heat pumps improving energy security. The main differences between the scenarios are listed below:

- **Domestic hydrogen production for the built environment prevents large scale curtailment of renewable energy sources.** Domestic hydrogen production makes it possible to harvest more

renewable energy due to the storage capabilities and, in the process, copes with the intermittency issues of renewable energy sources.

- **Energy system efficiency is negatively affected by domestic hydrogen production.** The import of hydrogen mitigates system efficiency losses. However, this could be reflected in the price of foreign hydrogen.
- **Large scale hydrogen implementation in the built environment creates new dependencies.** Large scale hydrogen imports decrease energy security. A balance between domestic production and import of hydrogen is most favourable in terms of energy security performance.
- **Industrial output increases when hydrogen is introduced into the built environment.** Domestic hydrogen production for use in the built environment improves industrial output and creates new business models/opportunities.
- **Large scale hydrogen production for the built environment can compete with freshwater supply.** In terms of environmental concerns, large quantities of hydrogen production potentially challenge freshwater sources.
- **Hydrogen for the built environment faces less societal resistance than electrical solutions.** Large scale hydrogen production faces local societal challenges when organized primarily domestically. Hydrogen imports face resistance with cloudy international contracts.

Reflecting on the results given the geotechnical characteristics has several implications. From a sources point of view, hydrogen is less geographically constrained in comparison with natural gas. This suggests that future hydrogen markets are globally orientated and competitive. This makes it hard to stipulate to what extent the Netherlands will be able to produce hydrogen domestically. From a generation perspective, hydrogen is produced most economically in large central facilities. These facilities are connectable to large offshore wind parks, decreasing societal resistance for more renewable energy sources. The inherent Dutch gas culture provides even more leverage for renewable gaseous energy carriers to supply heating demand. The generation of hydrogen is set to green hydrogen only. Electrolysis of water is the most mature form of green hydrogen, but still an expensive hydrogen production method. These efforts for decarbonization have adverse effects on the energy prices for consumers. From a distribution perspective, hydrogen makes international trade possible as it can be easily stored and transported. This characteristic of hydrogen, together with the fact it can be produced worldwide, potentially connects many players to the hydrogen market. More participants inhibit cheaper available hydrogen that could influence the potential for domestic hydrogen production.

From the results, different learnings are distinguished for the academic field of energy security. First, there is a need to update the definition of energy security and create indices suitable for future energy system analyses. Current energy security literature surrounds the traditional energy systems powered by fossil fuels. Future energy systems will replace these fuels with renewable energy carriers, dealing with other dependencies, different conversion processes, different actors, and a whole new energy geopolitics field. The relation between energy security of renewable and geopolitics is not sufficiently examined yet. The complexities of hydrogen as a novel energy carrier is challenging to inspect with the current energy security frameworks.

Several recommendations can be made for actors in the fields. The Dutch TSO should focus on developments considering improving the location, diversity, and policy dimension. Hydrogen is a critical component in diversifying the energy system. Additional gasses requires managing a new portfolio of gasses and provide coherent system integration. Next, they should seek partnerships and cooperation with neighbouring countries to develop the hydrogen infrastructure. The Dutch DSO's should focus on projects that improve the location, technology and efficiency, and culture dimension. They should investigate how to divide the Netherlands into different energy districts and find where in the Netherlands hydrogen integration in heating systems is most favourable. From here, infrastructure and appliance adjustments are necessary for end-users to use the hydrogen in selected homes or neighbourhoods. Hydrogen is socially favourable, and DSO's should leverage this into a lobby for hydrogen districts.

Future research should focus on developing an energy security framework that is more suitable for analysing future energy systems. Next, the difference in energy security performance of hydrogen production pathways is interesting to investigate. Finally, renewable energy policy and governmental involvement are important in the first stages of the energy transition. Future research could scope down on the policy dimension of the Netherlands to make concrete recommendations for policymakers.

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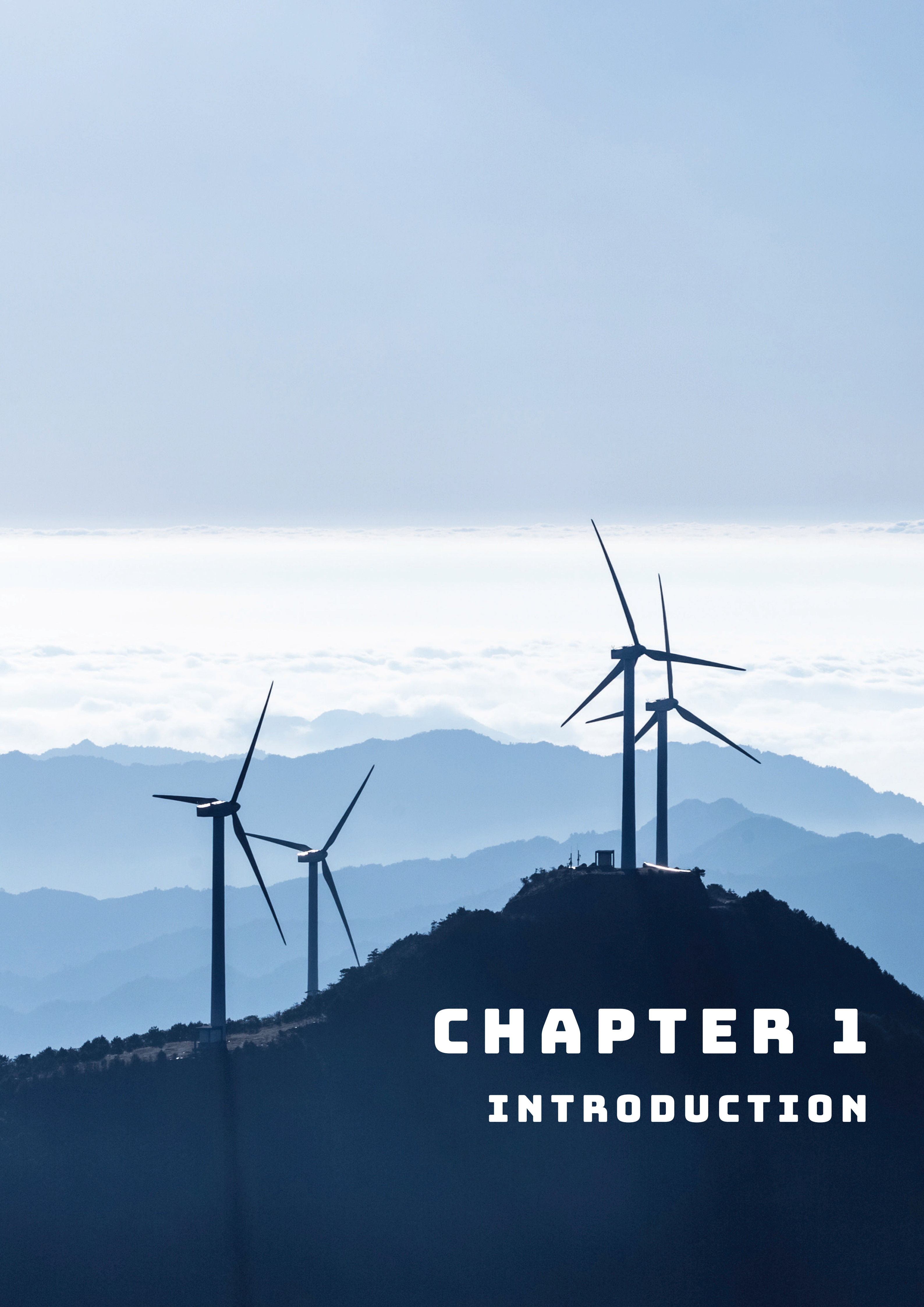


CHAPTER 1

INTRODUCTION

1. Introduction

To decarbonize energy demand and reduce carbon emissions, countries must adopt zero- or low-carbon technologies in the upcoming years (United Nations, 2015). As a result, renewable energy production in Europe grew significantly in an attempt to become the world's first climate-neutral continent by 2050 (Eurostat, 2020). The Netherlands lacks behind its 2020 target significantly (Appendix A). However, growth in renewable electricity production can be distinguished (figure 1).

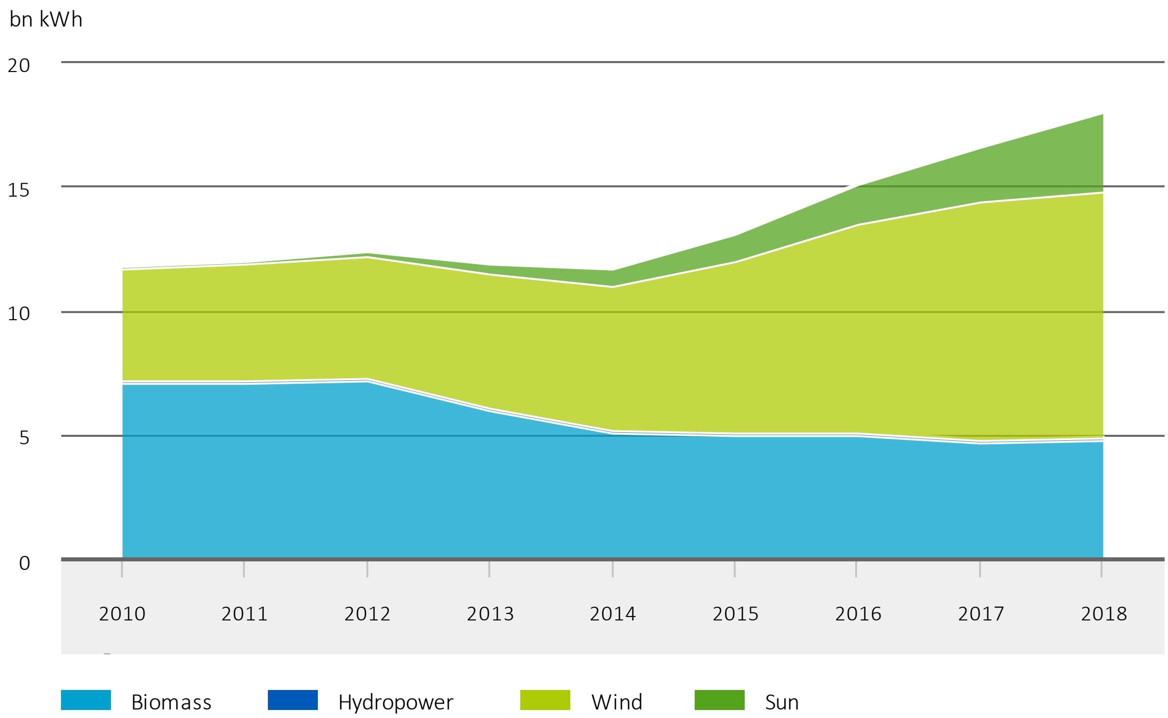


Figure 1: Renewable energy production in the Netherlands (CBS, 2020)

Producing renewable electricity is a means to mitigating carbon emissions, but it is not the best solution for each sector. Notably, heating of space and water contributes significantly to the total energy demand (Samsatli & Samsatli, 2019). Residential heating accounts for approximately 12% of final energy consumption in the Netherlands, and this share of energy consumption is satisfied for 71% by natural gas combustion (IEA, 2018). However, increasing debate on natural gas use puts this resource in a peculiar position due to the earthquakes initiated by extracting natural gas in the Dutch gas fields (Kester, 2017). Besides, an all-electric energy system cannot meet energy demand, given the capacity and a mismatch in availability and demand (Samsatli & Samsatli, 2019). This course of events creates renewable hydrogen opportunities to become the second-largest energy carrier in a future renewable energy system.

The possibility to utilize sustainable hydrogen for heat decarbonization is increasingly mentioned in the literature, either through fuel cells or grid injection (Dodds et al., 2015; Samsatli & Samsatli, 2019; Speirs et al., 2018). Also, the Netherlands possesses an abundant gas infrastructure with the capability to transport hydrogen. This proves to be valuable, given the trend of increased renewable energy production and its intermittent nature that requires coping mechanisms and flexibility. Gas networks may provide less expensive energy storage, simple operation, and flexibility of supply (Balcombe et al., 2018; Schiro et al., 2019).

There are several methods available for hydrogen production, of which two techniques eliminate greenhouse gas emissions. Blue hydrogen is produced by reforming fossil fuels and capturing carbon emissions with carbon capture and storage (CCS). Green hydrogen is produced through water's electrolysis and generates no carbon emissions (TNO, 2020). Producing hydrogen through electrolysis or steam methane reforming (SMR) with CCS strengthens the decarbonization potential of hydrogen, even more, making hydrogen as a future sustainable energy carrier an appealing option (Samsatli & Samsatli, 2019).

Introducing renewables to the energy mix also affects energy security because RES displace traditional fossil fuels to meet energy demands. There are many indexes available for national or global energy security analyses, each given different dimensions due to research scope or objective. Ang et al. (2015) identify a wide range of different indexes and definitions of energy security. The advent of renewables has new implications for these indexes since RES's geographic dependency is relatively low compared to fossil fuels. Renewables also bring diversification to the energy portfolio.

On the contrary, renewables are energy flow-dependent, and storage requirements and terrestrial competition raise new dependencies compared to traditional fossil fuels (Hache, 2018). Consequently, introducing different renewables in energy systems at different rates has divergent effects on current energy security. These effects are broadly presented as positive, but new challenges are acknowledged when dealing with renewable energy systems. One must consider the accumulation of rare metals essential in decarbonization technologies that can become critical drivers for technology prices and diffusion (Hache, 2018; Scholten, 2018). This confirms different energy security implications with different renewable energy sources or energy carriers, such as hydrogen.

Overall, renewable energy carriers for heating are lesser endowed in literature. Implications of renewable electricity for end-use appliances is available abundantly. However, heating in the built environment is somewhat arbitrary and case-specific. Not all houses can be electrified or connected to a heating grid. Besides, social acceptance for hydrogen implementation is expected to be higher as it is less of a radical adjustment than full electrification of all household appliances (González & Mulder, 2018). Expanding hydrogen production, increasing imports, or any other means to meet hydrogen demand for heating have different consequences than an all-electric system. This argument indicates an apparent need for further exploring the effects of renewable energy carriers on energy security in renewable heating systems (Augutis et al., 2014; Hache, 2018; Ralph & Hancock, 2019; Valdés Lucas et al., 2016).

1.1 Problem statement

Renewable hydrogen is a critical shackle in the quest to decarbonize the Dutch energy system. An all-electric energy system is unfavourable in terms of intermittency and grid capacity. To cope with this intermittent nature of renewable energy sources, seasonal energy demand, and increased flexibility, gaseous energy carriers should be integrated next to electricity. In the built environment, hydrogen can provide substantial greenhouse gas reductions and provide heating demand for hard to electrify homes. However, the vision on to what extent hydrogen will satisfy national heating demand in the built environment remains somewhat ambiguous. Also, introducing a novel energy carrier brings about implications for future Dutch energy security, given its geographical and technical characteristics that are currently unclear. This lack of knowledge can contribute to improper policymaking and delay in reaching sustainability goals.

1.2 Research questions

The research questions guide the process that ultimately leads to answering the main research question:

➔ *How will decarbonization of the Dutch built environment through hydrogen affect national energy security in the long-term?*

The following sub-questions have been formulated that contribute to answering the main research question:

Sub-question 1: *What theories and/or concepts can be used best to capture energy security in a renewable world?*

Sub-question 2: *What does the system integration of hydrogen as an energy carrier imply for heat supply chains in the Netherlands; what are the most realistic and relevant hydrogen penetration scenarios towards 2050?*

Sub-question 3: *How can the initial framework from the first sub-question be improved?*

Sub-question 4: *What geotechnical characteristics of hydrogen are responsible for the change in future energy security performance compared to the reference case?*

1.4 Objective

This research aims to explore how hydrogen as an energy carrier affects Dutch energy security when decarbonizing the Dutch built environment. To refrain from a regular energy security assessment, an extra dimension is added to the analysis. The geographical and technical characteristics and regional perspectives of hydrogen can explain why hydrogen potentially changes aspects of national energy security and helps establish comprehensive policymaking recommendations.

1.5 Research approach

It is paramount to choose a research approach that fits with the research project. By examining the main research question, two main themes are coming forward. The first is the energy security analysis of both current and possible future energy systems, and the second entails understanding the characteristics of hydrogen to understand its effect on national energy security. There are many different energy security indexes (Ang et al., 2015) to analyse a country's performance and a wide variety of scenarios and visions, each incorporating different levels of hydrogen penetration (Detz et al., 2019).

1.5.1 Exploratory research approach

This research undertakes an *exploratory research approach*. This approach allows for examining research problems that have not been clearly defined in literature. Exploratory research is conducted to determine the origin of the problem situation but not to provide conclusive evidence. It helps better to understand the problem situation (Dudovskiy, 2019). Consequently, during exploratory research, the researcher should be willing to adapt to the direction of the results concerning the revelation of new results and data. This research approach is suitable when the proposed research question entangles a theme that has not been studied or is not thoroughly investigated. Hence, the suggested research questions given the problem situation meet these criteria perfectly. Exploratory research is also a right approach when dealing with scenarios, considering the fuzziness and uncertain scenario analysis nature. Next, given the wide variety of workable frameworks and scenarios, it helps develop a holistic starting point for analysis that includes all different perspectives.

1.5.2 Literature

The literature review's origin should be broad to incorporate as many different perspectives on both energy security and hydrogen. This means that literature in the field of energy security (of renewables), future energy system scenarios, and geopolitics of renewables are included in the review. Scopus was used as a literature database to find relevant articles. Several search strings were used, and other articles have been found through snowballing. The reason for different search strings was due to the different themes in the review. The search query for the energy security review consisted of the two following to queries, combined:

“(TITLE ("energy security") AND TITLE-ABS-KEY (dimension* OR definition* OR index OR indexes)) AND PUBYEAR > 2014”

And,

TITLE ("energy security" AND renewable*)

For the geopolitics review, the following query was initiated:

(TITLE-ABS-KEY (geopolitic* AND renewables) AND TITLE-ABS-KEY ("energy security" OR security OR "energy relation*" OR "security of supply"))

All queries combined delivered 243 articles. After reading the titles, only 73 were left, of which the abstracts were read. Hereafter, 18 articles were taken into the review. Through snowballing and examining the references in these 18 articles, the rest of the reviewed articles were found.

Besides the queries and literature search, two papers stand out and will have a prominent place in this research. First, the paper from Azzuni & Breyer (2018) is crucial, as they developed the most comprehensive energy security analysis in literature covering 15 different dimensions. They argue that an energy security analysis ought to embody all different dimensions that relate to energy security. This is a promising foundation for this research as it includes all possible dimensions but allows us to remove irrelevant aspects of the analysis. Considering the specific scope for this research, this allows us to remove certain aspects of the framework to comply with the time constraints this research is bound to. The second paper that is evaluated in more detail in the paper from Scholten (2018). This paper allows us to create a logic that aids in analysing future energy systems when there is no real data available. This narrative allows us to create expectations and explain how the change in a country's energy security is caused by specific differences between current and future energy systems.

1.5.3 Framework selection

Literature is abundantly supplied with frameworks designed to measure energy security of countries or regions (Ang et al., 2015). The review from Ang et al. (2015) offers a comprehensive overview of the available energy security indices. An updated overview is presented by Gasser (2020), including 63 different indices found by combining studies by Ang et al. (2015), Valdés (2018), Apergis et al. (2015), and Bandura (2008). The index devised by Azzuni & Breyer (2020) is missing because this study is conducted more recently. The number of measurable indicators in the 64 indices differ substantially. Choosing what indicators to include in a study depends on the research scope and objective (Gasser, 2020).

Different energy security indices or composite indicators are applied throughout literature. One review from Ang et al. (2015) offers a comprehensive overview of the available energy security indices. An updated overview is presented by Gasser (2020), including 63 different indices found by combining studies by Ang et al. (2015), Valdés (2018), Apergis et al. (2015), and Bandura (2008). The index devised by Azzuni & Breyer (2020) is missing because this study is conducted more recently. For that reason, energy security analyses are highly contextual and of polysemic nature (Radovanović et al., 2017). On the contrary, Azzuni & Breyer (2018) argue that energy security assessments should address all the dimensions related to energy security. It is not surprising that the distinct indices measuring energy security have heterogeneous indicator sets. This inconsistency can be explained by the fact that each country has different shares of energy sources, political systems, geographical locations, economic welfare, and international relations (Gasser, 2020; Radovanović et al., 2017). Ang et al. (2015) point out that selecting these indicators can be somewhat arbitrary. The selection criteria are usually not well explained and transparent (Månsson et al., 2014). This lack of transparency is further elaborated in work from Azzuni & Breyer (2018). Therefore, it is paramount to substantiate index choice in this research, indicator selection, and how it is applied to find results with the framework construction method proposed in the paper from Gasser (2020).

This research will apply the framework developed in the paper from Azzuni & Breyer (2018). The index encloses 15 dimensions in which 76 indicators measure the energy security performance of a country. The index provides a comprehensive approach to finding the energy security scores of countries. However, due to this research's scope and its objective, not all dimensions will be equally relevant for the analysis. In an interview with dr. Azzuni concluded that covering all dimensions would not be possible, given the time constraints of this project. Therefore, the framework was adjusted by removing dimensions that were considered less relevant in this research's scope. This was done with the help of the framework construction method proposed in Gasser's paper (2020). This method is applied in chapter 4 but summarizes in the following steps:

- Framework development allowing explaining the measured phenomena
- Assessment of the framework from Azzuni & Breyer (2018), developing a rationale for leaving out or including dimensions.
- Elaborating on the indicators that were included and explaining why they are relevant to add to the framework.

1.6 Research methods

To tackle the research problem and find a coherent answer to the main research question, different sub-questions were formulated that facilitate all the data and knowledge necessary to solve the research problem. For this reason, different research methods are required that collectively solve the main research question. This section also elaborates on methods used to score the dimensions and individual indicators.

Theoretical framework – literature review (sub-question 1)

The first section aim at delivering more insight into the available theories that help explain how hydrogen as an energy carrier potentially influences Dutch energy security performance. This requires to define the concepts of energy security and explore the different available energy security frameworks. Moreover, potential future hydrogen supply chains and its geotechnical characteristics are explored that can aid in providing future energy scenarios to compare with the reference case and a rationale that links the geotechnical characteristics of hydrogen to energy security.

Hydrogen supply chains and scenarios – desk research/ scenario development (sub-question 2)

The second part of the desk research deals with creating a better understanding of how future hydrogen supply may look and how they relate to the prevailing natural gas supply chain in the Netherlands. From here, desk research provides insight into the different available energy scenarios that incorporate hydrogen in the built environment to some extent. Two hydrogen scenarios are chosen, focusing on domestic hydrogen production and one that is more internationally orientated. Ultimately, energy security performance from the reference case is compared with the results from the scenarios.

Framework operationalization – desk research/ expert interviews (sub-question 3)

For this sub-question, the initial framework from Azzuni & Breyer (2018) needs to be adjusted to be in line with this research's scope and constraints. This is done following the framework construction method, as proposed in Gasser (2020). This is done in chapter 4, leading to the final workable framework. The final framework is validated in an interview with dr. Azzuni.

The data requirements for the reference case are delineated in this chapter as well, for each indicator. The output of the framework resulting from the data inputs is not in the same measuring units. To normalize these values, a reference min-max value is needed. As proposed in Azzuni & Breyer (2020), global values are used to find the energy security performance compared to other countries. Even though the research scope is the Netherlands, giving energy security, a score is difficult without reflecting it on the performance of different nations. Next, normalization is critical to add the different parameters and corresponding weights together into final scoring.

Parameters can positively or negatively contribute to the ES index. The positive parameters are simply added with a positive value. The parameters that affect the index negatively, their value is subtracted from unity (100%). After this, the parameters (Y_j) are multiplied with their weight (W_j) and summed up to form the value for each dimension (X_i). The final step is to sum each dimension's scores with the corresponding dimension weights (V_i), which form the energy security index. The energy security index formula is as follows:

$$\text{Energy Security Index } = \sum_{i=1}^{m} V_i * X_i \tag{1}$$

And for each dimension,

$$\text{Xi } = \sum_{j=1}^{m} W_j * Y_j \tag{2}$$

In the case there is more than one indicator for a given parameter, the following equation is applied

$$\text{Yj } = \frac{\sum_{n=1}^{0} I_{n.Yj}}{n} \tag{3}$$

Where I_n is an indicator that is normalized for the specific parameter Y_j and 0 is the number is indicators. In this analysis, all the parameters are assigned equal weights because there is no evident data available to assign different weight values with any certainty. The same is practiced for the dimensions. Each dimension is weighted equally in the energy security index.

For indicators that are not already in percentages, normalization takes place. This is done with a max-min approach in a linear regression that obtains the percentage of that indicator compared to that indicator's global achievement.

$$I_{n.Yj} = \frac{I_a + I_{min}}{I_{max} - I_{min}} * 100\% \quad (4)$$

With $I_{n.Yj}$ is the normalized indicator, I_{min} is the minimum value of that indicator in the world, I_{max} is the maximum value of that indicator in the world and I_a is the absolute value of that indicator.

For indicators within the 'diversity' dimension, another step is necessary to evaluate each indicator's diversity. The Simpsons Diversity Index is utilized to determine the degree of diversification for energy sources, energy carriers, different technologies, and consumers in the Netherlands. The Simpsons Diversity Index is determined with the following equation:

$$D = \frac{N(N-1)}{\sum n(n-1)} \quad (5)$$

In this equation, *N* represents the total number of either sources, carriers, technologies, or consumers summed up, *n* represents the total amount of one of the types mentioned above, and *D* is the Simpsons Diversity Index score. This score is a number between 0 and 1. The higher the score is, the more diversified that part of the analysis is.

Framework application and result analysis – expert interviews/ case comparison (sub-question 4)

The final sub-question is answered by applying the energy security framework from sub-question 3 to the current Dutch and future energy scenarios. Whereas desk research suffices the data requirements for the current Dutch situation, there is no data available for the indicators given the future energy system scenarios. To study the potential effect of hydrogen on energy security given the boundaries of the energy scenarios, experts in the Dutch energy sector are interviewed. The interviews provide data that is not available in literature, which is the case considering the research field's novelty. Next, the interviews allow the interviewees to record experiences and expectations that proved to be valuable, comparing the results from the scenarios with the reference case.

The results have been analyzed through the thematic analysis method borrowed from the work of (Evans & Lewis, 2018). This method helps to find recurring themes in the interviews and capture the key takeaways in these themes. Considering the dimensions of the energy security framework, this method can extract the key findings for each dimension when considered the themes. Arguments that occurred at least twice were considered as one of the key takeaways for that dimension. This method also enables us to reflect on the personal experiences of the interviewees. The list of interviewees is given below in table 1.

Organization	*Date*	*Dimensions discussed*
Stedin	17-08-20	Costs, Technology & Efficiency, Location, Culture, Policy
Gasunie	18-08-20	Location, Culture, Policy
Enpuls	19-08-20	Costs, Technology & Efficiency, Location, Culture, Environment, Policy
EBN	24-08-20	Costs, Technology & Efficiency, Location, Culture, Environment, Policy
Enexis	26-08-20	Costs, Technology & Efficiency, Location, Culture, Environment, Policy
TNO	27-08-20	Costs, Technology & Efficiency, Location, Culture, Environment, Policy
NVDE	27-08-20	Costs, Technology & Efficiency, Location, Culture, Environment, Policy
LUT Univerisity	17-07-20	Availability, Diversity, Costs, Technology & Efficiency, Location, Timeframe, Resilience, Environment, Health, Culture, Literacy, Employment, Policy, Military, Cyber security

Table 1: List of interviews and discussed topics

The results from both the reference case and two potential future scenarios are compared to each other. The reference case presents the outcomes for the current Dutch energy system, where analysis of the scenarios determines the possible effects of hydrogen on each of the relevant energy security dimensions. The difference between the two scenarios is also further delineated, and a reflection on these differences is presented in the discussion section.

1.7 Thesis overview

The project is carried out by creating an energy security framework based on the existing model by Azzuni & Breuer (2018). An extensive literature review of literature in the field of energy security and energy security of renewables is the first step into shaping the existing framework into a new, more specific framework that fits the Dutch context. This involves an understanding of the energy security concept and how it is portrayed differently across the literature. A definition of energy security is orchestrated that forms the red threat when examining the work from Azzuni & Breyer (2018). To make a specific energy framework for the Netherlands, an understanding of the current heating supply chain and possible future hydrogen supply chains must be delineated. After this, the final energy security framework can be constituted. This framework is applied to the current Dutch energy system to act as a reference case and two future energy system scenarios.

1.7.1 Research phases

The sub research questions support the main research question and form a structured road to answer the main research question. An exploratory research approach characterizes the main research question. The sub-questions can be seen as a sequence of different phases that collectively lead to answering the main research question. The end of each phase, and its corresponding deliverable, logically leads to the next research phase. In figure 3, the research flow diagram (RFD) is presented that gives an overview of the different research phases, methods, and deliverables.

Phase 1 – Information and data gathering

The first phase is the start of the literature review and forms the foundation for the energy security framework and hydrogen characteristics. The first research question is examined in this research question through literature review exploring the different definitions for energy security and the available indices. This research question's sub deliverables are index choice without any adjustments and a narrative that helps to analyse the effects of a novel energy carrier in future energy systems concerning energy security. This is needed to analyse energy systems in the absence of actual data. The first phase's deliverables are still in the generic form and cannot readily be applied to the current Dutch system and future scenario. This second part of the first phase explores the current Dutch heating system and determines realistic future energy system scenarios where hydrogen has a prominent role in the energy system and hence, answer sub-question 2. Through scenario analysis, according to the study from Detz et al. (2019), two future energy scenarios are chosen to analyse in the reflection of the reference case, which is energy security for the current Dutch energy system. Next, this phase establishes an understanding of the hydrogen supply chain characteristics and the geotechnical characteristics of hydrogen as an energy carrier. This will later provide a narrative for exploring how hydrogen affects energy security, given its geotechnical characteristics. The deliverable for the second sub-question is two future energy system scenarios.

Phase 2 – Operationalizing the energy security framework

The deliverables from both sub-question 1 and 2 provide coherent knowledge to narrow down the original energy security index. In this phase, sub-question 3 is answered. Shaping the framework to correspond with the Dutch energy system and time constraints of the research. An interview is conducted with dr. Azzuni himself supporting claims for leaving out specific dimensions and adding parameters/indicators within existing dimensions. The final framework is validated, as well. This sub-question deliverable is a fine-tuned framework that can be applied to the current Dutch energy system and future scenarios.

Phase 3 – Analysing energy security current system and future scenarios

This phase flows out the deliverables of both phases 1 and 2. The final energy security framework can now be applied to analyse the current Dutch energy system and the two possible hydrogen scenarios. The current Dutch energy system is analysed by applying the framework with the individual parameters' actual data. This is done through trusted databases and supplementary material provided by dr. Azzuni. For future energy scenarios, semi-structured interviews are conducted with stakeholders and experts in the field. Questions are formulated for each dimension and its parameters, asking the interviewees their perspective on the effects of hydrogen in the built environment and the consequences for the subsequent indicators. The deliverables for this phase entail the energy security score for the current Dutch energy system and the effects of hydrogen on the individual dimensions (for each scenario) compared to the reference case.

Phase 4 – Analysis of the results and conclusion

This final phase of the research consists of the result analysis and comparing the different scenarios' findings with the reference case of the current Dutch energy system. In this phase, the last sub-question is answered. The discussion section will evaluate the findings and differences in results in light of theory, practical relevance, and covers the framework's limitations and the effects on final results. The discussion will also reflect on how differences between the scenarios and the results, in general, can be explained in light of geotechnical characteristics of hydrogen and hydrogen supply chains.

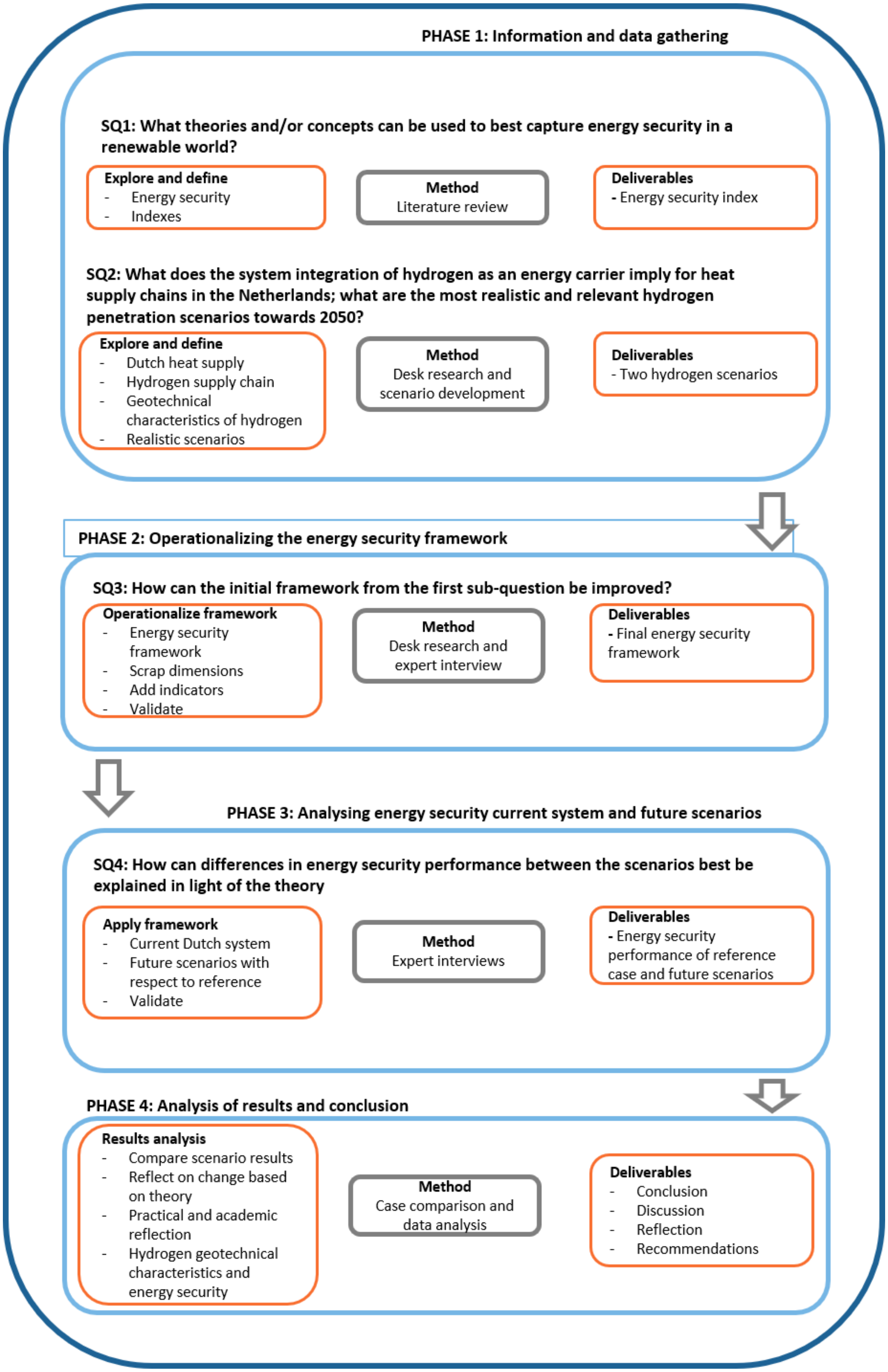
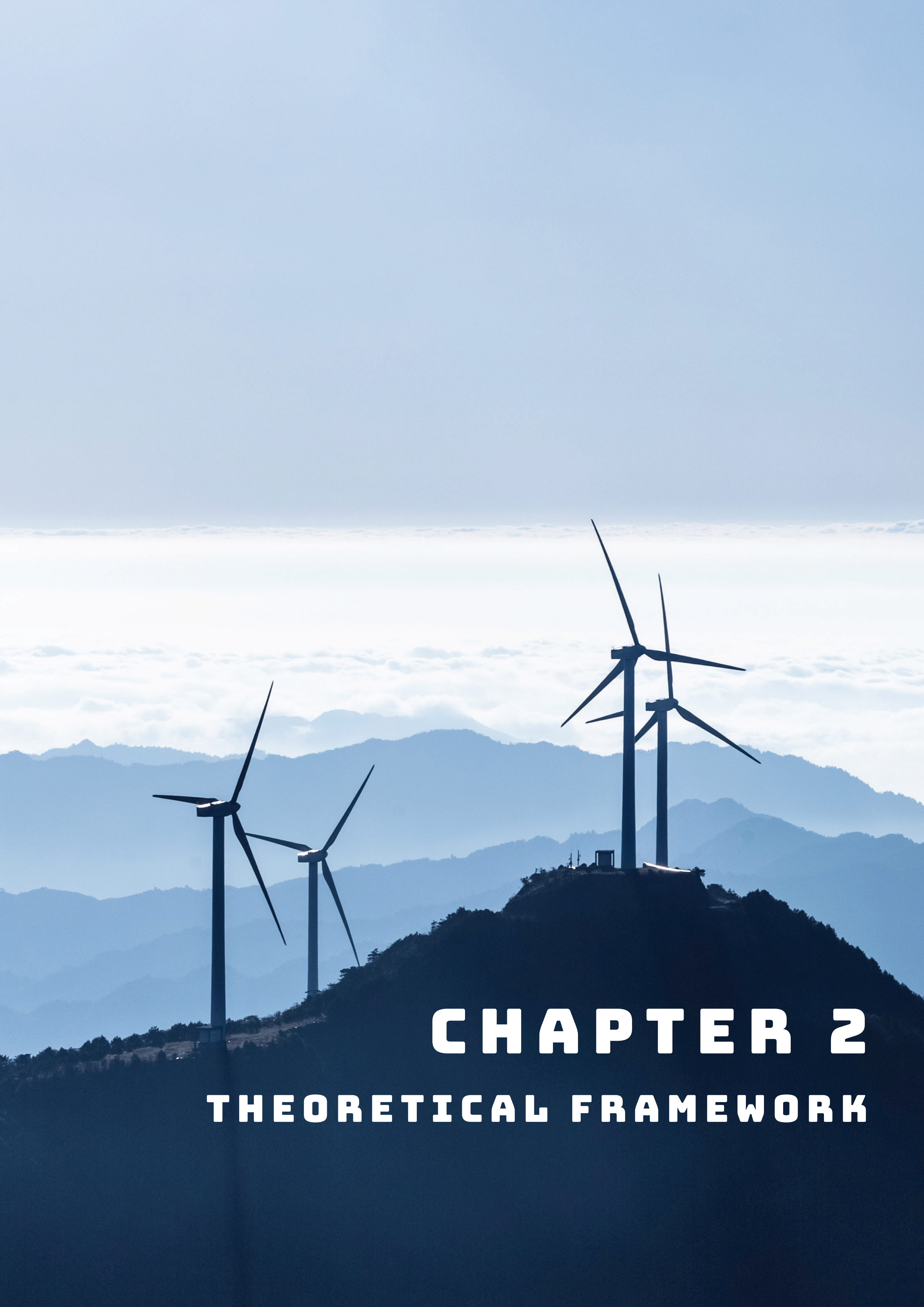


Figure 2: Research flow diagram



CHAPTER 2

THEORETICAL FRAMEWORK

2. Theoretical framework

This chapter intends to find available theories and concepts to make energy security tangible in a renewable world. Doing so, this section aims at answering the first sub-question:

"What theories and/or concepts can be used best to capture energy security in a renewable world?"

The chapter is broken down into smaller sub-sections, each providing insights, and tools necessary for developing a final energy security framework. The first section investigates the currently available energy security frameworks and proposes a new adapted framework. The second section will deal with the implications of energy security, and renewables explain how introducing a new energy carrier in the energy system affects energy security. This final section is crucial to create an understanding of the implications of hydrogen as a renewable energy carrier, its geotechnical characteristics and discusses the gaps in literature.

2.1 Energy security

Energy security is an important policy goal for many countries around the globe. Security of energy supplies is also one of the three pillars of the European energy policy, emphasizing the acknowledged need for action throughout Europe regarding energy security policy (European Commission, 2007). Despite its cruciality in energy policy, the opinion on the concept of energy security is rather dispersed. The terms energy security and security of supply are used interchangeably but signify different concepts. This notion of conceptual irregularities in literature is further stressed in the research of Winzer (2012) and Sovacool & Mukherjee (2011). Conceptualizing energy security also helps to prevent any unnecessary gaps in analysis. This does not mean that this analysis takes all concepts into the equation, which would be unnecessary and unrealistic for the Dutch situation (Sovacool & Mukherjee, 2011). Still, conceptualizing energy security allows for a direct translation to quantifiable measures (Winzer, 2012). As Aristotle seemingly said, 'he who controls the definition controls the debate.'(Azzuni & Breyer, 2018). Therefore, a suitable and overarching definition is obligatory to overcome complexity. Below paragraphs will further distinguish the different possible concepts and intends to find one compelling definition for the Dutch situation in this analysis. Next, the concepts ought to be shaped incorporating renewable energy source and carrier implications. Thus, more recent literature on energy security and its relation to renewables are included. Ultimately, the proposed concept of energy security is aligned with the geopolitical implications of introducing a new energy carrier to the energy system.

2.1.1 Definitions of energy security

As mentioned before, there is no universally agreed-upon definition of energy security (Hughes, 2012; Sovacool & Mukherjee, 2011; Winzer, 2012). As a result, many different frameworks and indicators exist in literature built upon different definitions and dimensions (Ang et al., 2015). Energy security analysis is very case-specific, and depending on the case at hand, different frameworks are applicable. Some scholars tried to develop a more generic framework, suitable in every energy security analysis (Hughes, 2012; Winzer, 2012). No matter the specific situation or type of analysis, different definitions of energy security affect the eventual results when no clear boundary is made before the analysis. Case study research in the work from Winzer (2012) illustrates how defining energy security in different ways affects the analysis results drastically. Hence, energy security needs to be specified before constructing the framework with its specific indicators.

Winzer (2012) performs an extensive review and analysis on the available energy security frameworks up until 2012. The article is peer-reviewed and broadly cited by other scholars proving its use as a global overview of different approaches to analyse energy security. The study from Ang et al. (2015) contributes to previous studies with a comprehensive research including available, indices and definitions of energy security. This stresses the need for an update, including more recent studies on energy security frameworks and corresponding definitions. Hence, literature is reviewed from 2015 onwards that deal with energy security frameworks, indices, definitions, and possible dimensions. The following paragraphs will delineate energy security descriptions in more recent literature and intents to provide a well-defined concept explaining energy security.

The International Energy Agency (IEA) (2019) defines energy security as *"the uninterrupted availability of energy sources at an affordable price."* Within this definition, two sub-types of energy security can be distinguished, long-term, and short-term energy security. Long-term energy security mainly deals with making timely investments in energy technologies to be in line with a nation's economic and social developments. Short-term energy security deals with an energy system's ability to handle sudden changes in supply/demand balance appropriately (IEA, 2019). This is also highlighted in the article by Radovanović et al. (2017) that the short-term approach examines energy security as the system's capability to satisfy the particular's country energy demands, with an absolute focus on security of supply. Another interesting comment in the work from Radovanović et al. (2017) is that creating a unique methodology applicable to all countries is not possible.

In contrast to the studies by Hughes (2012) and Winzer (2012) that explore possible frameworks applicable to every energy security analysis. However, the remark that defining energy security itself is bound to challenges, so that corrections or changes in the field implies new definitions throughout the future (Radovanović et al., 2017). These challenges are expressed by each country's different mix of energy resources, distinctive historical, political, and social specifications and that each country adopts different future energy plans. This expresses the need for a country-specific definition of energy security to avoid misunderstanding and a non-inclusive energy security definition. Nevertheless, definitions of energy security proposed in literature imaginably become outdated and correspond with current strategy or policy from the country to be analysed (Radovanović et al., 2017).

A more recent study from Azzuni & Breyer (2018) points out the problem described above. A clear definition of energy security is critical, mainly as energy security is more of a concept than a strategy or policy. They also argued that measuring or improving energy security requires a clear understanding of energy security perception. Moreover, the definition is highly contextual and of polysemic nature, which is in line with other authors (Azzuni & Breyer, 2018; Radovanović et al., 2017; Winzer, 2012). Another interesting argument in Azzuni & Breyer (2018) is that energy security should include the whole supply chain of energy systems. Hence, a comprehensive definition involves supply, demand, and energy transfer. This contrasts with other authors and institutions that define energy security only as security of supply, using the terms interchangeably (Ang et al., 2015; European Commission, 2007). The United Nations Development Program (2004) also argues that energy security should include all parts of the energy system. The notion of including both supply and demand is also accounted for in a study by Bompard et al. (2017). They underline the idea that a country's security in terms of energy not only depends on the possible energy imports (supply side) but is also determined by the flexibility of the end-users (demand-side).

There is much misconception between energy security and security of supply. Some authors argue that it is paramount to include the complete energy supply chain in energy security analyses, focusing more on the supply's energy security. The main reason for this misconception is that authors do not fully identify the actual energy supply implication. Löschel et al. (2010) interchangeably use 'security of energy supply' and 'energy security' but fail to distinguish importing security or consumer supply security. This ambiguity is reflected in their approach to conceptual irregularities, where it becomes apparent that energy security and security of energy supply both only deal with energy imports. This concept of different perspectives is stressed in the work of Jakstas (2019). Here, the definition of energy security is in line with the subject using the concept and to what end. Three perspectives are delineated: importer, exporter, and the perspective as a transit country. This is in line with the previous paragraph's arguments but expands by arguing that energy security should cover the full supply chain of energy systems. Again, there is no correct definition. Energy security is highly context-dependent. That implies that scholars ought to delineate the country's specific context and intent to define energy security appropriately.

2.1.2 Defining energy security

Energy security consists of two words: 'energy' and 'security.' In physics, energy can be defined as a measurement of something's ability to do work. It is paramount to understand that energy is not material but can be measured and stored in many different forms. Moreover, energy consumption is somewhat arbitrary, while energy is never really consumed but transferred from one form to another, doing work in this process. Energy can exist in many different forms; all of them are either kinetic or potential. Energy can be stored in both motion and position. 'Security' can be defined as something that is not likely to fail or be lost. Combining the terms defines energy security as the measurement of the ability of something to do work that is not likely to fail or be lost. Based on the research scope, the above definitions, and the objective to quantify energy security for the Netherlands, the definition of energy security in this research is the following: *"A sustainable supply of energy that is not likely to fail in any of its relevant dimensions."* A higher level of energy security indicates a lower possibility of system failures and vice versa. In this definition, a system failure is described as one where energy supply is interrupted for either a short or long time. This definition is used when examining the reference case and possible influences of hydrogen on the Netherlands' energy security.

2.2 Energy security dimensions

Previous work on energy security dimensions has uncovered up to 15 different dimensions (Ang et al., 2015; Azzuni & Breyer, 2018; Sovacool & Mukherjee, 2011). Just as for the definition of energy security, there is no generally accepted combination of dimensions. Again, dimensions of energy security are highly contextual and tend to evolve over the years (Azzuni & Breyer, 2018). The way these dimensions and indicators are selected affects the evaluation significantly. This fundamentally divides literature into those who aggregate a specific number of indicators and those who do not (Valdés, 2018). When it comes to energy security dimensions, there are two camps of research. The first one focuses on the core dimensions or aspects of energy security, including economic and security of supply. The other camp extends the concept into a more multidimensional perspective. Ang et al. (2015) have attempted to create an overview of the different literature dimensions and indicators. The concepts of energy security change over the years, and in literature, the ambiguity of energy security dimensions is instead projected than giving clear implications on what dimensions or indicators cover energy security to the full extend. However, other literature does present different approaches to how scholars ought to address energy security to provide a complete analysis. Azzuni & Breyer (2018) argue that every dimension that has a relationship with energy security should be addressed based on Yergin (2006) argument that the 'energy security discussion should be expanded to include more dimensions because the energy security challenges are heterogeneous.' There is a need for a holistic overview that is detailed enough for all individual countries but within its global context (Azzuni & Breyer, 2020). This statement devised 15 all-inclusive energy security dimensions: Availability, Diversity, Cost, Technology and Efficiency, Location, Timeframe, Resilience, Environment, Health, Culture, Literacy, Employment, Policy, Military, and Cyber Security (Azzuni & Breyer, 2018). These dimensions are operationalized in a recent study from the same scholars, further develop prior research by applying the dimensions as a novel energy security index. This recent paper by Azzuni & Breyer (2020) intends to analyse energy security with an energy security index that comprises sustainable development of the analysed energy system. The novel energy security index building upon the 15 energy security dimensions is the most recent approach to analysing energy security for any given country. However, literature presents different approaches with distinctive reasoning for analysing national, continental, or global energy security. This emphasizes the complexity and contextuality of energy security analysis.

2.3 Energy security indices

Different energy security indices or composite indicators are applied throughout literature. One review from Ang et al. (2015) offers a comprehensive overview of the available energy security indices. An updated overview is presented by Gasser (2020), including 63 different indices found by combining studies by Ang et al. (2015), Valdés (2018), Apergis et al. (2015), and Bandura (2008). The index devised by Azzuni & Breyer (2020) is missing because this study is conducted more recently. These different indices are built from individual indicators that collectively form an overall score. This is possible through instruments of Multi-Criteria Decision Analysis (MCDA) methods and allows exhibiting the performance of energy security for a specific given situation. The number of individual indicators differs throughout the 64 indices. Multiple indicators are necessary to address the different dimensions. The selection of indicators is, obviously, dependent on the scope of the study (Gasser, 2020). This enforces the arguments made previously about the contextuality and polysemic nature of energy security (Radovanović et al., 2017). This contrasts with the claim that energy security assessments should address all the dimensions that have a relationship with energy security (Azzuni & Breyer, 2018). However, previous sections in this chapter have substantiated why energy security analyses are bound to contextuality and, hence, each specific situation can be approached differently (Hughes, 2012; Radovanović et al., 2017; Winzer, 2012). It is not surprising that the distinct indices measuring energy security have heterogeneous indicator sets. This inconsistency can be explained by the fact that each country has different shares of energy sources, political systems, geographical locations, economic welfare, and international relations (Gasser, 2020; Radovanović et al., 2017). Ang et al. (2015) point out that selecting these indicators can be somewhat arbitrary. The selection criteria are usually not well explained and transparent (Månsson et al., 2014). Nevertheless, there are methods accessible to minimize subjectivity, including (Gasser, 2020):

- *Stakeholder involvement*: collecting the preferences of stakeholders through expert interviews, questionnaires, or surveys
- *Indicator assessments and literature review*: the first set of indicators could be developed through literature review. Then, each indicator should only be retained if it qualifies according to specific selection criteria. Foxon et al. (2002) identified such criteria:
    1. Comprehensiveness: Is the indicator relevant enough to measure the phenomenon?
    2. Applicability: Is the indicator applies to all countries?

3. Tractability: Is sufficient and reliable data available to quantify the indicator
4. Transparency: Are the reasons for selecting the indicator transparent?
5. Practicability: Does the indicator set fulfill the purpose of the decisions to be assessed?

The more recent index developed by Azzuni & Breyer (2020) emphasizes the lack of transparency and selection criteria considering selecting indicators in literature. Their criteria are the following for numerical indicators:

- Data used from trusted sources;
- Indicator values are available for all countries in the world or at least most of them;
- Close proxy parameters;
- Indicator values can be in absolute or relative numbers;
- Normalisation should be possible for energy security analysis;
- Availability for current and future scenarios;
- Accounting for sustainability as much as possible.

Their resolution is different from the criteria proposed by Foxon et al. (2002) and focusses on numerical indicators and not so much on the complex indicators that rely more on adding quantitative indicators in a single score (Månsson et al., 2014). Another tool that supports decision-making is multi-criteria analysis. Experts use pairwise evaluation of various aspects, scenarios, or policies and rank them based on a pre-determined criterion. Lee et al. (2009) used multi-criteria analysis to prioritize different energy technologies when the oil prices are high.

The selection of indicators remains arbitrary. There are two sides to this story, starting with the scholars favouring all indicators related to energy security in an analysis. However, many of these indices are not as specific and examine energy security in a continental or global context. Secondly, other scholars explain energy security analysis to be contextual and depending on the study's scope, consequently shaping the choice of indicators required for analysis. Concluding, depending on the scope of the research, different approaches are suitable for analysis. A more holistic energy security analysis that compares different countries across the world necessitates using all indicators related to energy security, ensuring a complete and thorough overview. More specific cases might require a different approach and a more constrained set of indicators given the research's scope.

2.4 Choosing an energy security index

The following section intends to define a comprehensive energy security index applicable to this specific research scope. This section does not intend to create a novel index but develop a workable framework based on popular and recent energy security literature. Several studies stand out, providing a comprehensive overview of the different available indices and their implications, as has been demonstrated in section 2.3 (Ang et al., 2015; Azzuni & Breyer, 2018; Gasser, 2020; Hughes, 2012; Radovanović et al., 2017; Sovacool & Mukherjee, 2011; Winzer, 2012). A complete, comprehensive, and holistic overview is required to formulate a substantiated index that fits this research. This means that the initial framework is subject to change once interviews with experts in the field are conducted. Their expertise will provide insights for complex indicators and help understand the Dutch energy security situation in the given context. Next, the choice indicators should be in line with the adopted definition of energy security in this study. Arguments for different approaches to developing an energy security index have been demonstrated in section 2.3. However, as has been demonstrated, there is no perfect approach to formulate an energy security index. The opinions on how this should be performed are divergent leaving room for contextuality and own interpretations. As was demonstrated by Ang et al. (2015), many different approaches exist in literature with different dimensions or aspects based on the authors' interest.

Azzuni & Breyer (2018) made a crucial comment that should apply for every energy security analysis: "Any dimension or parameter that has a relationship with energy security should be addressed." This statement proposes 15 different energy security dimensions that develop in one comprehensive and holistic analysis. Incorporating all possible dimensions eliminates the risk for misconceptions and allows for a substantiated energy security analysis. Arguably, not all dimensions share the same degree of relatedness to energy security, and this depends on the country, research scope, and time frame (Azzuni & Breyer, 2018; Radovanović et al., 2017). For this study, it is valued to provide a comprehensive and holistic energy security analysis. Therefore, for the sake of this study, the energy security dimensions adapted from Azzuni & Breyer (2018) are used to analyse energy security. Arguments for what dimensions and indicators are used for analysis are delineated in section 4.1. Here, insights from the interview with dr. Azzuni and desk research will give substantiated arguments for choices in designing the eventual framework. The table below will delineate all the different dimensions and corresponding parameters:

Dimensions	Parameters
Availability	Existence of resources
	Existence of consumers
	Existence of means of transport (access)
Diversity	Diversity of sources
	Diversity of fuel (energy carriers)
	Diversity of means (technologies, transportation)
	Diversity of consumers
Cost	Energy prices (consumers, producers, pricing system/subsidies, energy poverty, peak oil, and stability/volatility
	Cost of disruption
	Cost of securing the system
Technology and efficiency	New technology advancement
	Energy system efficiency
	Energy intensity
	Energy conservation
Location	Energy systems boundaries
	Location of energy storage
	Density factor
	Land use
	Globalization
	Industrial intensity
Timeframe	Timeline
	Length of the event
	Length of the effect (struggle or impact)
Resilience	Adaptive capacity
Environment	Exploration rate and resources' location
	Extraction and transportation methods
	Outcomes from energy use
	Impact resulting from environmental change
	Relationship to water

Health	Impact of people's health on the energy system Impact of the energy system on health of (energy sector workers, consumers, and international society)
Culture	Cultural effect on the energy system [production, connection, consumption, cultural acceptance (NIMBY, Not In My Back Yard)] Energy conditions shaping cultural aspects
Literacy	Information availability (quality, market information, public awareness, and structured educational program) Information presentation and provision Usage of energy information
Employment	Effect of energy security on unemployment rate Effect of employment rate on energy security
Policy	Political system, democracy/dictatorship (nature, stability, citizen's will, and internal and external relationship) Regulations (liberalized and controlled market, rules, subsidies) Governance (flowing the rules (transparency), following the rules selectively, not following the rules, corruption)
Military	Energy use for military purposes Militarization Energy as a mean in a military conflict (energy weapon) Destabilization factor (resource curse, environmental deterioration, and economies of violence)
Cyber security	Connectivity (Cyberattacks) Software use (Supervisory control and data acquisition, SCADA, program failures)

Table 2: Summary of the proposed energy security dimensions and parameters adapted from Azzuni & Breyer (2018).

The following next step is to examine the implications of energy security in a renewable world. More interesting will be to understand how hydrogen affects specific dimensions when integrated into the energy system for heating demand in the built environment. Before operationalizing the framework within the given scope of the research, there is a need to delineate the Dutch current heating system and compare this with a potential future heating supply chain that incorporates hydrogen. From here, substantiated choices are made, resulting in a comprehensive and realistic framework.

2.5 Energy security in a renewable world

In the years to follow, energy systems will gradually shift towards a more diversified renewable energy system. One of many reasons is the stringent climate action countries should undertake after signing the Paris agreement in 2015 (United Nations, 2015). The complicated relationship between climate change and energy security was primarily based on simplified indicators such as fuel mix diversity and import dependence. However, as a consequence, the trade-offs and synergies between energy security policy and climate change have not been explored in the broader context of the concept (Gracceva & Zeniewski, 2014). As delineated in the section before, most literature examines the effects of energy security indicators on renewable energy deployment using import dependence on other countries as a significant proxy for renewable energy implications for energy security (Valdés Lucas et al., 2016). The same paper criticizes this argument and suggests that the relationship between RES and energy security policies is twofold. First, the chosen energy security strategy and how this strategy is brought to live given the different energy security conceptualization. The result of this twofold relationship has significant implications for RES deployment. It is argued that RES deployment is a result of combining energy security strategies that include environmental concerns rather than it is pushed from governmental energy policies. (Valdés Lucas et al., 2016).

According to the IEA, RES can reduce dependence on energy imports. The role of renewable energies in energy security is substantial and can contribute positively while meeting environmental objectives. This is the same argument made in most of the literature reviewed in the paper from Gracceva & Zeniewski (2014). However, the IEA report is from 2007, which indicates the need to update energy security, incorporating RES and their implications (Ölz et al., 2007). Besides, this argument is refuted in the paper from Hache (2018) that discusses the appearance of possible new interdependencies such as critical materials, technological knowledge, and superiority and the implementation of renewable diplomacy. A strong favour for integrating renewable energies in the energy and the electric mix has emerged in the past decades to improve energy security and combat climate change. Implementing these novel renewable energies is all the more relevant since this allows the state to profit from double dividends as their diffusion reduces the import of fossil fuels (Hache, 2018).

Renewable energies have a complex relationship with energy security. The 2030 Climate and energy framework sets three main targets: research for energy efficiency and mastering the energy demand, diversifying energy provision, and reaching independence by increasing RES and combating climate change. Keeping these three targets in mind and assuming massive integration of RES demands reshaping the relationships between producers, consumers, and transit countries. Indeed, RES brings diversification to the system, and their geographic concentration is moderately low. However, RES potentially creates new dependencies where it is commonly acknowledged that a more diversified energy system possibly ends today's geopolitical fossil fuel-based relationships, new challenges could paradoxically be as complex as today's challenges (Hache, 2018). A shift towards a more renewable energy system is inevitable; hence, insight must deal with the new interdependencies that these systems might bring.

Moreover, complex geopolitical changes imply that energy security is an integral part of national security and should be considered as such (Radovanović et al., 2017). This implies a strong relationship between energy security and renewables' geopolitics when examining a renewable energy system. These geopolitical implications remain somewhat ambiguous (Hache, 2018; Paltsev, 2016; Scholten & Bosman, 2016). The following section will further explore this relationship in more detail.

2.5.1 Geopolitics and energy security

All of the covered energy security indexes in Gasser (2020) and the recent index of Azzuni & Breyer (2018) are built on the traditional energy system's premises. Analysing countries' energy security with these indexes is based on the data currently available, data from the traditional fossil fuel system. These systems have different geopolitical implications than those of possible future energy systems (Scholten, 2018). It is apparent in literature that classic energy security assessments are performed from the perspective of oil and gas geopolitics, more specifically, geographic location and international relations (Bradshaw, 2009; Correljé & van der Linde, 2006). In the paper from Bradshaw (2009), global energy security geopolitics are examined and defines this as the influence of geographic factors, production location, and energy demand. He argues that there is a need to rethink the geopolitics of energy security to include the interests of both new importing and exporting states and incorporate the challenge of climate change. This means that energy security assessments are primarily based on fossil fuel energy systems' geotechnical characteristics biases. Therefore, work such as that of Scholten (2018), Hache (2018), and Valdés Lucas et al. (2016) is paramount to assess the energy security of future energy systems.

Future energy systems include renewable energy sources, a different mix of energy carriers, new energy exporters, and new dependencies, as was delineated in previous sections. These novel energy systems have other geopolitical implications than the traditional energy system. Whereas current energy security analyses are based on existing data based on the geotechnical characteristics of fossil fuels, an assessment of potential future energy systems requires rethinking the geotechnical characteristics of the energy sources and carriers of those systems. To understand possible changes in a country's energy security landscape, one must first understand the geotechnical differences between the current system and potential future energy systems. Therefore, the following sections will delve into the geotechnical characteristics of renewable energy systems and the implications of novel energy carriers such as hydrogen.

2.6 The geopolitics of renewables: a complex relationship with energy security

To assess the geopolitical implications of a new renewable energy carrier in the system, there is a need to create an overview of renewables' technical and geographical characteristics. An overview of this kind links these characteristics to security notions applied in energy geopolitics literature (Scholten, 2018). There are 11 most commonly used methods when measuring energy security, which can be divided into two groups: measurement based on the aggregation of different indicators or based on security of supply (Radovanović et al., 2018). The association with energy security is also treated in the article from Hache (2018), where a new renewable geopolitical regime might be just as problematic due to other dependencies like energy flows and critical materials. The change in geopolitical connections is a dynamic process across the modern world and at an accelerated pace. Therefore, monitoring the different factors that affect these changes is of utter importance (Radovanović et al., 2018). This suggests utilizing an energy security index with a given set of indicators. A comprehensive overview of the system and its geographical and technical characteristics are necessary to explain what factors are causing changes in the given set of indicators when the energy system changes over time.

The framework proposed in the paper from Scholten (2018) systematically investigates the geopolitics of renewable energy systems. The first step in this framework deals with renewable energy systems' geotechnical features from a sources, generation, and distribution point of view. These characteristics are the most apparent of renewable energy systems at this moment and can be considered critical factors in shaping a future energy system and energy market (Scholten & Bosman, 2013).

The previous section discussed how RES substantially could improve energy security in the long run. However, there is a need to discuss and examine the degree to which RES can exacerbate new risks and geopolitical tension related to critical materials and flow dependency of renewable energies (Vakulchuk et al., 2020). Moreover, most authors do not separate the different RES and their associated risks to geopolitics compared with the prevailing fossil fuel energy systems. The geopolitics of renewables must be incorporated in the analysis considering energy security of a renewable energy system because it is impossible to create a unique methodology that applies to all countries. Each country has different resources, wealth, economic growth, climate conditions, and the likes (Radovanović et al., 2017).

Next to discussing the geotechnical features of renewable energy systems, the economic impact that renewable energy systems have should be considered (Hache, 2018; Scholten, 2018). The decrease in energy imports potentially creates double dividends for nations. Moreover, within the economic dimensions of renewable energy geopolitics, there is room for examining shifting trade patterns and dependencies compared to current affairs (Hache, 2018; Paltsev, 2016; Scholten, 2018; Vakulchuk et al., 2020).

2.6.1 Geographical and technical features of renewable energy systems

The first step in delineating renewable energy systems' geopolitical implications is to understand its geographical and technical characteristics. These relate to sources, distribution, and generation. Renewable energy sources are different from traditional fossil fuel resources because their availability across the world is less geographically constrained. This does not mean that each country is given the same potential as renewable energy. Thus, countries with a higher potential for renewable energy can produce energy more efficiently than nations that are less endowed. Nevertheless, the different renewable energy sources have differing potential (Scholten & Bosman, 2016). Second, many renewable energy sources are bound to intermittency. The consequence is that these energy sources are not available on demand but dependent on weather conditions. The results are unpredictable fluctuations, although predictions are getting more precise. Supply fluctuations are now added to the system; hence, the energy market experiences a shift from demand-driven to supply-driven.

When looking at renewable energy generation, several other vital factors are crucial when analysing the renewable energy system. First, renewable energy technology suggests a more distributed energy system. The units of generation are generally smaller than conventional plants. Even so, land and/or roof owners can become energy producers that increase the self-sufficiency of countries. Another factor considers the technology that is used to generate renewable energy. This determines material requirements of which some demand rare earth materials. This can result in a shift in dependencies for some counties, as the figure below indicates (Hache, 2018). For this reason, net exporters of fossil fuel, in general, are perceived as losers of the energy transition (Scholten, 2018).

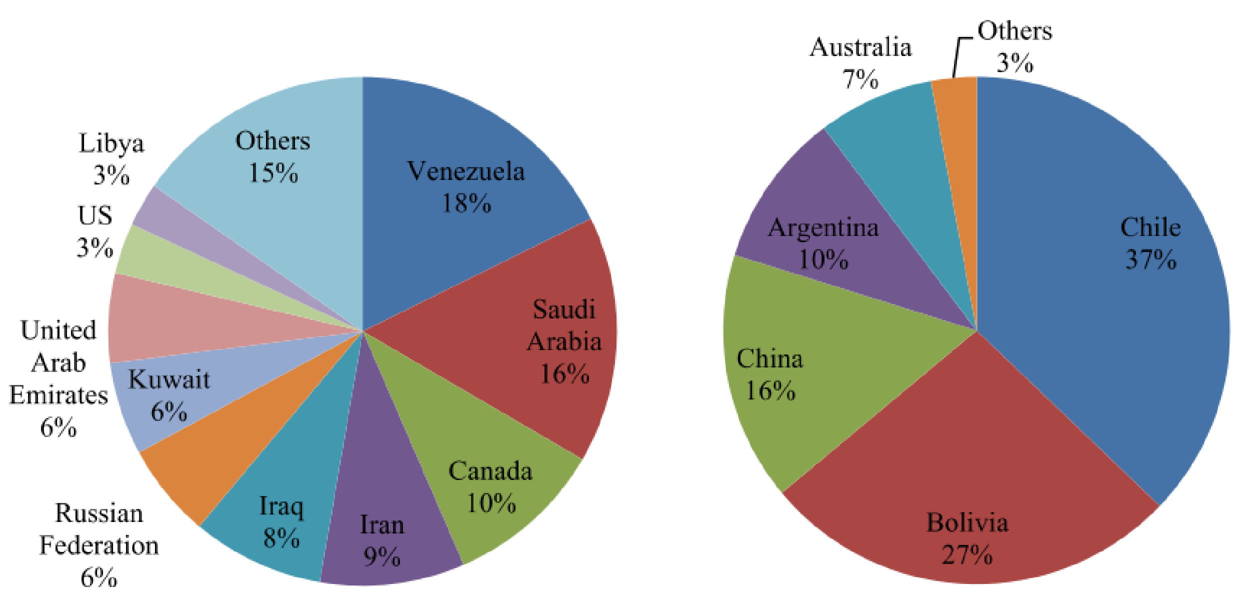


Figure 3: Oil reserves by country (left figure), lithium reserves by country (right figure) in 2016 (Hache, 2018).

Critical metals are essential to the energy transition and can be found in numerous decarbonization technologies. For fuel cells, platinum, palladium, and rhodium are required and cannot be mined in the

Netherlands. All three metals are mined mainly in South Africa, and just as other metals used for innovations in the energy transition, these materials are co-products from other mining activities. This means that the extraction of these required materials is dependent on the extraction of other metals (Hache, 2018). Overland (2019) argues that it is possible that prices for some critical materials will be high, generate high costs for importing countries, and revenues for exporting countries and that some of these materials are securitized. However, this does not imply that a geopolitical rally over control of these materials is inevitable. Next to critical materials, the primary resource for green hydrogen production is freshwater. Large-scale green hydrogen production can potentially compete with fresh water in that area and increase the country's water stress (van de Graaf et al., 2020).

Distribution of renewable energy deals with energy carriers in future renewable energy systems, making this an essential aspect of analysis. The dominant energy carrier in these systems is expected to be electricity since the energy sources with the most potential are most conveniently converted to electricity. This has significant consequences for the energy system. Due to distribution losses, the grid size is limited. An electricity grid implies a connection between producer and consumer, unlike the fossil supply chain facets. Additionally, electricity grids require on the spot management to cope with accidents. While various storage options exist, their efficiency needs improvement (Scholten & Bosman, 2016).

The article by Scholten & Bosman (2016) follows-up with the idea that a future renewable energy system will utilize electricity as its primary energy carrier. The notion of a renewable energy system with electricity as its dominant energy carrier is a recurring phenomenon throughout literature and, more interestingly, hydrogen literature (Detz et al., 2019; Dodds et al., 2015; Quarton et al., 2019; Samsatli & Samsatli, 2019). However, renewable gases are lesser endowed in literature, whereas their role in the transition towards a renewable energy system indispensable (Gasunie & TenneT, 2019).

Finally, to better evaluate the implications of renewable gases in the energy system, one must examine the energy market structure of renewables. This helps developing an initial idea of how the market dynamics when renewable energy sources are implemented on a large scale. Expert interviews and scenario analysis are necessary to understand what this implies when hydrogen is the second dominant energy carrier in the system. Examining the market structure of renewable has four significant implications, according to Scholten & Bosman (2016):

1. The relation between producer and consumer countries changes due to the abundance of renewable energy sources. One can assume that more countries become energy producers when they can efficiently harvest energy from renewable sources. This contrasts with the current situation of oil/gas geopolitics that is highly driven by geography. The results of this shift are more potential energy producers in the market; production now shifts to the countries that can most efficiently harvest renewable energy and, countries now face a make or buy decision, which means that some countries might opt for importing cheaper electricity across the border. This first implication is of great importance for the Dutch context due to its potential unique placing in future renewable energy markets (Kester, 2017; Government Strategy on Hydrogen, 2020).
2. The second implication deals with how the size of the grid constrains energy markets. In an energy system with electricity as its dominant energy carrier, producers and consumers are tightly connected through an electrical infrastructure. Greater transport distances equal higher losses, and so, one can expect renewable energy markets to span countries or continents but are not likely to be global

because of the technical characteristics of electricity transport. Introducing an energy carrier like hydrogen, which allows for storage and transport over higher distances, is a compelling means for opening these markets. Hence, a more in-depth discussion on choices within this implication for the Dutch situation is necessary.

3. Electricity is the dominant energy carrier in the system, accommodating producing electricity centrally or decentral. The difference is that the former relies on existing producers and grid operators, and the latter empowers households and communities to produce electricity and manage their distribution networks, improving self-sufficiency. This choice of capacity dispersion adds to the strategic awareness of the make and buy decision.
4. The variability of renewable energy generation is highly likely to cause more volatile electricity prices. Storage is needed to create stable energy markets. Scholten & Bosman (2016) mention the future emphasis on flexible demand but do not go more in-depth into storage possibilities and its implications. Therefore, the framework needs to be adapted and incorporate storage possibilities into this fifth implication for renewable energy markets. There is compelling evidence that hydrogen can play an essential part as a storage option for seasonal surpluses of renewable energy and provide security of supply and stability to the energy system (Detz et al., 2019).

The paper from Scholten 2018 offers an exciting approach towards defining the renewable energy system's geotechnical characteristics. This approach can be borrowed to examine the geotechnical characteristics of hydrogen. This independent variable relates to sources, generation, and distribution. These three aspects can also be used to examine the supply chain in chapter 3.

Sources examine their geographic location, variability/stability, and total potential to meet energy demand. It is of interest to examine the incumbent renewable energy technology, its central/decentral nature, site location, and material requirements for generation. Distribution in this approach can be operationalized as the operating systems, network topology and technology, and the storage means (Scholten, 2018). These aspects will be further explored in chapter 3, looking at the current system and future system's supply chains and possible hydrogen scenarios.

2.6.2 A novel renewable energy carrier; hydrogen

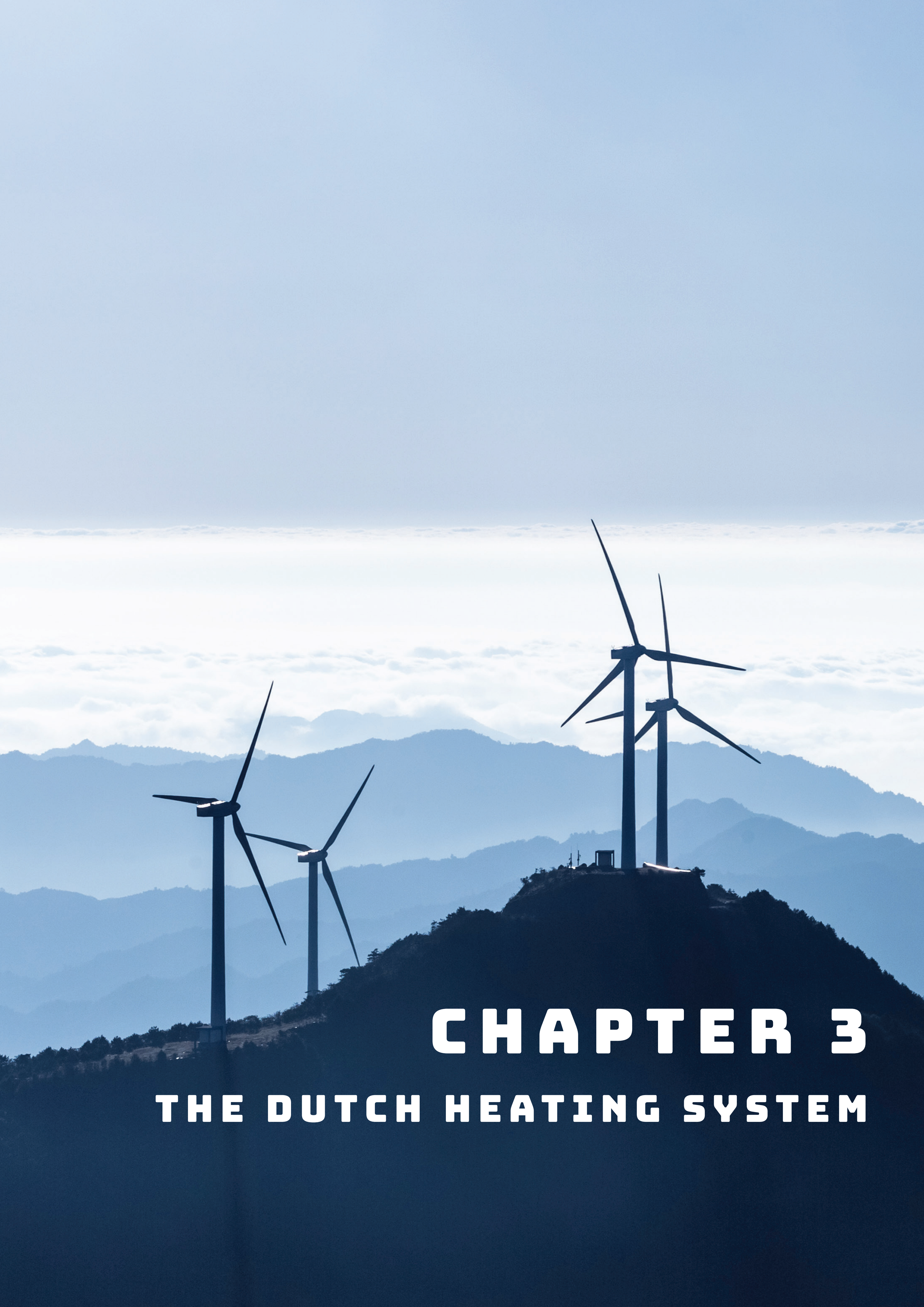
Previous sections attempt to illustrate how hydrogen as a novel renewable energy carrier for heating in the built environment affects energy security. This is done based on section 2.6 and the energy security dimensions delineated in section 2.4. This discussion supports analysing the results and gives coherent material for debate in the discussion. These expectations provide guidance for analysing future results from the interviews but should never lead and push results in a predetermined direction.

Introducing hydrogen in the heating supply chain several implications. From the availability perspective, green hydrogen from electrolysis and biomass gasification most effectively enhance availability (Ren et al., 2014). Looking at availability and access to consumers, dedicated pipelines for hydrogen have been in place for years. Transporting hydrogen through the existing gas infrastructure is being explored and could be possible with small adjustments to the existing grid. This would hamper investment needs for a new hydrogen infrastructure in the Netherlands considering its enormous gas infrastructure on an economic scale. Countries with significant natural gas infrastructure have the means to leverage these pipelines for hydrogen and act as sizeable low-cost storage capacity (IRENA, 2019; van de Graaf et al., 2020). Next, hydrogen transport via pipelines is economically more efficient than electricity transport and includes inherent storage. However, infrastructure costs for a hydrogen supply chain are costly for countries without an extensive gas grid like the Netherlands or for countries without a close geographic proximity. Next to this, hydrogen storage makes it nearly impossible for importers to get trapped in a small cartel of suppliers or for exporters to 'weaponize' hydrogen trade. Still, hydrogen trade will not be as reciprocal as electricity trade that allows electrons two move both ways. However, international hydrogen trade will improve the energy security of importers since it can aid in backing-up the electricity system (van de Graaf et al., 2020).

Large scale hydrogen integration diversifies the energy system as well. This is because hydrogen is versatile in terms of supply and use. However, as renewable gas, dependencies will shift towards countries that harvest the required rare earth materials for the technology.

The previous section demonstrated the implications of renewable energy systems on energy security from a geopolitical perspective. This was done through a funnel approach, where the broader concept of renewable energy systems is further specified into their geotechnical characteristics and implications for energy markets. Moreover, renewable gases are indispensable during the energy transition. However, their implications as renewable energy carriers on national energy security remain underdeveloped. Mostly, going deeper into the spectrum of renewable gases, hydrogen's effects on energy security remain ambiguous, given existing literature. Hydrogen can help combat critical challenges that deal with the energy transition and strengthen energy security (IRENA, 2019). These sections on energy security of renewables and geopolitics aids in pinpointing how hydrogen can positively or negatively contribute to energy security.

The next section focuses on operationalizing the previous chapter's theoretical notions into one coherent, workable framework. It is critical to adapt its implications according to the research scope and Dutch situation.



CHAPTER 3

THE DUTCH HEATING SYSTEM

3. The Dutch heating system

The current Dutch heating system will change considerably with large scale integration hydrogen in the energy system. This chapter reviewed the Dutch heating system and possible future setting in the perspective of energy sources, generation and distribution. Renewable energy is available abundantly and practically free from geographical constraints and allows for hydrogen production everywhere in the world. The heating system is affected the most from a sources perspective considering a potential future hydrogen heating supply chain. There are many different scenarios and visions available in literature, of which two stand out. These scenarios replace natural gas with hydrogen, one examining an energy autonomous Dutch energy system and one that is internationally orientated with major energy imports. The background of the Dutch heating system and potential future energy scenarios help formulating the final energy security framework. Ultimately, the framework is applied on both current system and both energy scenarios.

This section aims at answering sub-question 2:

"What does the system integration of hydrogen as an energy carrier imply for heat supply chains in the Netherlands; what are the most realistic and relevant hydrogen penetration scenarios towards 2050?"

Synthesis towards a final, workable framework requires an understanding of a new energy carrier's implications in the future energy system. Hence, this section forms the basis for selecting indicators for the energy security analysis (Ang et al., 2015; Azzuni & Breyer, 2018, 2020; Scholten, 2018; Sovacool & Mukherjee, 2011). Before this is possible, the current Dutch heating system must be delineated to reflect upon and understand the major differences of both current and potential future systems with large-scale hydrogen implementation. The Dutch heating system is dissected into three workable parts that fully cover the system at hand. First, energy sources for heating are discussed, then generation pathways, and finally, the distribution is highlighted. This structure is adapted for both the current system and the potential future system. The future Dutch heating system is based on the scenario's from TKI Nieuw Gas and the TNO report dealing with the future role of hydrogen in the Dutch energy system. These insights are reflected in the findings presented in the Infrastructure Outlook 2050 from Gasunie and TenneT (Detz et al., 2019; Gasunie & TenneT, 2019; Gigler & Weeda, 2018). The final deliverable of this chapter is two future energy system scenarios. At the end of this chapter, a clear explanation of the scenarios' exact role for analysis is explained in more detail.

3.1 The current Dutch heating supply chain

3.1.1 Sources

The Netherlands makes an interesting case when examining its heating system. Based on historical energy policy choices, households in the Netherlands overwhelmingly utilize natural gas for heating demands. This development also led to the vast natural gas infrastructure the Netherlands possesses.

Figure 4 represents the different gas fields that are available in the Netherlands. Figures 5 and 6 represent the total energy demand in the residential sector and indicate it is, for large part, satisfied by natural gas (71%). Electricity makes up 21% of this total demand, with the final 8% consisting of district heat, renewable energy, and solid fuels (IEA, 2018; Kreijkes, 2017).

Figure 4: Dutch gas fields. Source: milieudefensie

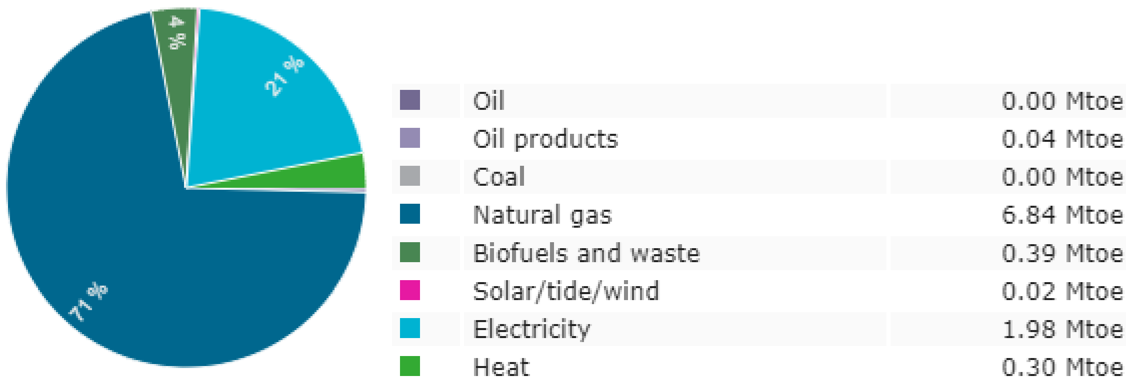


Figure 5: Dutch residential energy consumption by fuel (IEA, 2017).

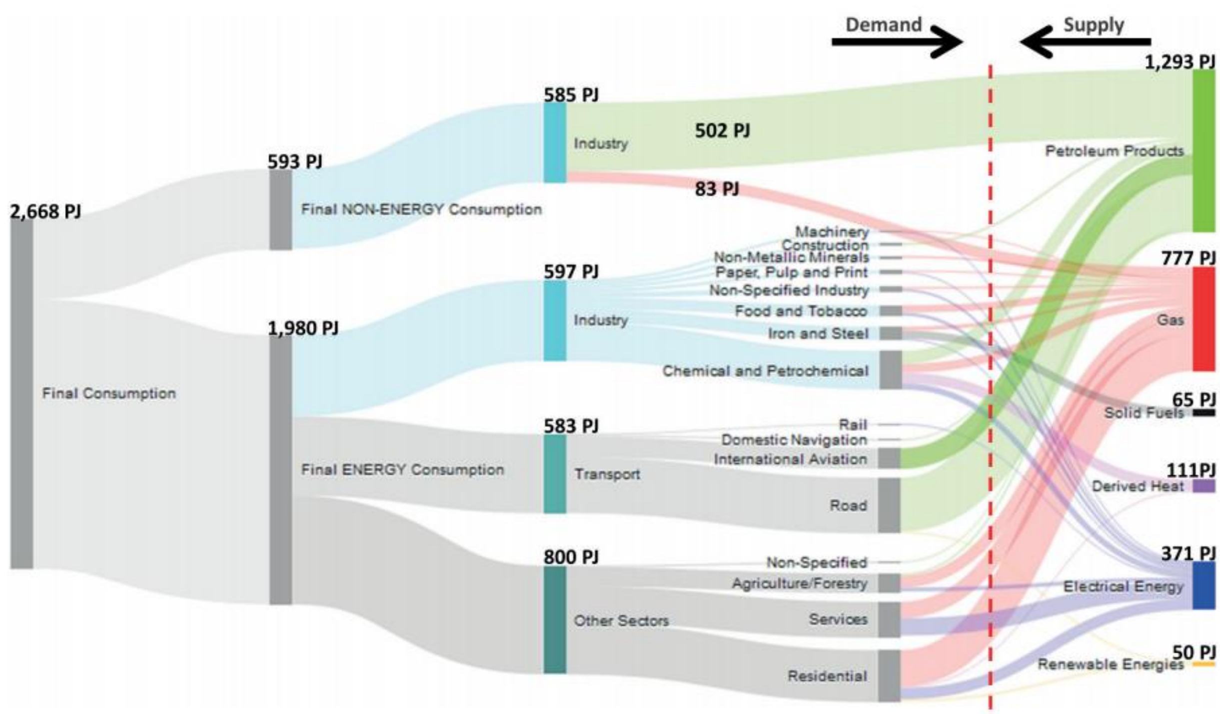


Figure 6: Dutch energy consumption 2014, adapted from Kreijkes (2017).

Examining heating demand within this total demand, a trend towards gas combustion can be seen partly due to historical policymaking. This policy strategy contributed to a relatively clean and efficient baseline for low-temperature heat (broadly defined as all heat under 100°C) that can be used for space heating when compared to other countries (Kreijkes, 2017). To put this thought into perspective, 93% of Dutch households were heated with natural gas compared to 50% in Germany, in 2015 (Energieonderzoek Centrum Nederland, 2015). The remaining 50% of heating demand was satisfied by burning solid fuels, district heating, electricity or biomass.

The production of natural gas decreases in the Netherlands, this expected decrease is displayed in figure 7. Natural provided approximately 40% of the final energy demand in 2019 with 38 billion m^3 natural gas (GasTerra, 2020).

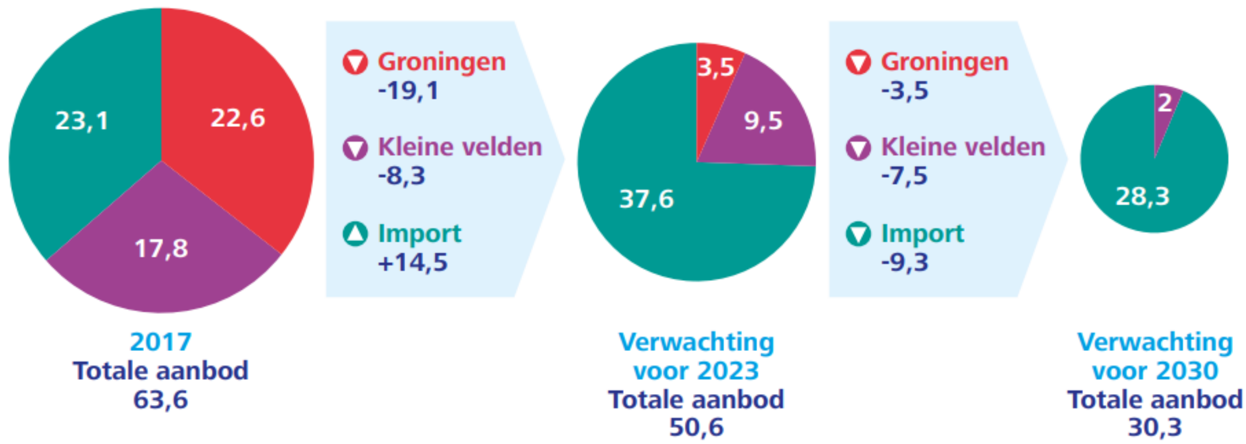


Figure 7: Development of natural gas offerings (GasTerra, 2019)**.**

3.1.2 Generation

Moving from the sources aspect of the current Dutch heating system, the generation pathways to low temperature heat from their respective sources is reviewed. The first aspect of this section will elaborate on the site location of gas production. Then, different generation technologies for end use applications are discussed that deal with heat generation and at last the implications of the central nature of the gas infrastructure.

Dutch gas extraction is fully centralized and for the most part extracted by a handful of companies. The presence of so many gas fields led to a concentration of experience and knowledge. This also contributed to the vast infrastructure for gas distribution. For end-use appliances, gas combustion boilers are highly efficient in supply heat in the built environment. Some part of the heat demand is satisfied by other means as has been delineated in section 3.1.1.

3.1.3 Distribution

The Netherlands is in possession of a large, highly connected natural gas infrastructure. It has been briefly touched upon in section 3.1.1. The natural gas infrastructure includes all the pipelines that transport the natural gas across the country, storage services, compressions and metering stations and the natural gas processing facilities. The Netherlands is anchors an open access transmission network for high-quality gas that has good connection to world gas market (Government of the Netherlands, 2011). This gas distribution system contains over 15.500km of pipelines (figure 7). The network is fully owned by gas infrastructure company Gasunie and is operated by the Transmission System Operator Gas Transport Services (GTS) which is 100% subsidiary of Gasunie (Government of the Netherlands, 2011). The infrastructure of the Netherlands is part of strategic opportunities for hydrogen in the Netherlands. This combination of location and infrastructure

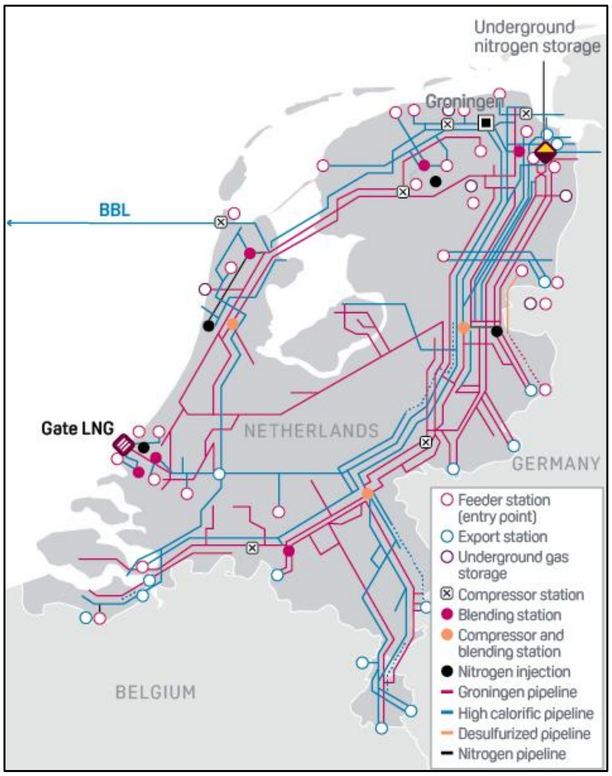


Figure 8: Dutch gas pipeline network. Source: Oxford institute for Energy Studies, Dutch Government

availability will be further delineated in the sections hereafter.

3.2 A future potential heating supply chain

The following sections discuss the potential of hydrogen as renewable energy carrier in the Netherlands based on the TNO report and Infrastructure Outlook from Gasunie and TenneT (Detz et al., 2019; Gasunie & TenneT, 2019). The structure of these sections are aligned with section 3.1 and hence, the sources, generation and distribution dimensions are discussed. This section will create insight on a future Dutch heating system that can be used to make the energy security assessment for the future and give implications of hydrogen implement in the Dutch energy system.

For sources, it would seem irrelevant to look at the geographic location, stability/variability, and the potential of hydrogen to meet energy demand. Considering the specific case, and application of hydrogen in the Dutch energy system this is true. However, it is paramount to analyse the potential of hydrogen to decarbonize the Dutch heating system. For this, insights are needed in the potential of hydrogen to meet heating demand in the Netherlands. Therefore, for sources, it is examined whether the potential of hydrogen in the Netherlands satisfies demand, and what stability/variability lessons can be learned given the intermittent nature of renewable sources necessary for hydrogen production. From here, the next element can be assessed looking at generation. The main interests of this element consider generation site location, the technology used for generation and its central or decentral nature and finally material requirements. The final element in this initial step of analysis looks at distribution. The operationalization of this aspect deals with transportation technology or topology, storage means and operating systems that are necessary for integrating hydrogen in the energy system. For any aspect in the first step of the framework, it is essential to understand how it relates to different parts of the hydrogen supply chain. There are many configurations thinkable that are hydrogen focussed. Figure 4 displays the possible hydrogen-based renewable energy systems, as according to Acar & Dincer (2019).

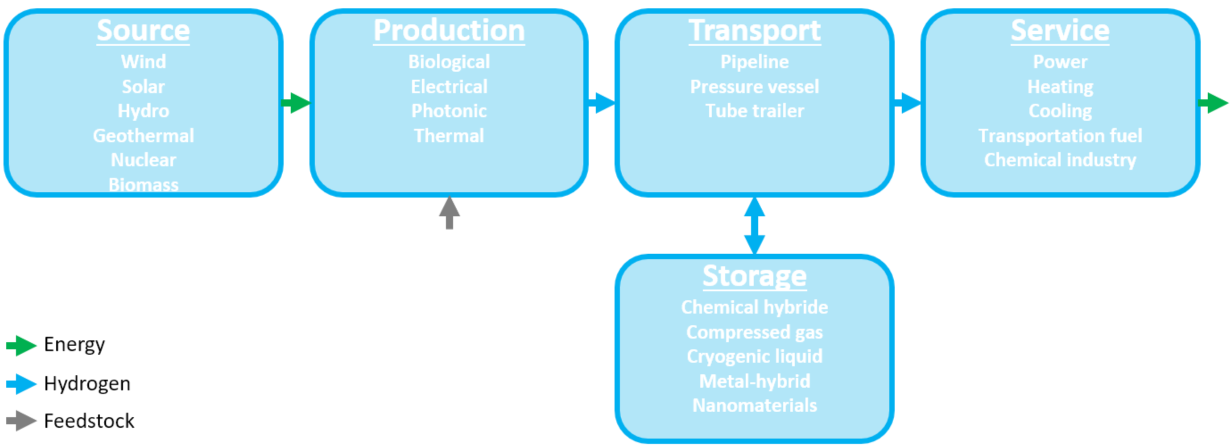


Figure 9: Possible configurations of the hydrogen supply chain Acar & Dincer (2019)

3.2.1 Sources

The first aspect will cover the potential of hydrogen in the Netherlands, whether this satisfies the demand and what hydrogen implementation implies for stability and variability. These elements combined give a coherent indication to what extent hydrogen is suitable for decarbonizing the Dutch heating sector. Insights from this section lead to finding realistic hydrogen scenarios that are used for results analysis based on the TNO report and Infrastructure Outlook from Gasunie and TenneT (Detz et al., 2019; Gasunie & TenneT, 2019).

Besides these scenarios, there is broad range of hydrogen scenarios available in literature. The study from Quarton et al. (2019) reviews the role of hydrogen in 12 global energy scenarios. It is argued that the role of hydrogen in these global scenarios are conflicting with each other. Also, the prevalence of hydrogen in these global scenarios is rather low compared to more local energy scenarios. A comprehensive scenario and modelling analysis by Samsatli & Samsatli (2019) on hydrogen heating pathways for the United Kingdom indicate that an optimal pathway to heat is 20% hydrogen and 80% electricity. For the Netherlands, an exhaustive analysis has been done by Detz et al. (2019) exploring the future roles of hydrogen as an energy carrier or as feedstock in a low-carbon future energy system. This study evaluates an extensive list of different studies or scenarios coming to a substantiated analysis of the future constitution of hydrogen in the Netherlands.

According to the report initiated by Ministry of Economic Affairs, it is a complicated to connect older residential houses to heating grids or heat these buildings completely on electricity. There lies a great challenge due to the scale and insulation needs of these older premises, hence, solutions as mentioned above will not suffice (Gigler & Weeda, 2018). Hydrogen can contribute to generating heat to these residences next to electrical options. Depending on the local alternative, hydrogen can be utilized in different ways and hence, hydrogen demand is subjected to different applications it is used for. It is unlikely that hydrogen is only energy carrier to satisfy future heating demand. Electricity will remain the main energy carrier in a future energy system as is demonstrated in most scenarios, visions and studies (Detz et al., 2019; Gasunie & TenneT, 2019; Gigler & Weeda, 2018; Scholten, 2018). There is no concession in literature that hydrogen demand for heating will surpass production, especially, considering storage possibilities and utilizing the existing gas grid for transport. The studies assessed in the report from TNO (2019) project an average of 34PJ/y hydrogen use in 2050. The main reason for this low average is that roughly half of the examined studies in the report of TNO do not include the possibility to heat buildings with hydrogen. On the contrary, other studies envisage that half of the current heating demand will be provided by hydrogen gas. The TKI Nieuw Gas Hydrogen Roadmap expects a hydrogen demand for low temperature heating of approximately 100 PJ/y in a climate neutral energy supply system (Gigler & Weeda, 2018). In the study from CE Delft, this is even double as indicated in figure 9 (Afman & Rooijers, 2017). It is crucial, though, to understand that the assumption of evenly spread heating demand throughout the Netherlands, has consequences for distribution of hydrogen. Production of hydrogen is site specific, and thus, a proper infrastructure is required to ensure availability anywhere in the country.

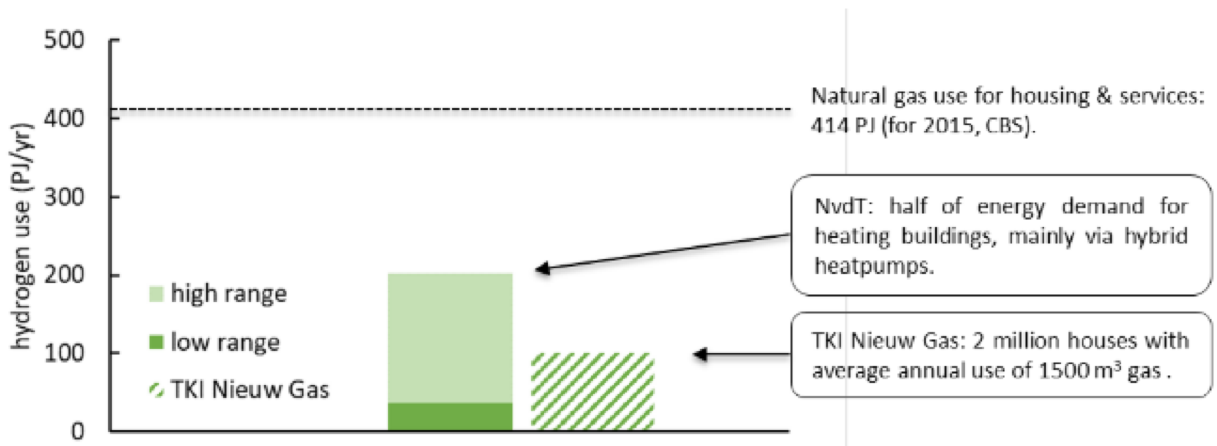


Figure 10: Hydrogen use in 2050 in the built environment (Detz et al., 2019)

Finally, the stability and variability of hydrogen as a renewable energy carrier is analysed. Renewable energy systems based on RES must manage variability and temporality. Without any coping mechanisms, the installed capacity of renewables should of sufficient such size to prevent any outages given any weather conditions (Blanco & Faaij, 2018). Consequently, coping mechanisms are an efficient means to ensuring uninterrupted power supply in future renewable energy systems. The wider system role of hydrogen can enhance reliability, flexibility and integration of these renewable based energy systems in cost-effective way (Detz et al., 2019). In particular, the production of green hydrogen offers the opportunity to integrate sizable amounts of surplus renewable energy in the system. Moreover, by means of both energy storage and demand response, hydrogen can offer large scale flexibility considering balancing the power market (from seconds to minutes) or seasonal storage for the energy system as a whole (including, heat, gas and electricity) (Blanco & Faaij, 2018; Detz et al., 2019).

3.2.2 Generation

Moving forward from the sources aspect, generation deals with the possible site location, generation technologies, the decentral or central nature of hydrogen and required rare earth materials. The first section deals with hydrogen production site location.

Hydrogen can be produced in three different ways of which two are renewable. As has been indicated, for the sake of this study only green hydrogen will be discussed. One important comment to that is: *the energy transition is a process, spanning decades and is not completed one day on the other*. This must be kept in mind when analysing a future energy system and when explaining certain phenomena. Understanding this and incorporating this in examining a hydrogen focussed energy system is crucial. The hydrogen production trajectory towards 2050 will most likely undergo changes, with first, natural gas reforming with CCS to produce blue hydrogen that shifts towards green hydrogen (Detz et al., 2019). Following these statements, the possible production sites for hydrogen can be examined. Blue hydrogen is less constricted geographically as green hydrogen since the latter requires adjacent renewable energy sources. Renewable energy sources are not as geographically constrained as fossil fuels, but weather conditions play an important role in deciding the most cost-efficient sites for renewable energy sources (Scholten, 2018). Even more so for the Netherlands with a strong sea climate and higher wind speeds at coastal areas or in the see (Appendix A). Also, sun irradiation is more intense closer to the sea (Appendix B). Hence, green hydrogen production is somewhat bound to these locations given that transporting electricity over long distances causes potential high energy losses. Blue hydrogen, produced by steam methane reforming natural gas, is less constricted to locations close to renewable energy sources. Interesting is how to evaluate how infrastructure develops throughout the years considering the shift from dominantly produced blue hydrogen towards green hydrogen.

Generation technology for hydrogen is mature and market ready. The most common technologies are alkaline electrolysis and proton exchange membrane (PEM) electrolysis. The former is the most mature and commonly used technology in electrolyser applications and are available in MW scale. However, both technologies possess considerable potential to be improved in the coming years (Gigler & Weeda, 2018). Table 1 illustrates the different possibilities for electricity production and conversion for end use, combined with the technological maturity, for hydrogen. The framework from Scholten (2018) does not necessarily mention end use applications as part of the generation aspect of the first step. However, given the specific scope of the research, it is favourable to take end use application technologies in consideration. The maturity and cost of different technologies have major effect on actual implementation and time span. The research initiated by TKI Nieuw Gas evaluates different possible applications for supplying low temperature heat in the Netherlands. According to their study, low temperature heat supply by means of utilizing hydrogen is expected to be market ready in 3-10 years. However, this does not imply that integration is simply a matter of “technology push”. More than 80% of the buildings in the Netherlands are supplied with natural gas to provide heat. Consequently, changing the incumbent technology with a novel renewable solution can be experienced as difficult (Dodds et al., 2015). The actual time span for implementation will be combination between the development time for the technology and national policy. The roadmap indicates that there is a high priority for developing alternatives for gas in existing buildings unable to be electrified or connected to heat grids. The Dutch governmental strategy on hydrogen is not specific on the actual role of hydrogen in the future heat system but acknowledges that hydrogen will be concentrated in transport, industrial clusters and to heat buildings in the Netherlands (Government Strategy on Hydrogen, 2020).

Table 3: Overview of hydrogen production technologies, applications, and maturity. Colour coding: level of priority for the development of activities in the Netherlands. Green = highest priority, orange = important but not priority, red = limited importance (Gigler & Weeda, 2018).

Development stage of H_2 application / Energy-function	Exploration and study of feasibility TRL 1-3) | market-ready in 10+ yrs	Industrial research and experimental development TRL 4-7 | market-ready in 3-10 yrs	Demonstration, practical trials and market introduction TRL 8-9 | (almost) market-ready
	Power and Light		
Electricity production		- Gas turbine (flexible gas turbine power stations) (green) - Fuel cell power plants (1-10 MW) - Fuel cell gensets (orange) - Fuel cell micro CHP plant (kW scale) (red)	Fuel cell systems for back-up and remote power (red)
Conversion and end use	Hydrogen production using - AEM electrolysis - Solid Oxide Electrolysis (orange)		Hydrogen production using - Alkaline electrolysis - PEM electrolysis (green)

Table 4: Overview of possible applications of hydrogen for supplying low temperature heat. Colour coding: level of priority for the development of activities in the Netherlands. Green = highest priority, orange = important but not priority, red = limited importance (Gigler & Weeda, 2018).

Development stage of H_2 application / Energy-function	Exploration and study of feasibility TRL 1-3 | market-ready in 10+ yrs	Industrial research and experimental development TRL 4-7 | market-ready in 3-10 yrs	Demonstration, practical trials and market introduction TRL 8-9 | (almost) market-ready
	Low-temperature heat		
Energy use/fuel		- Alternative for natural gas in existing buildings that cannot be electrified or connected to heating grids - District-level plants combined with local heating grids (green)	

It is essential to examine whether the incumbent hydrogen technologies constitute centrally or rather decentral in a future renewable energy system. The findings in table 1 indicate that there is minor focus on decentral production technology development. The main national focus for technological development and implementation is on central production and distribution of hydrogen (Gigler & Weeda, 2018). This judgement is strengthened when exploring the different hydrogen projects currently executed or planned for the near future. In an overview from TKI Nieuw Gas published in 2020, it is apparent that the majority of projects consider large scale, decentralized hydrogen production facilities (de Laat, 2020). However, this does not exclude decentral generation to be part of the transition towards a hydrogen based renewable energy system. Depending on the success of rolling out a hydrogen distribution infrastructure in the Netherlands, some regions in the country will be less endowed in terms of hydrogen supply. Still, the existing natural gas grid of the Netherlands is extensive and can potentially be transformed to distribute hydrogen across the country.

3.2.3 Distribution

The final aspect of the geotechnical features of renewable energy systems concerns distribution. It has been briefly touched in the final part of the section on generation and illustrates how each aspect is connected. The distribution aspect can be placed under transport and storage in the model of possible hydrogen supply chain configurations in figure 4. The distribution is the final supply chain aspect that connects renewable produced hydrogen to the industry or the consumer's end-use appliance. The storage possibilities are also examined, hence, this aspect is closely linked to 'sources' regarding coping mechanisms to provide back-up systems and prevent outages. The hydrogen infrastructure will d substantially on the government as they intend to play a key role in the development of the required infrastructure (Government Strategy on Hydrogen, 2020). Alongside TenneT and Gasunie, the government will evaluate to what extend the existing gas grid can be utilized for the distribution of hydrogen. On regional level, the local operators and network companies are involved in the process (Government Strategy on Hydrogen, 2020).

The infrastructure developments should be in line with how the hydrogen demand progresses over the years. In the early years of developing a hydrogen economy it could be adequate to utilize lorries or ships to transport hydrogen from production facilities to industry and other end use applications. Interesting is to examine to what extend it is necessary to create a new infrastructure considering the well-developed gas infrastructure already operational. Recent studies have examined how this existing infrastructure can be used for the transportation of hydrogen. It has been concluded that high-pressure pipelines can be used to distribute 100% hydrogen without any significant technical or economic consequences (Gigler & Weeda, 2018). However, determining what specific pipes can be used to transport hydrogen depends on the demand for natural gas and the speed of hydrogen development (Detz et al., 2019; Gigler & Weeda, 2018). On local level hydrogen can be combined with the existing natural gas infrastructure to provide heat for houses that cannot be electrified or connected to a heating grid.

3.3 Choosing the future hydrogen scenario

As indicated before, there are many scenario's available that depict possibilities of a future energy system (Afman & Rooijers, 2017; Detz et al., 2019; Gasunie & TenneT, 2019; Gigler & Weeda, 2018). To perform a qualitative analysis of the effects of hydrogen on future Dutch energy security, scenarios must be used. The work from Detz et al. (2019) provides an extensive analysis of different scenarios than include hydrogen as an energy carrier. *The report from Afman & Rooijers (2017) came forward as most promising because report* *included three different scenario possibilities based on the degree and form of governmental interference.* The first scenario is based on regional direction, the second on national direction and the third scenario is developed from an international perspective.

Multiple stakeholders indicated in the interviews that governmental interference is crucial for making hydrogen possible in the Netherlands. •"The government should be completely involved with rolling out this hydrogen infrastructure and market. The government should indicate who has what role, this is very important. Private parties do not have the power to really get things done in the beginning." – Hans Warmenhoven EBN. Next, different stakeholders indicated that there is need for international markets to provide cheap and sustainable hydrogen, *For these reasons, the national and international scenario are used for analysing energy security for a future Dutch energy system.* The Infrastructure Outlook 2050 picks up on these scenarios from an infrastructure perspective and is of great value for a complete overview. *Hence, this infrastructure outlook is incorporated in the analysis (Gasunie & TenneT, 2019)*. The sections below will discuss the scenario's in more detail and gives the reader an idea on how the scenarios are implemented into the analysis.

3.3.1 The national scenario

This scenario is based on the premises that the government will have a strong role central position in terms of the energy transition. The central government directs on energy-autonomy for the Netherlands through a mix of mostly centrally constituted energy sources, with a focus on wind energy on the sea. The central government organises and orchestrates 'big projects', for example, wind energy on the sea and energy islands in the North-Sea to create central points for the conversion to sustainable gasses. On regional level,

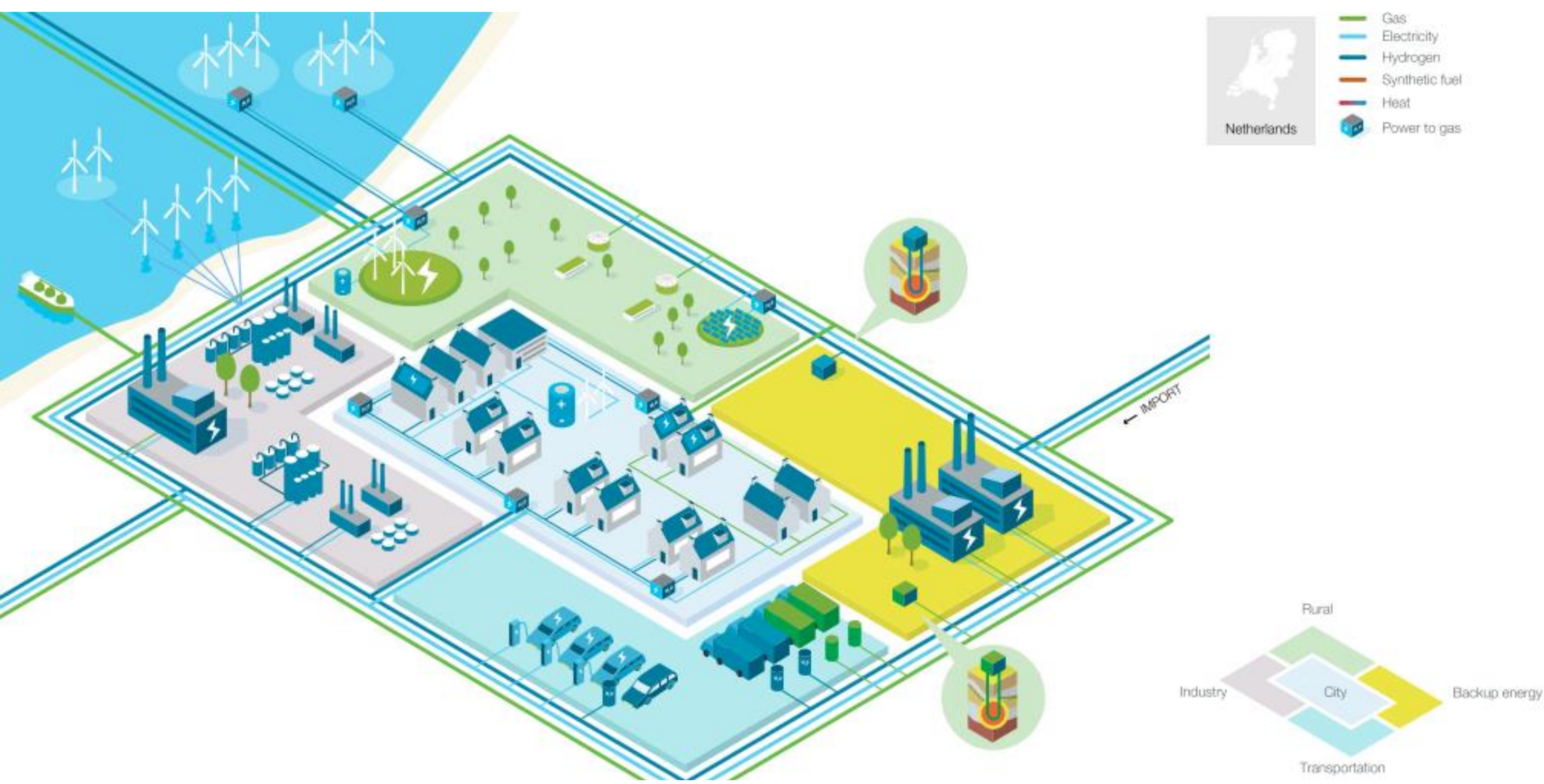
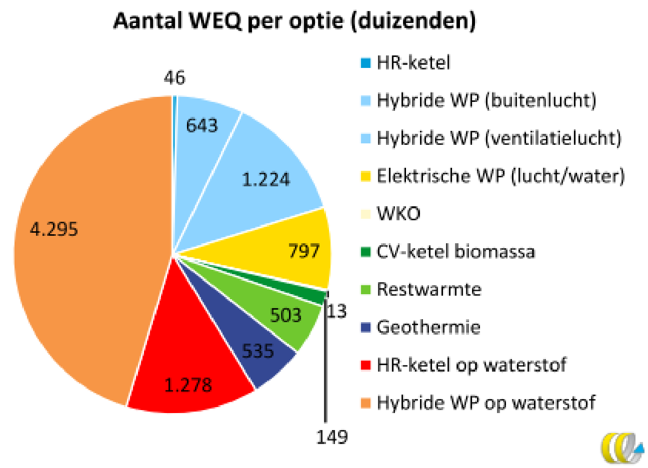


Figure 11: The national scenario (Gasunie & TenneT, 2019)

choices are made with regard to heating networks and regional renewable energy production. In this scenario the industry undergoes a change to circular. Appendix G shows in detail what the scenario entails with corresponding energy flows. Figure 10 gives an overview of different system components are integrated and connected into this future energy system configuration.

Change in heating functions

In this future scenario, the Netherlands is self-sufficient in their energy demand. This includes the energy sources for low-temperature in the built environment. All utilized energy sources must be available in the Netherlands itself. Demand is satisfied through large scale centrally produced hydrogen that is transported to the built environment and is applied for individual and collective solutions, like hybrid heat pumps, and accounts for nearly half of all heating solutions. A hybrid heat pump powered by green gas will account for nearly 20% of the heating demand in the built environment. The all-electric solution represents little heating demand due to higher system costs. District heating will account for approximately 12% of heating demand and will satisfy the more denser populated regions in the Netherlands. The following figure represents the distribution of different technologies for heat demand in the built environment (in Dutch) (Afman & Rooijers, 2017).



Noot: Definitie WEQ - woningequivalent: woning of 150 m² utiliteitsbouw

Figure 12: Distribution of heating solutions in the Dutch built environment, national scenario (Afman & Rooijers, 2017)

Final demand of different energy carriers

The Netherlands is energy autonomous in this scenario. This strongly determines the mix of different energy sources. A large amount of intermittent energy sources like solar PV, wind on the sea or land shape the base load of this self-sufficient energy system. In this scenario, 80% of the total capacity is of central nature and 20% of the capacity is arranged in a decentral manner. To ensure the balance between supply and demand, there is a considerable need for flexible energy supply. This is satisfied by storing hydrogen that is generated from a surplus of renewable energy sources. The final energy demand given with its respective energy carriers is displayed in the figure below.

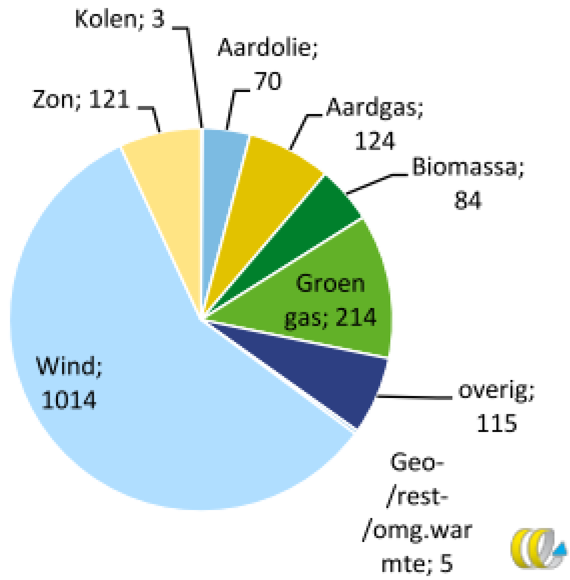


Figure 13: Primary energy demand in PJ, national scenario, in Dutch (Afman & Rooijers, 2017).

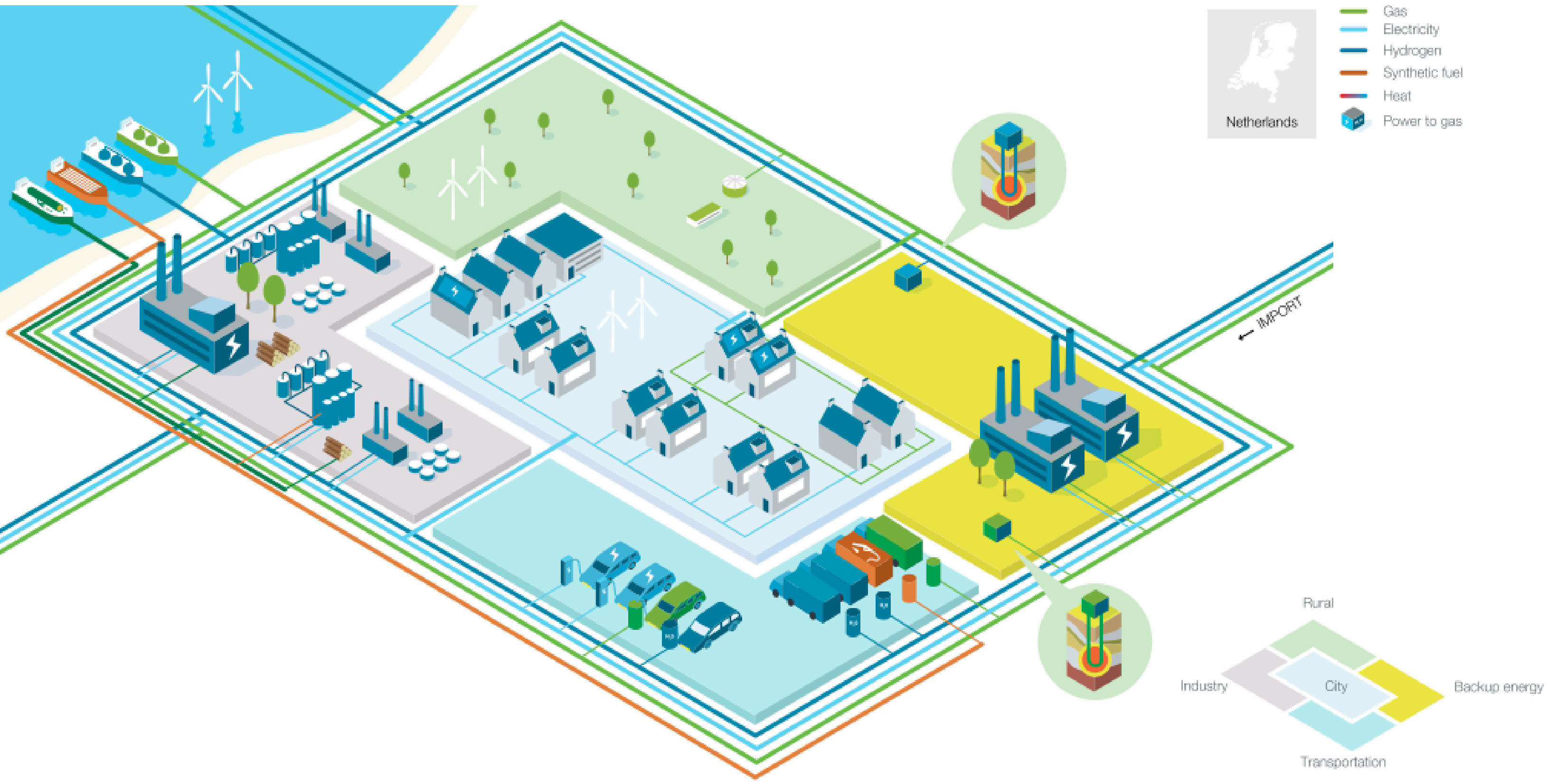
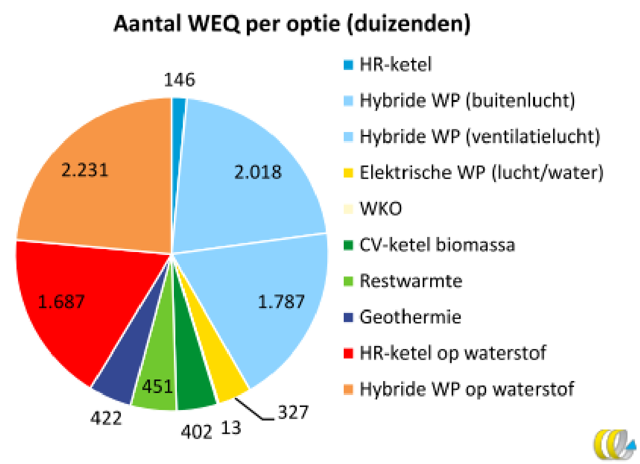


Figure 14: The international scenario (Gasunie & Tennet, 2019)

3.3.2 The international scenario

In this scenario, the import of renewable energy in different forms, plays an important role. This scenario delineates the Netherlands as a globally orientated nation that allows for international energy trade in energy carriers, of which many are renewable in 2050. This is not limited to biomass and hydrogen, but ammonia an renewable hydrocarbon are included as well. The government stimulates international energy trade. This has enormous consequences for industry, transport and the built environment. The availability of a more diverse portfolio of energy carriers translates in different energy solutions for decarbonization. Appendix G shows in detail what the scenario entails with corresponding energy flows. Figure 12 gives an overview of different system components are integrated and connected into this future energy system configuration.



Noot: Definitie WEQ - woningequivalent: woning of 150 m² utiliteitsbouw.

Figure 15: Distribution of heating solutions in the Dutch built environment, international scenario (Afman & Rooijers, 2017)

Change in heating functions

The Netherlands has the opportunity to import energy sources and carriers to meet low temperature heating demand in the built environment. The range of different energy carriers can vary from biomass or gaseous energy carriers like hydrogen and green gas. There are two consequences due to these premises; first, the availability of biomass and green gas will increase, and secondly, the price of energy sources decreases when international trade is allowed and incorporated in the scenario. The green gas hybrid heat pumps are most cost efficient because this scenario allows large scale green gas imports. After this, hydrogen hybrid heat pumps are most favourable and cost efficient. Within this scenarios boundaries, the heat networks only make up 6% of the total heating solutions. The hydrogen infrastructure has been modelled to be more expensive compared to the green gas infrastructure. For this reason, hydrogen is less emergent compared to green gas utilization.

Final demand of different energy carriers

There is a possibility to import energy carriers in this scenario. Consequently, the energy mix is different from the national scenario. Intermittent energy sources like wind and solar only make up 10% of the energy mix while the rest is satisfied by imported energy. This energy mix indicates that the balance between demand and supply is similar to the current situation. The final energy demand given with its respective energy carriers is displayed in the figure below.

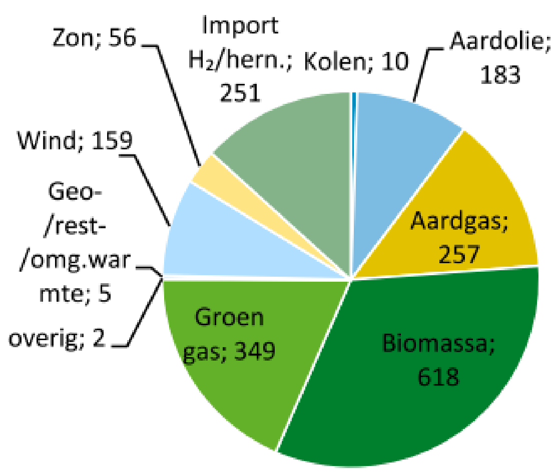


Figure 16: Primary energy demand in PJ, international scenario, in Dutch (Afman & Rooijers, 2017).

The following figure gives a clear overview of how these final energy demands relate to each compared to 2017.

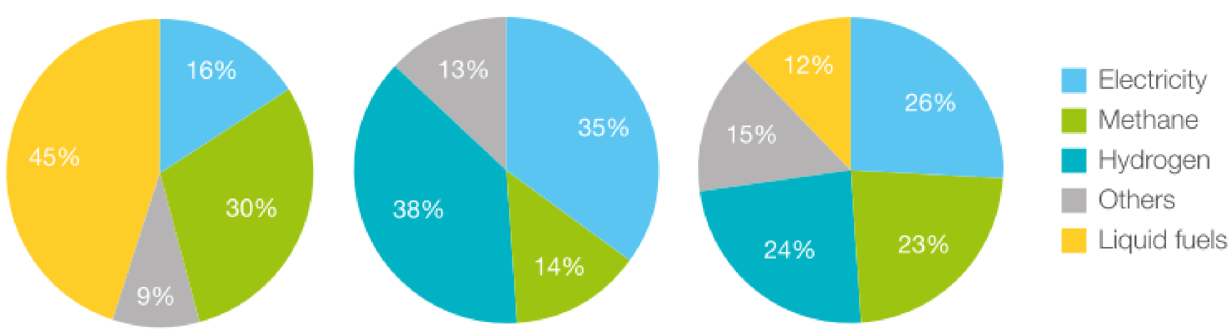
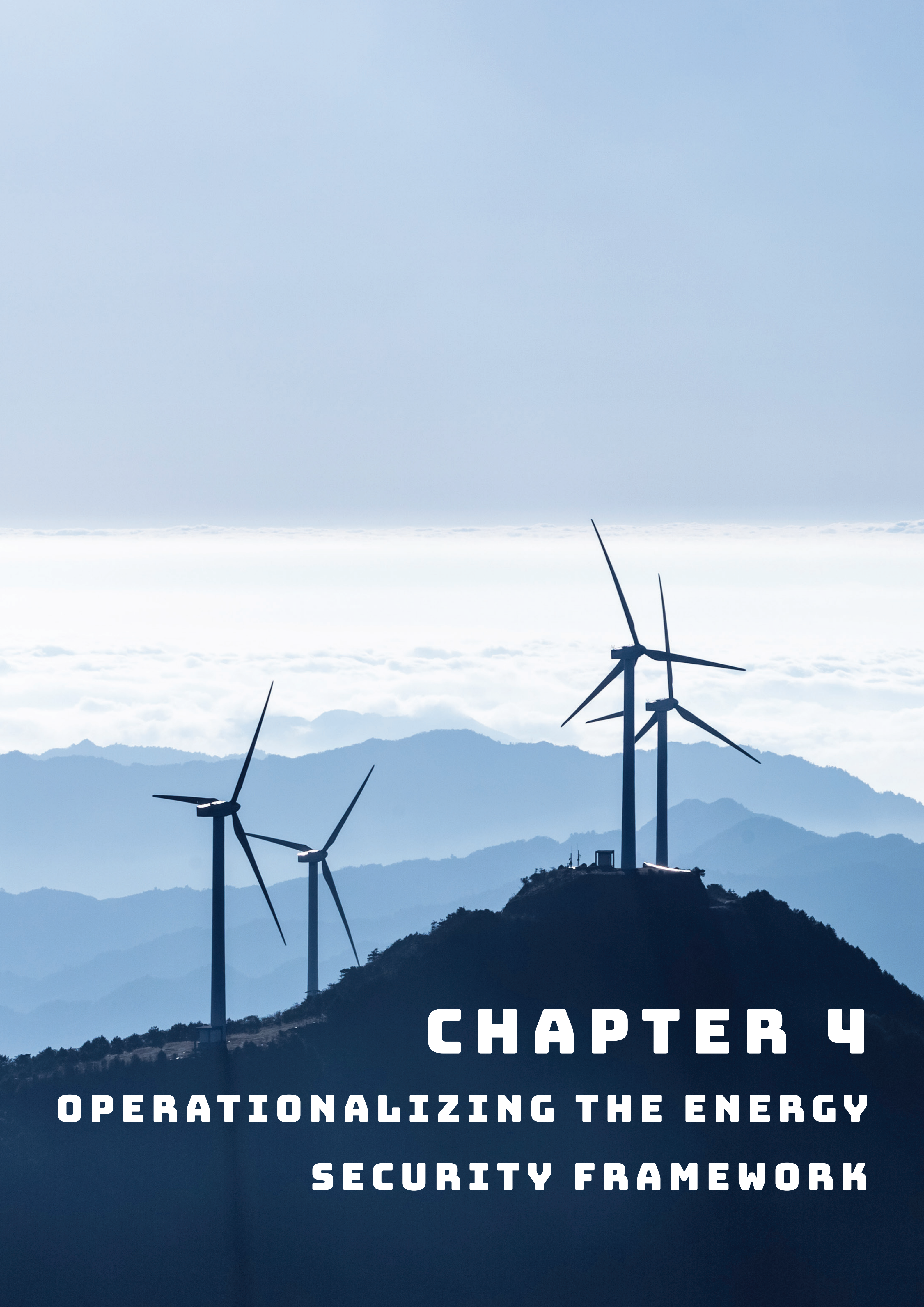


Figure 17: Final energy demand. Left: 2017, middle: 2050 national, right: 2050 international



CHAPTER 4

OPERATIONALIZING THE ENERGY SECURITY FRAMEWORK

4. Operationalizing the energy security framework

This chapter aims at answering research question 3:

"How can the initial framework from the first sub-question be improved?"

A recent paper from the authors operationalized the index from section 2.5 globally (Azzuni & Breyer, 2020). Their index consisted of the 15 dimensions, 50 parameters and 78 indicators. Given the limited time frame of this research, a selection must be made to analyse. According to Azzuni & Breyer (2018) all dimensions and its parameters should be considered. However, a selection of indicators is possible as some data will be unavailable for specific indicators. The relevance of indicators can be tracked back to the frequency of mentioned dimensions in literature. One cannot simply add or remove dimensions based on the frequency they are mentioned throughout literature. However, it does imply that dimensions are case specific and that some dimensions are more likely to be included in analysis. This calls for creating a better understanding of what dimensions are necessary for this research and what is realistic given the time constraints. With that knowledge, indicators from irrelevant dimensions can be removed or simplified. The frequency of dimensions mentioned in literature is displayed in figure 3 and is copied from the author's paper.

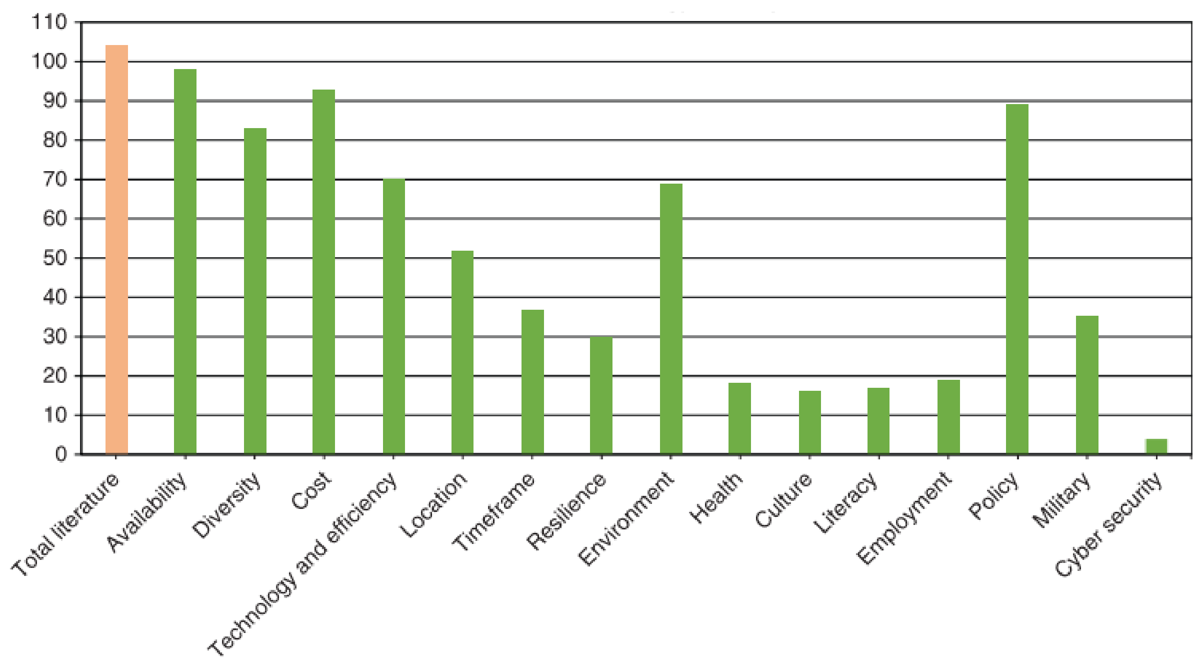


Figure 18: The frequency of different dimensions mentioned/discussed in literature (Azzuni & Breyer, 2018).

In the paper from Azzuni & Breyer (2018), it is indicated that involving every dimension that has any relation to energy security should be included. However, due to the time constraints of this research, an interview was scheduled with dr. Azzuni to discuss how it could be possible to cope with this time constraint. The interview with dr. Abdelrahman Azzuni pointed out that analysing all 15 dimensions would take at least a year of research. This is seen from an experienced researcher's perspective, implying that a student potentially requires more time. Hence, the framework must be simplified to conform to strict time constraints. Here, dr. Azzuni advised on how the framework can be simplified but still be suitable for a comprehensive analysis. From this advice, choices are made to remove parts of the framework that are not, or less, relevant for the specific scope of this research. Dr. Azzuni indicated that using figure 3 as an argument for removing indicators does not suffice independently. Next to this figure, each dimension should be considered, and its relation to energy security given the specific context ought to be examined.

4.1 Framework 2.0

Insights from the interview with dr. Azzuni, combined with desk research, provide substantiated arguments for what dimensions and indicators will be adapted from the original framework to create a more specific framework for this study. Each dimension will be covered, and a choice is made either to keep the dimension or remove it from the analysis. After this, each dimension that is adapted is reviewed to design what indicators will fill the different dimensions.

Availability

The first dimension is *availability* and is critical for energy security. Hence, this dimension is always included in energy security analyses (Azzuni & Breyer, 2018). In figure 3, it displayed how often this dimension is mentioned in other literature as well. Still, it is necessary to examine the relevance of these dimensions concerning this research's objective. As this dimension does not consider diversification, the main link to renewable energy sources is limited. However, the population will grow in the Netherlands towards 2050, and that means that there will be more consumers in a future energy system. Growth in energy consumers indicates an increase of energy demand, which was depicted previously (Detz et al., 2019; Gigler & Weeda, 2018). However, to examine if the expansion of energy sources is in line with future energy demand, one can look at population growth and total available resources (Azzuni et al., 2020; Azzuni & Breyer, 2020). Hence, it is critical to evaluate this dimension regarding a possible future energy system.

Diversity

The next dimension is *Diversity* and is widely used in literature to analyse and enhance energy security. According to Stirling (2014), diversity's main parameters are diversity of sources, diversity of fuels (energy carriers), diversity of supply energy means to the consumer (e.g., transportation or technologies), and diversity of different consumers that deals with markets and sectors. This dimension is urgently essential for this analysis that introduces a new energy carrier in the heating market. Considering the transition phase from the current fossil fuel-based system to a renewable system, adding energy carriers like hydrogen makes this dimension captivating. Hence, this dimension is included in the framework.

Cost

The cost dimension covers the affordability of energy services and its relation to energy security (Azzuni & Breyer, 2018). In many other studies, this dimension also inspects competition in energy markets and price volatility (Ang et al., 2015). Introducing green hydrogen in the energy system implies dealing with intermittent electricity generation and hydrogen production. So, this dimension will be included in the energy security analysis with a focus on price volatility.

Technology and efficiency

There is a strong relationship between energy security and technological advancement, directly and indirectly. Accordingly, new technological solutions for transportation, production, conversion, distribution, and storage affect energy security. Due to hydrogen's system role, this new energy carrier can fulfil many of these different roles in the future energy system. This research aims to understand why a change in Dutch energy can be perceived when integrating hydrogen in the energy system. This is done by looking at the technical and geographical characteristics proposed in the framework from Scholten (2018). This implies that the *technology and efficiency* dimension is crucial regarding the scope of this research and, hence, is included in the energy security analysis.

Location

The *location* dimensions deal with an energy system's geographical features and the relation to energy security (Azzuni & Breyer, 2018). As the previous dimension covered the technical element towards understanding how hydrogen might affect energy security, dimensions examine how hydrogen potentially affects energy security, given its geographical context. This gives compelling evidence to include this dimension in the energy security analysis, creating a connection between hydrogen's technical and geographical characteristics with possible energy security changes in a future Dutch energy system.

Timeframe

The *timeframe* dimension examines how energy security is experienced. To give some more context, and what is meant by this, should energy security be considered in the long-run or very short-term to provide appropriate information? This also relates to evaluating what the ideal time is for analysing energy security. The short-term range (a couple of years) appeals most to policymakers and private stakeholders. However, energy-related investments and decisions can have implications for energy security in the long-term (decades/decennia). For the sake of this research, an exact time scope has been developed in which the current situation is compared to a future energy system. This implies that there is no need to examine how different stakeholders perceive energy security in terms of time. Hence, the timeframe dimension is not included in the analysis.

Resilience

The dimension of resilience means the capability to withstand disruption from the outside environment without experiencing any change in delivering demanded power or explained as an adaptive capacity that tolerates disturbances to a certain level. A resilient energy system is undoubtedly vital for a renewable energy system, given the intermittent nature of renewable energy sources. However, moving from the fossil fuel-based system, it is assumed that the Netherlands' energy system is designed in such a fashion that it can ensure to be resilient to disturbances to a certain level. Hence, this dimension is not deemed as valuable for the research scope and will be excluded from the analysis.

Environment

This dimension is of great importance for the analysis. It examines the effect that energy systems have on its environment based on the depletion of resources, energy usage, extraction methods, and the outcome of the energy usage. This dimension is included in the analysis.

Health

The *health* dimension involves all the factors that either affects the health of the humans within the boundaries of the energy system and how the health of the energy system operators is reflected in successfully managing the energy system. Whereas this is an important dimension, especially concerning environmental concerns regarding traditional powerplants, there is no need to compare the current situation with a fully renewable system.

Culture

Culture is considered an essential aspect of energy security for both the status quo and a future renewable energy system. More general, culture shapes how people react or deal with specific situations from the interview with dr. Azzuni revealed that culture would be an influential dimension for this research scope, and so, this dimension is taken into analysis. However, to grasp culture in the context, one parameter with five indicators has been added. This is validated by dr. Azzuni.

Literacy

This dimension includes the knowledge and access to information that involves energy security. According to Azzuni & Breyer (2018), knowledge of energy security includes understanding how the system works, how it can be improved, and, ultimately, how to use it securely. Whereas depicted as an essential dimension within the framework, literacy is challenging and time-consuming to measure. For this reason, the dimension is excluded from the analysis based on the following assumption: Dutch citizens are adequately informed and educated to understand the energy system. Next, operating the energy system is placed in the hands of TSO's, DSO's, and corporates with expertise within the field.

Employment

In the article by Azzuni & Breyer (2018), no significant use for this dimension is mentioned when dealing with one country's energy security. In the context of a continental or global analysis, it could prove attractive better to understand the relationship between employment rates and energy security. However, for that reason, this dimension is excluded from the analysis.

Policy

There is a strong relationship between energy security and policy. Achieving energy security can be considered a policy goal, as its concerns affect policy decisions. For this reason, energy security cannot be separated from its political implications and is included in the analysis. Recommendations from the IEA country report of the Netherlands (2014) indicate the need to foster a dialogue between stakeholders and the government to create opportunities for international innovation and technology partnerships to develop clean energy technologies. According to Azzuni & Breyer (2018), "energy politics will determine our survival as we know it on our planet." Additionally, this dimension is useful when comparing present and future states of the system so that policymakers can anticipate accordingly.

Military

The 14th dimension is military and is depicted as relevant since energy is crucial in the military. Likewise, the military is there to protect to energy system at hand. However, considering this research's scope, there is no relevance to taking this dimension into the analysis.

Cyber security

Nowadays, all energy systems and infrastructures depend on coherent digital support. Whereas the destruction of the cyber dimension dramatically affects the physical energy system, it is complicated to measure or analyse this dimension. Considering the time constraints of this research, the assumption is made that the cyber dimension is operating accordingly and protected to its full extent preventing any outages or significant failures in the digital domain.

4.2 Dimensions and their indicators

The operationalized framework includes the following eight dimensions:

1. Availability
2. Diversity
3. Cost
4. Technology and efficiency
5. Location
6. Environment
7. Culture
8. Policy

The original index has been adjusted so that the included dimensions fit with the research scope and time constraints but leave room for a comprehensive analysis and comparison of the present and future energy systems. The work from Hofman (2015) resulted in adding a parameter to the culture to dimension. In the interview, dr. Azzuni indicated that the culture dimension is crucial when analyzing future systems that deal with hydrogen. The adjustments are validated through email correspondence. To finalize the framework, there is a need to find the right indicators to evaluate each dimension. The paper from Azzuni & Breyer (2018) gives a prescribed set of indicators for each dimension. Likewise, it is appropriate to evaluate the most relevant indicators for the analysis given the constraints and what indicators can be added from other papers. However, the baseline that is proposed in the reference paper is maintained as much as possible to prevent any missing indicators. It is paramount to align the indicators so that these can be applied to create insights on how hydrogen as a renewable energy carrier for heat in the built environment can affect energy security in the given eight dimensions.

Dimensions	**Parameters**
Availability	Existence of resources
	Existence of consumers
	Existence of means of transport (access)
Diversity	Diversity of sources
	Diversity of fuel (energy carriers)
	Diversity of means (technologies, transportation)
	Diversity of consumers
Cost	Energy prices (consumers, producers, pricing system/subsidies, energy poverty, peak oil, and stability/volatility

	Cost of securing the system
Technology and efficiency	Energy system efficiency Energy intensity Energy conservation
Location	Location of energy storage Density factor Land use Industrial intensity
Environment	Exploration rate and resources' location Outcomes from energy use Impact resulting from environmental change Relationship to water
Culture	Cultural effect on the energy system [production, connection, consumption, cultural acceptance (NIMBY, Not In My Back Yard)] Social acceptance of renewable energy
Policy	Regulations (liberalized and controlled market, rules, subsidies)

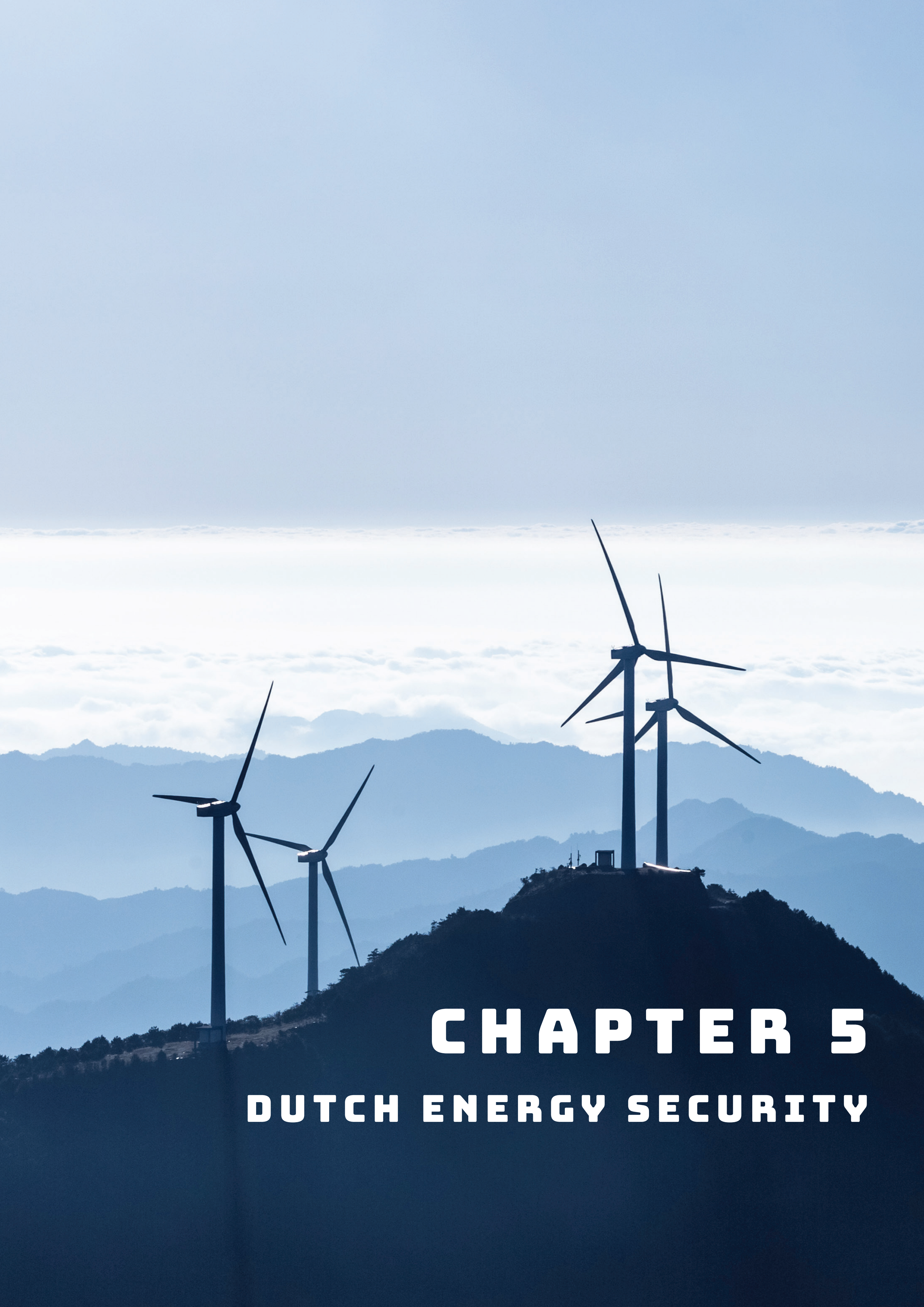
Table 5: Final set of dimensions and indicators adapted from Azzuni & Breyer (2018).

The measurable indicators that are connected to each parameter are delineated in the table below. Beside demonstrating how each parameter is linked to quantifiable indicators, the measuring unit and normalisation method is given.

Dimensions	Parameters	Indicators	Unit	Normalisation
Availability	A_1	Total available resource of fossil fuel and potential renewables	TWh	Max-min
	A_2	Population	Persons	Dividing by the world's population
	A_3	Number of airports	Airports	Dividing by the maximum in the world
Diversity	D_1	Simpsons Diversity Index of sources	Percentage	Normalized
	D_2	Simpsons Diversity Index of carriers	Percentage	Normalized
	D_3	Simpsons Diversity Index of technologies	Percentage	Normalized
	D_4	Simpsons Diversity Index of consumers	Percentage	Normalized
Cost	Co_1	Weighted average price of power demand	€/kWh	Dividing by the maximum in the world
	Co_2	LCOE total	€/MWh	Max-min
Technology and efficiency	TE_1	Supply efficiency	Percentage	Already normalized
	TE_2	Energy intensity level of primary energy	(MJ/USD PPP GDP)	Dividing by the maximum
	TE_3	Fuel economy	(Litres of gasoline equivalent)/100 km	Max-min
Location	Lo_1	Distance between production and consumption	Km	Max-min
	Lo_2	Energy use per area	kWh/km^2	Dividing by the highest

	Lo_3 Lo_4	Total renewable surface water Industrial added values	$m^3/(year*km^2)$ USD/km^2	Dividing by the maximum Dividing by the second highest
Environment	E_1 E_2 E_3 E_4	Ecological footprint (number of earth required) CO_2 intensity Total GHG emissions excluding land-use change and forestry per GDP Water stress	Number Kg per kWh energy use $MtCO_2/USD$ Percentage	Max-min Dividing by the maximum in the world Dividing by the highest in the world Normalized
Culture	Cu_1 Cu_2	1: Energy use per capita 2: Air transport, passengers carried per capita 1: Awareness of climate change and knowledge of the technology 2: -making process 3: Overall evaluation of costs, risks and benefits of technology 4: Local context (NIMBY) 5: Trust in decision-makers and other relevant stakeholders	1: kWh/capita 2: Number per capita 1: Percentage 2: Percentage 3: Percentage 4: Percentage 5: Percentage	1: Dividing by the maximum in the world 2: Dividing by the maximum in the world 1: Normalized 2: Normalized 3: Normalized 4: Normalized 5: Normalized
Policy	P_1	1: Subsidies and other transfers (percentage of expense) 2: Regularity indicator for sustainability (RISE)	Percentage	Normalized

A representation of the incorporated dimensions and the corresponding indicators is presented in the table above. Each indicator is measured with available data for the Netherlands. The next chapter will present what system integration of hydrogen as an energy carrier implies for supply chains and how these are translated into a possible scenario. With the help of experts in the field, a future scenario is shaped wherein possible outcomes for the composite indicators can be analysed and argued for.



CHAPTER 5

DUTCH ENERGY SECURITY

5. Dutch Energy Security

This chapter is dedicated to analysing Dutch energy security with the final framework presented in chapter 4. This chapter applies the proposed energy security framework and builds on the Dutch heating system presented at the beginning of chapter 3. In doing so, each dimension of the framework is discussed and calculated based on literature and open-source data. These results of the Netherlands' current situation serve as a reference case for the analysis of both future scenarios in chapter 6.

5.1 Energy security index for the Netherlands

This section will cover every dimension in the energy security index. Each dimension is discussed separately, and the scoring is given based on the formulas presented in section 4.3. The data sources for each dimension vary; hence, the utilized source is given in each section. For some dimensions, with more complex indicators, an extensive data sheet is provided in the appendix covering all elements. For a complete overview, each section hereafter will quickly sum-up the indicators that are to be analysed. All the data for other countries in the world is extracted from the supplementary data sheet provided by Azzuni & Breyer (2020).

5.1.1 Availability

The first indicator that is measured is availability. The table below provides an overview of the different indicators that are to be examined. The primary data sources for this dimension are adapted from Azzuni & Breyer (2020), the World Energy Balances 2016, data from the Netherlands Central Bureau of Statistics (2020), and the supplementary data sheet provided by Azzuni & Breyer (2020). The first parameter considers the total available resource of fossil fuel and the potential of renewable energy sources. This indicator is calculated by adding the available fossil fuel (based on total production), available renewable energy sources (potential), and comparing the total available energy with other countries in the world. The values are normalized by applying equation 4 from section 4.3. As displayed in the table below, the Netherlands scores significantly low on these indicators. The Netherlands' total available energy is compared with other countries regardless of population sizes or total area.

The second and third parameter data requirements are extracted from the Central Bureau of Statistics (2020) and are normalized using the same equation for the first parameter. The scores of individual indicators are reflections of Dutch performance in comparison with other countries in the world.

Dimensions	Parameters	Indicators	Unit	Normalization
Availability	A_1	Total available resource of fossil fuel and potential renewables	TWh	Max-min
		Population		Dividing by the world's population
	A_2	Number of airports	Persons	
	A_3		Number	Dividing by the maximum in the world

Parameter	Subpart	Indicators	Value	Normalization
A_1	1	Available renewable energy renewables (TWh)	1614.465745	**0.8%**

	2	Available fossil fuel-based on current production (TWh)	482.61011	
	3	Total available energy resources (TWh)	2097.075855	
A_2	1	Population (in thousands)	16 938	**0.2%**
A_3	1	Number of airports (2013)	29	**0.2%**

Each of the parameters weights 33%, now the following equation is applied

$$\mathrm{Xi} = \sum_{j=1}^{m} W_j * Y_j \tag{2}$$

Resulting in a score of **0.4%** in the availability dimension. The low score of this dimension will be further delineated in the discussion section.

5.1.2 Diversity

The diversity dimension is measured by applying the Simspons Diversity Index to the data. This equation helps with determining the degree of diversification. Usually applied to problems to determine diversity within a group of different species, this method is suitable for determining energy sources, technology, and consumers. Data is gathered from the Netherlands Central Bureau of Statistics (2020) and the supplementary data sheet provided by Azzuni & Breyer (2020). The first parameter, diversity of sources, is calculated by examining the share of local production and energy imports in total energy consumption. The current Dutch energy system relies substantially on energy imports, especially now local production of natural gas is decreasing. The diversity of energy carriers is relatively low in comparison with other countries. Even more so in the heating sector, as indicated in figure 5 of chapter 3. Gas consumption in the Netherlands makes up approximately 40% of the Netherlands' final energy demand in 2019; this is also translated in the score for diversity in technologies. Natural gas, and end-use appliances, have a prominent role in the Dutch energy system. However, there is a great diversity of different end consumers in the Netherlands. There is a wide variety of sectors; energy is a commodity available for everyone in the Netherlands. The scores are displayed below.

Dimension	Parameters	Indicators	Unit	Normalization
Diversity	D_1	Simpsons Diversity Index of sources	Percentage	Normalized
	D_2	Simpsons Diversity Index of carriers	Percentage	Normalized
	D_3	Simpsons Diversity Index of technologies	Percentage	Normalized
	D_4	Simpsons Diversity Index of consumers	Percentage	Normalized

Parameter	Subpart	Indicators	Value	Normalization
D_1	1	Simpsons Diversity Index of sources	**35 %**	None

D_2	1	Simpsons Diversity Index of carriers	**37 %**	None
D_3	1	Simpsons Diversity Index of technologies	**39 %**	None
D_4	1	Simpsons Diversity Index of consumers	**81 %**	None

The weight from each parameter is 25%, and thus, applying the following equation

$$\mathrm{Xi} = \sum_{j=1}^{m} W_j * Y_j \quad (2)$$

Gives the final score for diversity of **48 %**

5.1.3 Cost

The cost dimension is composed of two indicators that define the energy security score. The data for these two indicators are extracted from the supplementary data sheet provided by Azzuni & Breyer (2020) and is checked for completeness and most recent values with data from the Central Bureau of Statistics. The table below gives an overview of the parameters and indicators accompanied by the cost dimension. The first indicator, the weighted average price of power demand, examines the residential, commercial, and industrial sectors' energy prices and the total demand for each sector. The average is compared with other countries in the world. The Netherlands' energy price scores relatively low; one reason is the decreasing domestic fuel production and increasing energy imports. However, the levelized cost for electricity production scores particularly well because natural gas satisfies most Dutch electricity generation. Natural gas is moderately cheap, considering the exploitation of domestic natural gas fields. However, due to a decrease in the extraction of these fields, the LCOE is under pressure.

Dimensions	Parameters	Indicators	Unit	Normalization
Cost	Co_1	Weighted average price of power demand	€/kWh	Dividing by the maximum in the world
	Co_2	LCOE total	€/MWh	Max-min

Now the score for each parameter is given below.

Parameter	Subpart	Indicators	Value	Normalization
Co_1	1	Weighted average price of power demand (in all three sectors, €/kWh)	0.145	**24%**
Co_2	1	LCOE total (€/MWh)	64.42150423	**81%**

Both parameters weigh 50%, and so, by applying equation (2), the total score for the cost dimension is **53 %**.

5.1.4 Technology & Efficiency

The fourth dimension included in this analysis is technology and efficiency. The data is adapted from the Central Bureau of Statistics and Trading Economics (Trading Economy, 2015). The first parameter is calculated by dividing the total electricity demand into all sectors by the total electricity generation (imports and exports included). The second parameter is gathered from Trading Economics for the year 2015. This indicator explains how much energy is needed to produce a unit of economic output (Trading Economics). The third indicator is expressed in fuel economy, or liters of gasoline-equivalent/ 100km. Higher values indicate less stringent standards for fuel economy that result in higher consumption of fuel. This affects energy security negatively.

Dimensions	Parameters	Indicators	Unit	Normalization
Technology and efficiency	TE_1	Supply efficiency	Percentage	Already normalized
	TE_2	Energy intensity level of primary energy	(MJ/USD PPP GDP)	Dividing by the maximum
	TE_3	Fuel economy	(Litres of gasoline-equivalent)/100 km	Max-min

The scores for each indicator are given below

Parameter	Subpart	Indicators	Value	Normalization
TE_1	1	Supply efficiency	**99%**	None
TE_2	1	Energy intensity level of primary energy	**85%**	None
TE_3	1	Fuel economy	5.6	**90%**

Each indicator's weight is 33%, so by applying equation (2), the total score for the technology and efficiency dimension is **90%**.

5.1.5 Location

The location dimensions are the fifth dimension to be analysed. The first indicator calculates the distance between production and consumption and is the weighted average for all the crude oil imports to Europe divided by the sum of all distances. The second indicator is the energy use per area and is calculated by multiplying the energy use per capita with the population divided by area (kWh/km^2). The third indicator measures how much renewable surface water there is available each year. The last indicator expresses the industrial added value sourced from the supplementary data sheet provided by Azzuni & Breyer (2020). Below is an overview of the parameters with corresponding indicators. The distance between production and energy consumption in the Netherlands is defined mainly by energy imports and domestic natural gas resource exploitation. Due to the Dutch gas fields, there is some self-sufficiency in comparison with other countries. However, decreasing natural gas extraction will change this indicator in the coming years when replaced with imported energy sources. The Netherlands is an energy-intensive country with many large consumers of energy. This is reflected in the second indicator's score, a high score for energy use per area. The Netherlands is not challenged by a dry climate and extreme drought seasons; therefore, the third indicator is scored relatively high. As indicated before, the Netherlands is an energy-intensive country. Many large consumers are big industry players. This extensive industry delivers substantial added values for the economy, resulting in a good score for the fourth indicator.

Dimensions	Parameters	Indicators	Unit	Normalization

Location	Lo_1 Lo_2 Lo_3 Lo_4	Distance between production and consumption Energy use per area Total renewable surface water Industrial added values	Km kWh/km^2 m^3/(year*km^2) USD/km^2	Max-min Dividing by the highest Dividing over the area Dividing by the second-highest

The scores for each indicator are given below

Parameter	Subpart	Indicators	Value	Normalization
Lo_1	1	Distance between production and consumption	4608.4	**75%**
Lo_2	1	Energy use per area	20074323.26	**96%**
Lo_3	1	Total renewable surface water	91	**84%**
Lo_4	1	Industrial added values	1.383^{11}	**69%**

Each indicator's weight is 25%, and so, by applying equation (2), the total score for the location dimension is **81%**.

5.1.6 Environment

The environment dimension is essential in energy security analysis, especially considering a future renewable energy system. The first indicator expresses how many earths would be required if everyone lived like the Netherlands. The second metric indicates how much CO_2 is emitted by consuming one kWh. The third indicator implicates the total amount of GHG emissions per USD in the Netherlands, and the following ratio defines the last indicator

$$Water\ stress\ (\%) = \frac{TFWW}{TRWR - EFR} * 100\% \tag{6}$$

TFWW is the total freshwater withdrawn; TRWR is total renewable freshwater, and EFR are the environmental flow requirements (UN Water, 2018). The first indicators are adapted from data from the Central Bureau of Statistics, and the final indicator is extracted from the United Nations paper on Clean Water and Sanitation (UN Water, 2018). The rate of exploitation is calculated by the ecological footprint. This indicates how many earths are required to cope with human activity. The energy intensity of the Netherlands is strongly related to this score. Due to the Netherlands' energy-intensive industry, carbon emissions per kWh energy use are high, decreasing this indicator's score.

Dimension	Parameters	Indicators	Unit	Normalization
Environment	E_1 E_2 E_3 E_4	Ecological footprint (number of earths required) CO_2 intensity Total GHG emissions excluding land-use change and forestry per GDP Water stress	Number Kg per kWh energy use $MtCO_2$/USD Percentage	Max-min Dividing by the maximum in the world Dividing by the highest in the world Normalized, but subtract from unity

The scores for each individual indicator is given below:

Parameter	Subpart	Indicators	Value	Normalization
E_1	1	Ecological footprint	3.1	**51%**
E_2	1	CO_2 intensity	0.197	**41%**
E_3	1	Total GHG emissions excluding land-use change and forestry per GDP	2.7^{-10}	**77%**
E_4	1	Water stress	21%	**79%**

The weight of each indicator is 25%, and so, by applying equation (2), the total score for the environment dimension is **62%**.

5.1.7 Culture

The seventh dimension in the energy security analysis is culture, and likewise environment, this dimension is essential in the face of a new renewable energy system. For this reason, a new parameter has been added based on the article on the climate policy info hub written by Hofman (2015). The first indicator represents the energy use per capita; more energy use per capita implies higher energy security. The second indicator is extracted from the supplementary data sheet provided by Azzuni & Breyer (2020).

To find values for this second parameter, interviewees have been asked to score each indicator on a scale from 0% to 100% compared to other countries in the world based on their perspective. The average of these scores is taken as the final score for each indicator.

The two first indicators are straightforward and require no additional explanation. The second parameter is more complicated. This parameter comprises five indicators. Interviewees were asked to score the indicators for the current energy system, with the Netherlands as a reference case compared to other countries in the world. The first indicator entails the perception of society on climate change and renewable energy technologies. Interviewees estimated this to considerably high. The perceived fairness in decision-making regarding renewable energy projects received an average score due to the need for more transparency in these processes and communication to society. The third indicator was scored moderately; while there are ample opportunities for gaseous energy carriers, policy/decision-makers fail to communicate the benefits of other solutions. The local context indicator received a low score; Dutch society is incredibly reluctant to decentralize renewable energy sources. Society stipulates decisionmakers as trustworthy due to their expertise and prior history in “getting things done.” Even more so considering the natural gas infrastructure and possible future applications for renewable gaseous energy carriers.

Dimension	Parameters	Indicators	Unit	Normalization
Culture	Cu_1	1: Energy use per capita 2: Air transport, passengers carried per capita	1: kWh/capita 2: Number per capita	1: Dividing by the maximum in the world 2: Dividing by the maximum in the world
	Cu_2	1: Awareness of climate change and knowledge of the technology	1: Percentage	1: Normalized

		2: Fairness of the decision-making process 3: Overall evaluation of costs, risks, and benefits of technology 4: Local context (NIMBY) 5: Trust in decision-makers and other relevant stakeholders	2: Percentage 3: Percentage 4: Percentage 5: Percentage	2: Normalized 3: Normalized 4: Normalized 5: Normalized

The scores for each individual indicator is given below:

Parameter	Subpart	Indicators	Value	Normalization
Cu_1	1	Energy use per capita	49230.301	**21%**
	2	Air transport, passengers carried per capita	2058.636	**9%**
Cu_2	1	Awareness of climate change and knowledge of the technology	**80%**	None
	2	Fairness of the decision-making process	**60%**	None
	3	Overall evaluation of costs, risks, and benefits of technology	**65%**	None
	4	Local context (NIMBY)	**30%**	None
	5	Trust in decision-makers and other relevant stakeholders	**70%**	None

The weight of each parameter is 50%, while the indicators are weighted differently for each parameter. The first two indicators belonging to the first parameter are weighted 50% each. The final five indicators belonging to parameter two are weighted 20% each. Applying equation (3) for each parameter, the score for each parameter is found. The final step is to apply equation (2), resulting in a total score of **38%**

5.1.8 Policy

The final dimension that is included in the analysis entails policy. There is one parameter accompanied by two indicators that make up for this dimension. The first indicator gives implications on how much energy-related subsidies and other transfers are available in the Netherlands as a percentage of expenses. A higher amount of subsidies indicates lower energy security; hence, the value is subtracted from unity. The second indicator grades the Netherlands in three areas: energy access, energy efficiency, and renewable energy. It is the first global scorecard of its kind and extremely comprehensive regarding regulations and policies regarding renewable energy (World Bank, 2016). A detailed overview of this indicator based scorecard is presented in Appendix E

Renewable energy projects are less reliant on governmental financial aid to reap financial returns. It is expected in the coming decade that sizeable offshore wind parks will no longer need subsidies for positive financial returns. The regularity indicator for sustainability is an extensive indicator-based analysis of multiple countries in the world. This score was taken from its report. The RISE score is calculated from three different renewable energy policy themes: energy access, energy efficiency, and renewable energy. The Netherlands' score is considerably high, resulting in fourth place for overall score, behind Denmark, the United States, and Canada. The renewable energy parameter stands out for the Netherlands, resulting in second place compared to other countries. Most room for improvement is expressed in the energy efficiency parameter. A detailed overview of the scoring card is presented in Appendix E

Dimension	Parameters	Indicators	Unit	Normalization
Policy	P_1	1: Subsidies and other transfers (percentage of expense, subtracted from unity) 2: Regularity indicator for sustainability (RISE)	Percentage	Normalized

The score for each individual indicator is given below:

Parameter	Subpart	Indicators	Value	Normalization
P_1	1	Subsidies and other transfers (percentage of expense, subtracted from unity)	**79%**	**21%**
	2	Regularity indicator for sustainability (RISE)	**90.00%**	None

The weight of each indicator is 50%, and so, by applying equation (2), the total score for the policy dimension is **84%.**

5.2 Energy security score of the current Dutch energy system

With all results from each dimension, the following equation is applied

$$\text{Energy Security Index } = \sum_{i=1}^{m} V_i * X_i \tag{1}$$

The energy security index score for the Netherlands is **57%**. Figure 18 gives a schematic overview of how the scoring of each dimension relates to each other. As mentioned before, the low score of the availability dimension will be explained in the discussion section. The next chapter will explore Dutch energy security, given the two future scenarios delineated in chapter 3. After this chapter, both results from the current system and potential future system are synthesized.

Following these scores, it is paramount to understand what these scores imply and how these scores are used in assessing the effects of hydrogen on energy security in a future system. Scoring Dutch energy security with these percentages is somewhat arbitrary but helps understanding how stable each dimension is or where improvement will have a significant effect. The definition of energy security, developed in section 2.1.2, is *"a sustainable supply of energy that is not likely to fail in any of its relevant dimensions."* Linking this definition of energy security to each dimension's scores in the analysis of the reference case permits to argue what dimensions are likely to fail under stress and where improvement is most beneficial. Of course, there is no right or wrong in this assessment since the scores reflect the Dutch performance with other countries in the world, but one can assume that high scores mirror a smaller probability of failures.

Moreover, it is assumed that higher scores in the dimensions suggest that improvement is less likely, while deterioration is easier. Based on these results and assumptions, the dimensions' scores help signify what dimensions are more susceptible to change because of hydrogen, either positive or negative. The rationale for depicting the effects of hydrogen in the built environment on the individual indicators is further delineated at the beginning of the following chapter.

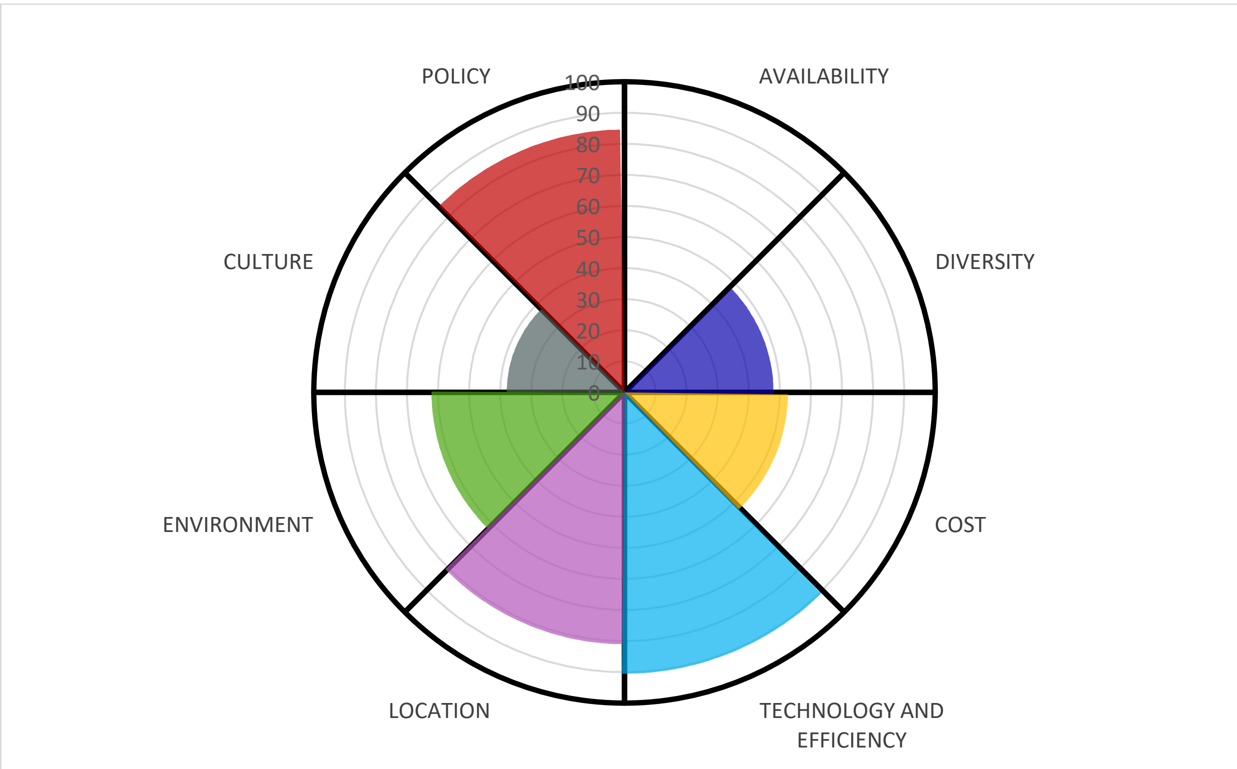
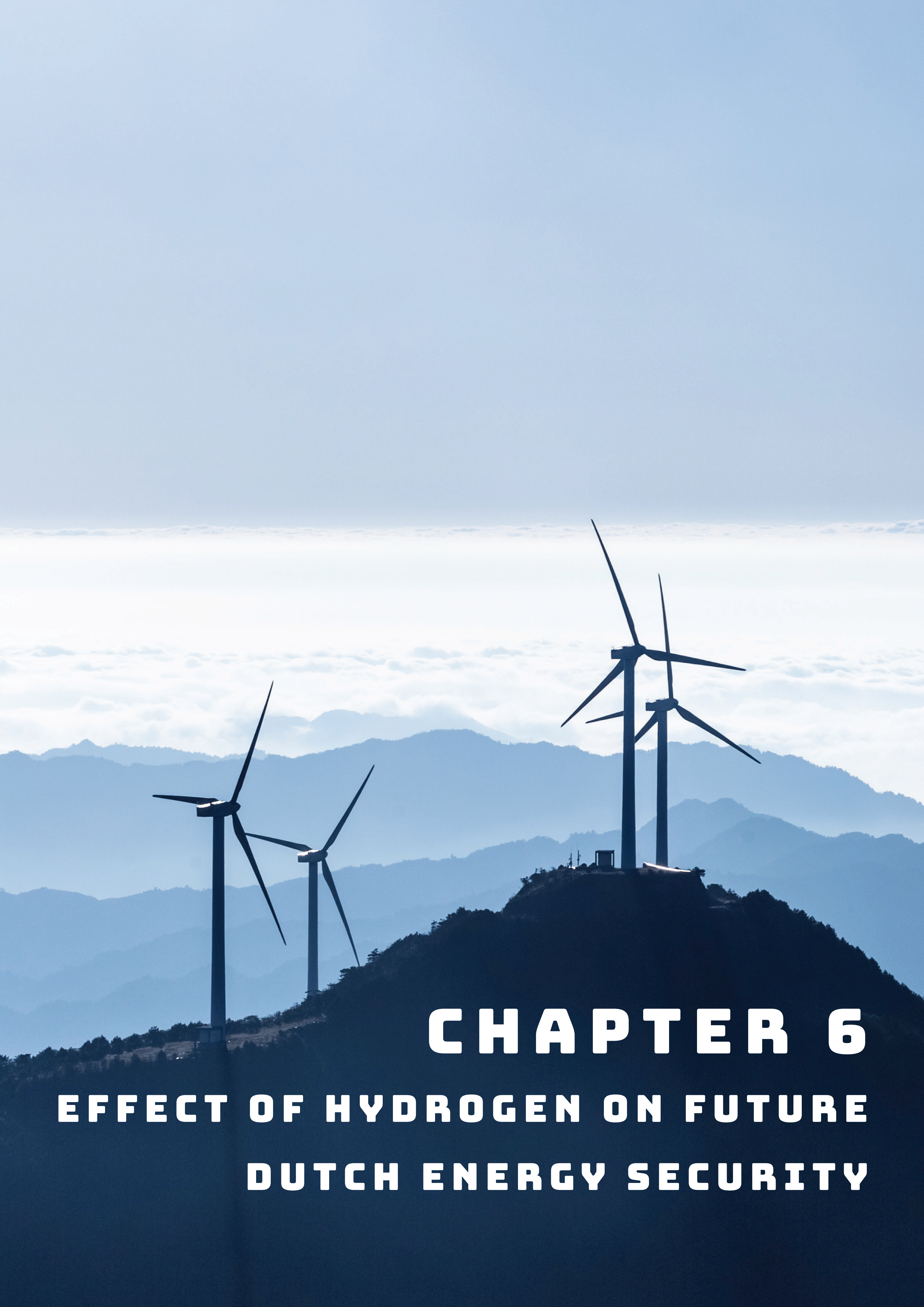


Figure 19: Score for each dimension according to the energy security framework.



CHAPTER 6

EFFECT OF HYDROGEN ON FUTURE DUTCH ENERGY SECURITY

6. Effect of hydrogen on future Dutch energy security

The following chapter intends to qualitatively analyse the effects of hydrogen on the Netherlands' future energy security given two different scenarios. The analysis is performed following the same conceptual framework and dimensions, as was done for the current system in chapter 5. The effect of hydrogen utilization on each of these dimensions is established with strong argumentations from both the scenarios and interviews with experts in the field. The interview themes are linked to the dimensions using the thematic analysis method, as proposed in Evans & Lewis (2018). The takeaways for each dimension are constructed based on the frequency different interviewees mention the matter. If certain statements are recurring frequently, its validity is deemed high and taken into the scoring for the indicator at hand or dimension. This rule of thumb is applied for all arguments made in the interviews and used to score each dimension's parameters in this fashion. The geotechnical characteristics delineated in chapter three are also incorporated in the arguments for scoring the indicators because many indicators in the dimensions are dependent on the geotechnical characteristics of the energy system, in more detail, hydrogen in this case. For example, the availability, diversity, technology and efficiency, location, and environment dimension contain parameters affected by altering geotechnical characteristics compared to the reference case.

The analysis addresses every parameter of each dimension and demonstrates how hydrogen positively or negatively affects this dimension. A positive relation is denoted with a positive sign, an adverse effect is denoted with a negative sign, and a neutral score is awarded when there is no clear relation between hydrogen in the built environment and that parameter. The overall evaluation for that dimension is a numerical sum of the negative and positive signs. The results for each dimension are colour coded, and the colour is determined by the total number of positive and negative impacts the dimension obtained in the analysis. Green is allocated when the dimension contains more positive impacts than adverse effects. The colour red is awarded when the dimensions are affected negatively. When an equal amount of positive and negative impacts are distinguished, a yellow colour is awarded. The chapter is structured as follows: first, the effect of hydrogen on each dimension is evaluated for the national scenario. Hereafter, the same method is applied to the international scenario.

6.1 Energy security of the national scenario

This section will qualitatively determine the consequences of integrating hydrogen in the built environment on energy security, given the national scenario's boundaries. The same method is applied, as in chapter 5, discussing each dimension individually.

6.1.1 Availability

	Indicators	Score
Availability	Existence of resources	+
	Existence of consumers	O
	Existence of means of transport (access)	+

The availability dimension is analysed with three parameters, as is displayed in the table above. This dimension is examined using the available data in the national scenario and from the CBS (CBS, 2020b).

Existence of resources

The first parameter entails the existence of resources. This parameter was measured by examining the availability of fossil fuel-based on the current production and the difference between the potential of renewable energy sources and the actual amount harvested. Studying the energy flows presented in the appendix corresponding to the national scenario, there is a decrease in domestic fossil fuel production and a significant increase in renewable energy generation. The Netherlands had the substantial potential for renewable energy sources, and these are exploited entirely in this scenario because it aims at energy autonomy. The role of hydrogen as an energy carrier is significant in achieving renewable energy exploitation in this quantity. Without coherent storage, it is impossible to have an autonomous energy system that meets demand and supply. The high quantity of renewable energy sources contributes to hydrogen production due to surpluses. For this reason, approximately one-third of hydrogen production is available for the built environment. Consequently, hydrogen in the built environment has a positive effect on the first parameter but is more a result of the large share of renewable energy sources (mainly wind).

Existence of consumers

According to the Central Bureau of Statistics population outlook, the expected population growth in the Netherlands will be from 17.4mln to 19.35mln. In the overall energy security context, this would be beneficial for the second parameter because more inhabitants imply more potential consumers of energy and that more energy is consumed. However, there is no direct relationship between this parameter and utilizing hydrogen in the built environment. Hence, this parameter is scored as neutral (yellow).

Existence of means of transport

This is an interesting parameter to analyse. The current system to distance to energy is based on the total imports of energy across the world. The weighted average is scored and compared to other countries in the world. In the national scenario, there is an aim of complete energy autonomy. That indicates a significant decrease in distance to energy. The importance of hydrogen is undisputable considering its role as storage carrier and fuel for the built environment. Hydrogen in the built environment consumes approximately one-third of the total hydrogen production, and all hydrogen is produced domestically. Hence, in this scenario, hydrogen in the built environment contributes considerably positive to this parameter.

6.1.2 Diversity

	Indicators	**Score**
Diversity	Diversity of sources	O
	Diversity of fuel (energy carriers)	+
	Diversity of means (technologies, transportation)	+
	Diversity of consumers	-

The diversity dimension is analysed with four parameters, as is displayed in the table above. All the parameters are measured by determining the Simpson Diversity Index. The data is extracted from the national scenario to evaluate this dimension and total final energy consumption from the IEA (IEA, 2018).

Diversity of sources

The diversity of sources is based on the amount of domestic energy production and imports. An evenly split distribution of local energy production and imports translates into the highest score possible. The national scenario builds on the premise that the Netherlands becomes energy-autonomous towards 2050. That means that this parameter is drastically affected negatively. The effect hydrogen plays in this negative attribution is significant. The amount of hydrogen consumed in the built environment in this future scenario requires a large share of renewable energy sources. However, since this scenario builds on the assumption that the Netherlands waives energy imports in the first place, this parameter is scored as neutral.

Diversity of fuel

This parameter is evaluated by inspecting how much each energy carrier contributes to the total final consumption. The most apparent method to analyse this parameter for the national scenario is to examine the figures from chapter 3. The flow diagrams are given in appendix G.1 and G.2 Interesting is that hydrogen is not a primary energy source and is, consequently, positioned differently in the energy flows. From these figures, it

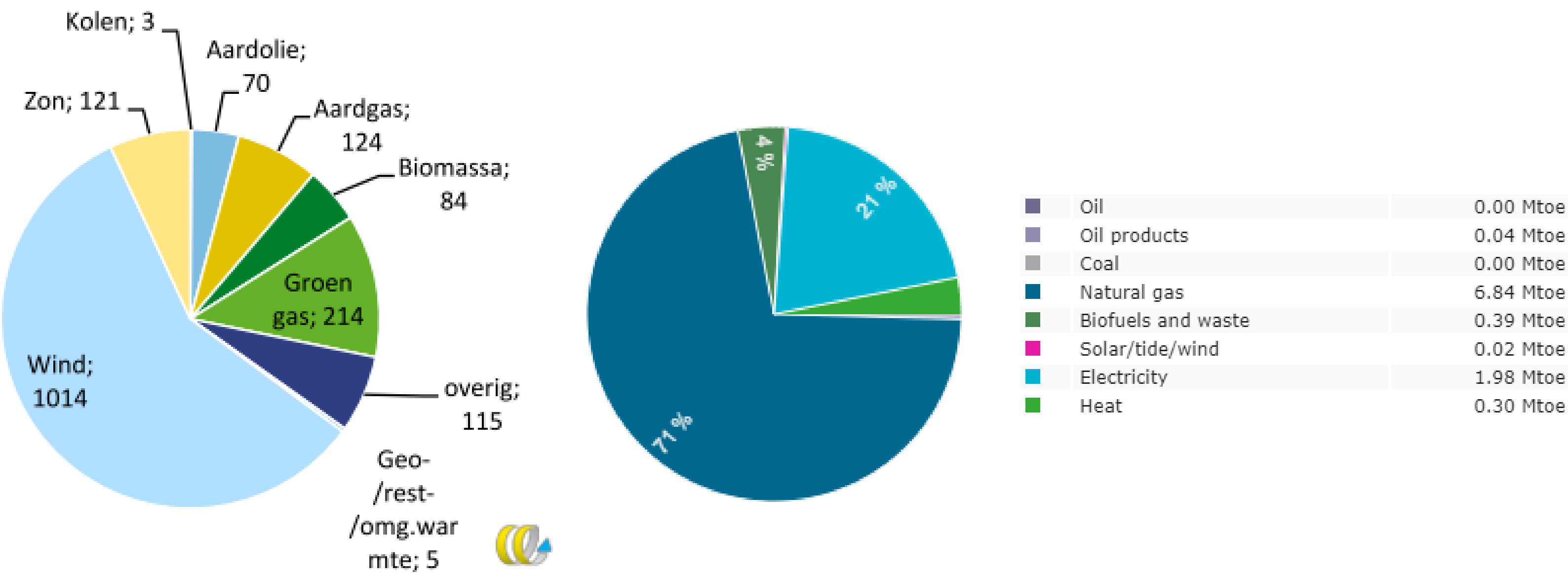


Figure 20: Energy carrier consumption diagrams. Left: 2050, national scenario, right: 2018 current system.

is apparent that over one half of the produced electricity is converted into hydrogen, of which one third is used in the built environment. Given this premises, wind and solar energy in the diagram in the figure below should be split approximately 60% electricity and 40% hydrogen as of final carrier state before end-use. This implies that hydrogen significantly diversifies this parameter; hence, a positive score is awarded.

Diversity of means

This parameter is twofold; one part analyses the diversity of technologies, and the other signifies the diversity of energy transport commodities. Current heating in the built environment is majorly accomplished by combusting natural gas in condensing boilers. This is presented in the Sankey Diagram of energy flows for the current energy system in Appendix G.1 However, in the national energy scenario, the Netherlands is divided into clusters. For each cluster, the most cost-efficient heating technology is implemented. This cluster type of heating design for the Netherlands is acknowledged in several interviews with experts in the field. This diversifies the means for heating significantly, as figure 11 indicates in section 3.3.1.1. The role of hydrogen as an energy carrier for heating is significant across different technologies and heating applications. Hence, the effect of hydrogen in the built environment is positive regarding this parameter.

Diversity of consumers

Diversity of consumers is measured by considering the energy demand of different consumers/sectors in the energy system. According to the national scenario, final energy demand will decrease, moving towards 2050. Examining the figure below gives an impression of consumers' eventual division in the total final energy demand. There is a slight increase in diversification; however, the share of low-temperature heat in the built environment increases in terms of total consumption. Hydrogen in the built environment does not contribute to the diversity of consumers. This parameter is awarded a negative score.

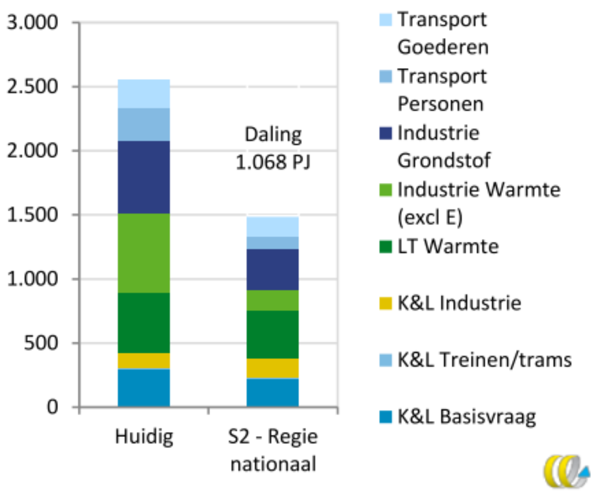


Figure 21: Total final energy demand, national scenario, in Dutch (Afman & Rooijers, 2017).

6.1.3 Cost

	Indicators	Score
Cost	Energy prices (consumers, producers, peak oil, and stability/volatility	-
	Cost of securing the system	+

The cost dimension is evaluated with two parameters, as indicated in the table above. The data for this dimension is gathered from semi-structured interviews with experts in the field.

Energy prices

According to an interviewee, energy price is not solely determined by hydrogen in the future. The energy price consists of all the efforts we make to decarbonize our energy needs. However, hydrogen is a means to decarbonize energy systems. Towards 2050, the energy price can grow concerning hydrogen since its production costs are relatively high compared to electrification (Interview EBN). Energy prices for solar and wind are gradually decreasing. However, electrifying the energy system comes with increased costs to prevent congestion and grid expansion.

For this reason, renewable gasses like hydrogen are necessary to dampen these costs and complexities (Interview Enexis). Still, an energy scenario that relies primarily on domestic energy production cannot lower energy prices than the current energy system. Dealing with these renewable energy sources' intermittency, a great deal of hydrogen and battery storage is installed in the national scenario. These investment costs are all translated into the price of energy (interview EBN).

Regarding stability and volatility, hydrogen will have a significant role in providing stable and non-volatile prices, especially in the national scenario, where the share of intermittent renewable energy sources is considerably large. Utilizing hydrogen in the built environment is believed to be beneficial because there is no extra conversion to electricity, improving efficiency (Interview EBN). Hence, hydrogen in the built environment prevents the curtailment of renewable energy sources in combination with storage. Still, the substantial investments in renewable energy sources and storage capacity probably result in higher energy prices. Hence, this indicator is given a negative score.

Cost of securing the system

The levelized cost of energy is closely related to the first parameter. The price of hydrogen is linked to the LCOE of electricity from renewables. Ultimately, the LCOE of hydrogen depends on how hydrogen is used for creating energy. Hydrogen in the built environment is favourable over utilizing hydrogen for electricity production (interview TNO). Hence, hydrogen in the built environment has a positive effect on the LCOE.

6.1.4 Technology and efficiency

	Indicators	Score
Technology and efficiency	Energy system efficiency	-
	Energy intensity	-
	Energy conservation	O

The technology and efficiency dimension is measured through three parameters. As displayed in the table above. The data is extracted from the interviews with stakeholders and experts in the field

Energy system efficiency

The energy system efficiency was measured through the energy return on energy invested method in analyzing the current system. The Netherlands scored high on this parameter, along with other countries in the world. However, this parameter is bound to change in the future. With increasing renewable energy deployment and the need for balancing supply and demand, renewable energy sources are bound to curtailment when demand is lower than supply. However, moments in time when potential supply is larger than demand offers the opportunity to produce hydrogen from the excess amount of renewable electrical energy. This increases the amount of energy delivered by renewable technologies because hydrogen provides extra running hours.

On the contrary, when hydrogen is produced and converted back to electricity in times of electrical supply shortages, hydrogen harms energy system efficiency. When considering hydrogen in the built environment, there is no need for this conversion step. That implies that when the built environment consumes hydrogen generated in the oversupply hours of the energy system, there is a positive effect on the energy systems efficiency (interview EBN/Enexis/Enpuls). This implies that the way hydrogen is consumed and produced determines system efficiency. Nevertheless, *"at some moments in time it is energetically inefficient to convert hydrogen back to electricity but economically favourable" – Enpuls*. For these reasons, hydrogen in the built environment harms system efficiency compared to the current system.

Energy intensity

Energy intensity level of primary energy is the ratio between energy supply and gross domestic product measured at purchasing power parity. Energy intensity is an indication of how much energy is used to produce one unit of economic output. A lower ratio indicates that less energy is used to produce one unit of output.

Hydrogen has a lot of dimensions and a wider system role than traditional fuels. For example, hydrogen utilized in the industry sector has significant differences with utilizing fossil fuels for feedstock. *"in this sense, nature has already done part of the job in these energy-intense conversion process" – TNO.* When renewable energy carriers are introduced in these processes, there is an extra conversion step that increases energy intensity. When hydrogen is utilized directly in the built environment, these conversion losses are less significant. However, this implies that hydrogen in the built environment increases energy intensity compared to the current heating system; hence, a negative score is awarded to this parameter.

Energy conservation

The energy conservation parameter is based on the consumption of fuel by light vehicles. A lower consumption awards a better score for this parameter. This parameter is not influenced by hydrogen applications on the built environment and given a neutral score.

6.1.5 Location

	Indicators	Score
Location	Distance between production and consumption	+
	Energy use per area	+
	Total renewable surface water	-
	Industrial added values	+

The location dimension is analysed with four parameters, as indicated in the table above. The data is extracted from the scenarios and interviews with stakeholders and experts in the field.

Distance between production and consumption

The distance between production and consumption improves significantly by integrating renewable energy sources into the energy system. In the energy-autonomous national scenario, there is complete independence of foreign energy sources, implying that all energy demand is generated domestically. This prerequisite makes it challenging to examine the effects of hydrogen in the built environment and the distance between production and consumption in general terms. However, within the Dutch system context, utilizing hydrogen in the built environment relies primarily on the central production of hydrogen that requires to be distributed in the Netherlands utilizing (existing) gas grids (interview Stedin, TNO, Enexis, Gasunie). Compared with different heating solutions, like heat pumps, energy inputs can be produced more locally, hence, decreasing the distance between production and consumption.

Consequently, hydrogen in the built environment increases the distance between production and consumption in terms of the overall system context and comparison with other heating solutions. However, compared with the current system, the overall distance between production and energy consumption decreases significantly in this scenario. Therefore, this indicator is given a positive score.

Energy use per area

This parameter is scored by calculating the energy use (kWh) per area. There is an expected increase in approximately 11% population while there is a decrease in final energy demand of approximately 40%. This implies that the energy use per area decreases in this future scenario, thus, increasing the score of this parameter. The built environment's contribution to this decrease in final energy demand is relatively lower than in other sectors (figure 19). Still, a decrease in energy demand in the built environment is expected.

Considering the prominent role of hydrogen in this scenario's built environment, the effect on energy security for this parameter is rated positively.

Total renewable surface water

This is an exciting parameter in terms of hydrogen production for utilization in the built environment. The current Dutch energy system has a high score for this parameter, given water use and precipitation. However, large scale hydrogen production requires hefty amounts of freshwater that could compete with consumption in other sectors. Multiple stakeholders indicated that hydrogen production for the built environment would not drastically deplete freshwater supply (interview TNO, Enexis). Still, large-scale hydrogen production intended for the built environment harms the total renewable surface water; hence, this indicator is awarded a negative score.

Industrial added values

According to the interviews, there is much potential to export hydrogen (products) to the rest of the world, especially considering the geographic location of the Netherlands and the Rotterdam port. The difference between oil and hydrogen is their respective energy densities and transportation commodities. This implies that the industrial output will change over the years when the products change from fossil fuels to renewable energy carriers (interview TNO). Given the Netherlands' unique location, there is great potential to be a frontrunner in hydrogen production and, hence, the export of hydrogen to other countries. Utilizing hydrogen in the built environment in the quantities mentioned in section 3.3.1.1 creates a coherent hydrogen supply chain dependency. The hydrogen supply chain allows for carrier exports and new business models. As indicated, the Netherlands’ unique location stimulates an increase in industrial output with regards to hydrogen. Hence, this indicator is rated with a positive score.

6.1.6 Environment

	Indicators	Score
Environment	Ecological footprint (number of earths required)	+
	CO_2 intensity	+
	Total GHG emissions excluding land-use change and forestry per GDP	+
	Water stress	-

The environment dimension is analysed with four indicators that are listed in the table above. The indicators in this dimension are closely related to each other. The data is extracted from the scenario and interviews with stakeholders and experts in the field. This dimension is rather evident in terms of the effects of a sustainable energy system, but it is worth mentioning hydrogen's contribution in the built environment shortly for each indicator.

Ecological footprint

The ecological footprint considers the biocapacity of a region. Currently, the ecological footprint of the Netherlands exceeds the biocapacity of the country. The ecological footprint of the Netherlands will decrease, moving towards a renewable energy system. Any efforts at decarbonizing different sectors and parts of the energy system reduce the Netherlands' ecological footprint. Hydrogen is one part of the chain in achieving a decarbonized energy system. Determining the effects of hydrogen in the built environment in terms of decreasing the ecological footprint is exceptionally challenging, considering a potential future energy system.

However, several studies predict a great decarbonizing potential from hydrogen when produced from renewable wind energy, as depicted in section 3.3.1. This indicator is given a positive score.

CO_2 intensity

Carbon intensity is examined by considering the amount of carbon emissions (in kg) per kWh energy use. The energy intensity of hydrogen is directly related to the electricity source. This implies that hydrogen produced from the electricity that is generated from renewable energy sources is carbon-free. Compared to natural gas combustion in condensing boilers, the hybrid heating systems do not emit any carbon dioxide. The only emissions are related to technology production, considering the whole supply chain. Therefore, this indicator is awarded a positive score.

Total GHG emissions

The total GHG emissions will to near zero in this scenario. The contribution of hydrogen in the built environment is significant, considering its share in the final energy system. Therefore, the score attributed to this indicator is positive.

Water stress

The water stress indicator evaluates the reduced availability of clean water for consumption. Just as the third parameter in the location dimension, the effect of hydrogen production for the built environment is negative on freshwater availability for consumption. However, different stakeholders acknowledged in the interviews the potential environmental problem regarding water supply for hydrogen solutions. Still, the environmental gain of hydrogen in the built environment weighs considerably more. Next, each type of energy harvesting has negative environmental consequences (interview TNO, Enexis). Nevertheless, for practical reasons, this indicator is scored negatively.

6.1.7 Culture

	Parameter	Indicators	Score
Culture	1	Energy use per capita	+
		Air transport, passengers carried per capita	O
	2	Awareness of climate change and knowledge of the technology	+
		Fairness of the decision-making process	+
		Overall evaluation of costs, risks, and benefits of technology	+
		Local context (NIMBY)	-
		Trust in decision-makers and other relevant stakeholders	+

The culture dimension is analysed with seven indicators in two different parameters, as indicated in the table above. The data for this dimension is gathered from the scenario and interviews with stakeholders and experts in the field.

Energy use per capita

The Netherlands' final energy demand is decreasing (figure 19), and the total population will increase over the years. This indicates a decrease in energy use per capita. The energy use in the built environment decreased the least in relative terms compared to other sectors. However, the relation of hydrogen in the built environment is positive in terms of this indicator. Therefore, this indicator is given a positive score.

Air transport, passengers carried per capita

There is no relation between this indicator and hydrogen in the built environment distinguished. Hence, this indicator is awarded a neutral score.

Awareness of climate change and knowledge of the technology

For the current Dutch energy system, this indicator was measured with the expert interviews where interviewees were asked to score this indicator from the second parameter from 1 to 10. There is a great deal of effort and resources mobilized to create more awareness among citizens considering climate change and the implications of different renewable technologies. Interesting is that multiple stakeholders mentioned the ease of implementation of hydrogen in the built environment. Dutch citizens are used to burning gaseous energy carriers in households to satisfy heat demand and cooking utilities. Hence, the knowledge of the incumbent technology of hydrogen combustion is well developed. Though there is no clear relation between climate change awareness and hydrogen in the built environment, it does contribute to easier knowledge diffusion of the incumbent technology. Hence, this indicator is awarded a positive score.

Fairness of the decision-making process

The fairness of the decision-making process is based on how citizens perceive the fairness and transparency of the decision-making process regarding renewable energy projects and decarbonization efforts. Currently, interviewees indicated that there is much room for improvement in providing enough transparency and better communication regarding decarbonization. However, hydrogen in the built environment is generally easier to communicate because citizens are more used to gaseous energy carriers than all electric solutions (interview NVDE). Therefore, this indicator is given a positive score.

Overall evaluation of costs, risks, and benefits of technology

This effect of hydrogen in the built environment was rated outmost positively by different interviewees (interview Stedin, Enexis, Gasunie, EBN, NVDE, TNO). However, some improvements concerning the communication of costs ought to improve (interview NVDE). Due to the Netherlands' gas background, risks and benefits of the technologies that hydrogen in the built environment necessitate are regarded as common knowledge. For this reason, many districts and regions in the Netherlands are even hesitant for other heating solutions like district heating. They feel more familiarised with gaseous energy carriers. As a result, this indicator is allocated a positive score.

Local context (NIMBY)

The local context of the culture dimension is an important indicator given the two different scenarios. The national scenario relies on self-sustainment and energy autonomy, increasing the demand for domestic renewable energy capacity. Besides, domestic energy generation and production of hydrogen require sizable facilities to satisfy energy demand. Hydrogen for heating in the built environment will experience less resistance than other heating solutions, a frequently returning comment in the interviews with stakeholders and experts in the field. However, considering a full energy autonomy scenario requires an extensive domestic renewable capacity with corresponding hydrogen infrastructure. This can inhibit a NIMBY problem (interview Enpuls). Therefore, this indicator is given a negative score.

Trust in decision-makers and other relevant stakeholders

This indicator is closely related to indicator four. According to interviews with experts in the field, acceptance of hydrogen in the built environment is more straightforward than other heating solutions due to the background of Dutch society. This has been mentioned before and is a critical aspect of the success and acceptability of hydrogen in the built environment. The relation of hydrogen in the built environment and trust in decision-makers is twofold. First, hydrogen in the built environment is expected to experience the least resistance compared to other solutions. Therefore, trust in contractors and decision-makers is somewhat positive (interview Enexis, TNO, EBN, Enpuls). Second, trust in decision-makers is based on their historical performance, and considering gas infrastructure stakeholders, their trustworthiness is credited and embroidered in Dutch society (interview NVDE). Hence, this indicator is scored positively in the context of hydrogen in the built environment.

6.1.8 Policy

	Indicators	Score
Policy	Subsidies and other transfers (percentage of expense, subtracted from unity)	-
	Regularity indicator for sustainability (RISE)	+

The policy dimension is constituted from one parameter with two indicators. Data for this scenario is retrieved from expert opinions on renewable energy policy. The second indicator is more extensive, reviewing the policy indicators that make up the regularity indicator for sustainability. The overview for these metrics is presented in Appendix F

Subsidies and other transfers

Currently, renewable energy production is bound to subsidy support to be profitable. The levelized cost of electricity for both wind and solar technologies is decreasing. Giant offshore wind parks will not be needing any subsidy anymore from five years onwards (interview Enpuls). However, hydrogen developments and implementation in the built environment are not ready before 2025 (Gigler & Weeda, 2018). This implies that the starting point for hydrogen implementation in the built environment requires government subsidies or investments. That indicates a new wave of government subsidies to provide coherent incentives utilizing hydrogen in the built environment (interview Enpuls, Stedin, Enexis, EBN, NVDE). For that reason, this indicator is awarded a negative score since a lower reliance on subsidies is depicted as better for energy security.

Regularity indicator for sustainability (RISE)

The regularity indicator for sustainability scores assesses a countries' regulatory and policy support given the three pillars of sustainable energy: 1. Access to modern energy, 2. Energy efficiency, and 3. Renewable energy. The first theme, energy access, is stable over the years towards 2050. Interviewees expect no risks regarding policymaking and providing energy access in the coming years. This is and will be, the first priority (interview Gasunie, Enexis, Enpuls). Still, the national scenario requires substantial grid expansion due to a large number of renewable energy sources. Hydrogen in the built environment helps to prevent congestion when utilized in the built environment. However, this creates energy efficiency losses. The second theme, energy efficiency, will somewhat change over the years, especially in the national scenario. There is no comprehensive legislation concerning hydrogen in general. There is a need for clear role distribution in the built environment and how to deal with seasonality or conversion for grid assistance in times of supply deficits (interview Enexis, TNO, EBN, NVDE, Stedin). The third theme considers renewable energy. The regulatory support for hydrogen needs to be put in place. There is no legislation for hydrogen as a gaseous energy carrier, but only for its use as feedstock for industrial processes.

However, many interviewees acknowledged this problem but did not expect any risk towards the future. The role of the government should be prominent in the early stages of implementation. *"Last decades, we had quite a neo-liberal government, looking at markets. We see now that, especially with COVID, that this is backcast to the society. This raises the question of whether the government should maybe get involved more. I believe that they should. More and more public parties join in these initiatives, and I believe that this is interesting and good." – Stedin*. There is a need for inclusive regulation, with an accentuated role for the government. Therefore, this indicator is scored positively.

6.2 Summary of energy security dimensions for the national scenario

Dimensions	Availability	Diversity	Cost	TE	Location	Environ.	Culture	Policy
Impact	+ O +	O + + -	- +	- - O	+ + - +	+ + + -	+ O + + + - +	- +

Table 6: Summary of energy security dimensions for the national scenario

The summary of the effect of hydrogen utilization in the built environment on energy security for the national scenario has been presented in table 5. The green colour coding indicates a positive correlation, yellow a neutral impact, and the red colour expresses a negative impact of hydrogen in the built environment on that dimension. In general, hydrogen in the national scenario's built environment has positive effects on the distinct indicators. A comparison between results from this scenario and the international scenario is made in section 7.1.

6.3 Energy security of the international scenario

This section will qualitatively determine the consequences of integrating hydrogen in the built environment on energy security, given the international scenario's boundaries. The same method is applied as in the previous section. The indicators that are the same for the international scenario are copied from the national scenario. A short argument for why there are no significant differences between the national and international scenarios is given for that indicator.

6.3.1 Availability

	Indicators	**Score**
Availability	Existence of resources	-
	Existence of consumers	O
	Existence of means of transport (access)	+

The availability dimension is analysed with three parameters, as is displayed in the table above. This dimension is examined using the available data in the national scenario and from the CBS (CBS, 2020b).

Existence of resources

The first parameter entails the existence of resources. This parameter was measured by examining the availability of fossil fuel-based on the current production and the difference between the potential of renewable energy sources and the actual amount harvested. There is no wish for energy autonomy in the international scenario, resulting in a considerable amount of energy imports. Domestic renewable energy production is 27GW of either wind or solar power, which satisfies 10% of final energy demand. A considerable amount of final energy demand is imported in the form of different energy carriers. Hydrogen for heating in the built environment finds a share of approximately 40% either in hybrid heat pumps or hydrogen condensing boilers. However, almost all hydrogen demand is imported from other countries. This implies that their hydrogen is not produced from domestic renewable energy from either wind or solar sources. This affects this indicator negatively, even more so hydrogen in the built environment considering all the hydrogen is imported. Hence, this indicator is awarded a negative score.

Existence of consumers

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. According to the Central Bureau of Statistics population outlook, the expected population growth in the Netherlands will be from 17.4mln to 19.35mln. In the overall energy security context, this would be beneficial for the second parameter because more inhabitants imply that there are more potential consumers of energy and that more energy is consumed. However, there is no direct relationship between this parameter and utilizing hydrogen in the built environment. Hence, this parameter is scored as neutral.

Existence of means of transport

An interesting indicator for discussion. In the current energy system, the distance to energy is based on the total energy imports across the world. The weighted average is scored and compared to other countries in the world. There is a shift in fossil fuel imports to importing renewable energy carriers and electricity in the international scenario. The implications of high quantities of hydrogen in the built environment would suggest a mere shift in import dependencies. However, indicated in the interviews, renewable energy carrier imports are likely to come from these carriers' European market (interview Gasunie, TNO). There is the expectation of competitive European markets in terms of hydrogen. This implies a slight improvement in the distance to energy compared to traditional fossil fuel imports from Saudi Arabia and Russia. However, currently, the Dutch energy system is supplied with domestic natural gas even though significant decreases in extraction are detected. Still, the final energy demand in this future scenario is 40% lower than the current final energy demand. This outweighs domestic natural gas extraction resulting in a slight positive effect in terms of distance to energy. That being said, hydrogen in the built environment positively affects this indicator due to quantity and the expected European hydrogen markets. Hence, this indicator is given a positive score.

6.3.2 Diversity

	Indicators	**Score**
Diversity	Diversity of sources	O
	Diversity of fuel (energy carriers)	+
	Diversity of means (technologies, transportation)	+
	Diversity of consumers	-

The diversity dimension is analysed with four indicators, as is displayed in the table above. All the indicators are measured by determining the Simpson Diversity Index. The data is extracted from the international scenario to evaluate this dimension and total final energy consumption from the IEA (IEA, 2018).

Diversity of sources

The diversity of sources is based on the amount of domestic energy production and imports. An evenly split distribution of local energy production and imports translates into the highest score possible. The international scenario relies primarily on energy imports instead of domestically produced renewable energy. This would drastically affect this indicator negatively. The effect of hydrogen in the built environment is significant as all the required hydrogen is imported elsewhere. However, this scenario is based on the assumption that citizens do not accept the burdens of domestically produced renewable energy. Hence, 90% of the final energy demand is satisfied from imported energy, like hydrogen. Based on this pre-assumption, there is no direct relationship between hydrogen in the built environment and this indicator. This indicator is awarded a neutral score.

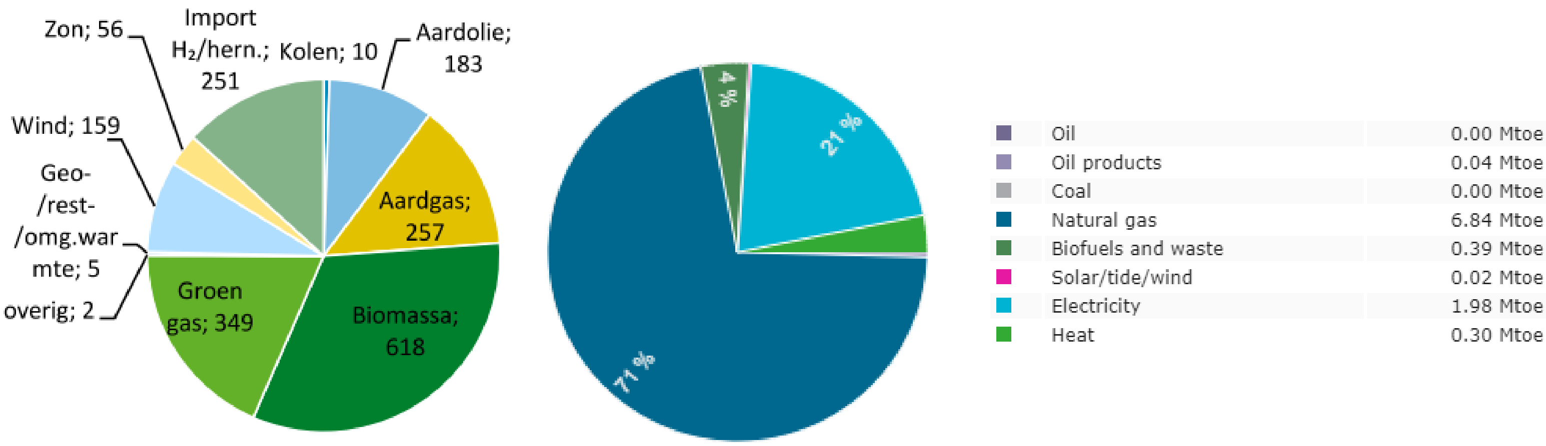


Figure 22: Energy carrier consumption diagrams. Left: 2050,international scenario in Dutch, right: 2018 current system.

Diversity of fuel

This parameter is evaluated by inspecting how much each energy carrier contributes to the total final consumption. The most apparent method to analyse this indicator for the international scenario is to examine the figures from chapter 3 and the flow diagrams in Appendix G.1 and G.2. In this scenario, hydrogen is a primary energy source due to imports, and little conversion takes place. The international scenario is recognized as diverse in energy carriers, illustrated in the figure below, comparing it to the current system. Over half of the imported hydrogen is used in the built environment, indicating a significant positive effect on this indicator. Therefore, a positive score is awarded.

Diversity of means

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. This indicator is twofold; one part analyses the diversity of technologies, and the other signifies the diversity of energy transport commodities. Current heating in the built environment is majorly accomplished by combusting natural gas in condensing boilers. This is presented in the Sankey Diagram of energy flows for the current energy system in Appendix H. However, in the national energy scenario, the Netherlands is divided into clusters. For each cluster, the most cost-efficient heating technology is implemented. This cluster type of heating design for the Netherlands is acknowledged in several interviews with experts in the field. This diversifies the means for heating significantly, as figure 11 indicates in section 3.3.1.1. The role of hydrogen as an energy carrier for heating is significant across different technologies and applications for heating. Hence, the effect of hydrogen in the built environment is positive regarding this parameter.

Diversity of consumers

The only difference with the national scenario is that the energy savings in low-temperature heat supply are lower.

Diversity of consumers is measured by considering the energy demand of different consumers/sectors in the energy system. According to the national scenario, final energy demand will decrease, moving towards 2050. Examining the figure below gives an impression of consumers' eventual division in the total final energy demand. There is a slight increase in diversification; however, the share of low-temperature heat in the built environment increases in terms of total consumption. Hydrogen in the built environment does not contribute to the diversity of consumers. This parameter is awarded a negative score.

6.3.3 Cost

	Indicators	Score
Cost	Energy prices (consumers, producers, peak oil, and stability/volatility)	-
	Cost of securing the system	+

The cost dimension is evaluated with two parameters, as indicated in the table above. The data for this dimension is gathered from semi-structured interviews with experts in the field.

Energy prices

According to an interviewee, energy price is not solely determined by hydrogen in the future. The energy price consists of all the efforts we make to decarbonize our energy needs. However, hydrogen is a means to decarbonize energy systems. Towards 2050, the price for energy can grow concerning hydrogen since its production costs are relatively higher than electrification (Interview EBN). These decarbonization activities translate into the energy price of the consumers. However, final energy demand is mainly satisfied through energy imports. Hence, the Netherlands' final price of energy depends on the best possible price on international markets. *"Electricity prices regarding renewables will become lower. At the same time, projections show an increase in electricity prices. How does this happen? Because we will still need gases, like hydrogen, and these solutions can become the price-setting technologies." – TNO.*

Regarding the demand for hydrogen in the built environment, hydrogen prices rely on European hydrogen markets (interview TNO, Gasunie, Stedin, NVDE). For domestic efforts for decarbonization, energy price of imported energy sources also includes costs for decarbonization activities. Hydrogen in the built environment is part of multiple solutions to decarbonize the energy system; therefore, this indicator is awarded a negative score.

Cost of securing the system

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. The levelized cost of energy is closely related to the first parameter. The price of hydrogen is linked to the LCOE of electricity from renewables. Ultimately, the LCOE of hydrogen depends on how hydrogen is used for creating energy. Hydrogen in the built environment is favourable over utilizing hydrogen for electricity production (interview TNO). Hence, hydrogen in the built environment has a positive effect on the LCOE.

6.3.4 Technology and efficiency

	Indicators	Score
Technology and efficiency	Energy system efficiency	+
	Energy intensity	-
	Energy conservation	O

The technology and efficiency dimension is measured through three parameters. As displayed in the table above. The data is extracted from the interviews with stakeholders and experts in the field.

Energy system efficiency

The energy system efficiency was measured through the energy return on energy invested (EROI) method in analyzing the current system. The Netherlands scored high on this parameter, along with other countries in the world. The international scenario depends mainly on energy imports. For this reason, the balance between supply is accurately managed by international imports and limits the need for curtailment or energy storage. However, the transport of gaseous fuels is restrained by energy losses over long distances. This is included in the equation for the return of energy invested. The international scenario's energy mix includes different gaseous energy carriers that are subject to energy loss, just as in the current energy system. Still, the amount of energy imports is lower than in the current system, as is illustrated in figure 20. In section 3.1.2, it has been demonstrated how much of the total gas supply is from import. A decrease in final energy demand combined with the percentage of imported gaseous energy carriers will improve the Dutch energy system efficiency based on the EROI. The contribution of imported renewable hydrogen to this indicator is significant when its origin is European, indicated in multiple interviews with stakeholders and experts in the field (interview Gasunie, TNO, EBN, Stedin). For that reason, this indicator is awarded a positive score.

Energy intensity

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. Energy intensity level of primary energy is the ratio between energy supply and gross domestic product measured at purchasing power parity. Energy intensity is an indication of how much energy is used to produce one unit of economic output. Lower ratio indicates that less energy is used to produce one unit of output. Hydrogen has a lot of dimensions and a wider system role than traditional fuels. For example, hydrogen utilized in the industry sector has significant differences with utilizing fossil fuels for feedstock. *"in this sense, nature has already done part of the job in these energy-intense conversion process" – TNO.* When renewable energy carriers are introduced in these processes, an extra conversion step increases energy intensity. When hydrogen is utilized directly in the built environment, these conversion losses are less significant. However, this implies that hydrogen in the built environment increases energy intensity compared to the current heating system; hence, a negative score is awarded to this parameter.

Energy conservation

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. The energy conservation parameter is based on the consumption of fuel by light vehicles. A lower consumption awards a better score for this parameter. This parameter is not influenced by hydrogen applications on the built environment and given a neutral score.

6.3.5 Location

	Indicators	Score
Location	Distance between production and consumption	-
	Energy use per area	+
	Total renewable surface water	+
	Industrial added values	-

The location dimension is analysed with four parameters, as indicated in the table above. The data is extracted from the scenarios and interviews with stakeholders and experts in the field.

Distance between production and consumption

There is a shift in interdependencies examining energy security from the international scenario perspective. Energy demand is satisfied by renewable energy imports for the most part. The majority of energy demand is contended by biomass and green gas, as illustrated in figure 20. Biomass is imported from Northern European countries and North America for the most part (interview Gasunie, Enpuls). Assuming that most of the green gas and biomass will come from European countries, the international scenario positively affects this indicator. Likewise, the effect of hydrogen import on this indicator depends on the origin of production. Different interviewees indicated that hydrogen would, for the most part, be imported from places with cheap electricity production. *"There will be a dependence on cheap hydrogen from places where electricity production much cheaper than in the Netherlands" – Stedin.* There is a high certainty for hydrogen imports originating in either the middle east or north of Africa, where there is a high solar power degree. This implies that hydrogen imports will contribute to a more considerable distance between production and consumption. Considering the substantial share of hydrogen utilization in the built environment, this indicator is awarded a negative score.

Energy use per area

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. This parameter is scored by calculating the energy use (kWh) per area. There is an expected increase in approximately 11% population while there is a decrease in final energy demand of approximately 40%. This implies that the energy use per area decreases in this future scenario, thus, increasing the score of this parameter. The built environment's contribution to this decrease in final energy demand is relatively lower than in other sectors (figure 20). Still, a decrease in energy demand in the built environment is expected. Considering the prominent role of hydrogen in this scenario's built environment, the effect on energy security for this indicator is rated positively.

Total renewable surface water

The current Dutch energy system has a high score for this indicator given water use and precipitation. Introducing domestic hydrogen production in the energy system requires considerable amounts of freshwater. However, the international scenario concerns a vision where hydrogen is not domestically produced but imported elsewhere. Reflecting on hydrogen utilization in the built environment, a large share of approximately 60% of total hydrogen imports is used in this sector. Due to hydrogen imports for use in the built environment, this indicator is scored positively.

Industrial added values

According to the interviews, there is much potential to export hydrogen (products) to the rest of the world, especially considering the geographic location of the Netherlands and the Rotterdam port. The difference between oil and hydrogen is their respective energy densities and transportation commodities. This implies that the industrial output will change over the years when the products change from fossil fuels to renewable energy carriers (interview TNO). Given the Netherlands' unique location, there is great potential to be a frontrunner in hydrogen production and, hence, the export of hydrogen to other countries. However, the international scenario depicts a low share of domestic hydrogen production for applications in, for example, the built environment. This implies a loss of industrial momentum in an economy with many opportunities for hydrogen-related exploitation. Hence, this indicator is given a negative score.

6.3.6 Environment

	Indicators	Score
Environment	Ecological footprint (number of earths required)	+
	CO_2 intensity	+
	Total GHG emissions excluding land-use change and forestry per GDP	+
	Water stress	+

Due to efforts of decarbonizing the energy system in both scenario's, the first three indicators are copied from section 6.1.6. The fourth indicator has different implications for the international scenario. The next chapter will go deeper into discussing the implications of the different scenarios. The environment dimension is analysed with four indicators that are listed in the table above. The indicators in this dimension are closely related to each other. The data is extracted from the scenario and interviews with stakeholders and experts in the field. This dimension is rather evident in terms of the effects of a sustainable energy system, but it is worth mentioning hydrogen's contribution in the built environment shortly for each indicator.

Ecological footprint

The ecological footprint considers the biocapacity of a region. Currently, the ecological footprint of the Netherlands exceeds the biocapacity of the country. The ecological footprint of the Netherlands will decrease, moving towards a renewable energy system. Any efforts at decarbonizing different sectors and parts of the energy system reduce the Netherlands' ecological footprint. Hydrogen is one part of the chain in achieving a decarbonized energy system. Determining the effects of hydrogen in the built environment in terms of decreasing the ecological footprint is exceptionally challenging, considering doing so for a potential future energy system. However, several studies predict a great decarbonizing potential from hydrogen when produced from renewable wind energy, as depicted in section 3.3. This indicator is given a positive score.

CO_2 intensity

Carbon intensity is examined by considering the amount of carbon emissions (in kg) per kWh energy use. The energy intensity of hydrogen is directly related to the electricity source. This implies that hydrogen produced from electricity that is generated from renewable energy sources is carbon-free. Compared to natural gas combustion in condensing boilers, the hybrid heating systems do not emit any carbon dioxide. The only emissions are related to technology production, considering the whole supply chain. Therefore, this indicator is awarded a positive score.

Total GHG emissions

The total GHG emissions will to near zero in this scenario. The contribution of hydrogen in the built environment is significant, considering its share in the final energy system. Therefore, the score attributed to this indicator is positive.

Water stress

The water stress indicator examines the quantity of available clean water for consumption. The amount of domestically produced hydrogen is neglectable in comparison with total energy consumption. *"I believe that the amount of water we need for electrolysis will not compete with the water we consume." – EBN.* For that reason, this indicator is given a positive score in connection to hydrogen utilization in the built environment.

6.3.7 Culture

	Parameter	Indicators	Score
Culture	1	Energy use per capita	+
		Air transport, passengers carried per capita	O
	2	Awareness of climate change and knowledge of the technology	+
		Fairness of the decision-making process	-
		Overall evaluation of costs, risks, and benefits of technology	+
		Local context (NIMBY)	+
		Trust in decision-makers and other relevant stakeholders	-

The culture dimension is analysed with seven indicators in two different parameters, as indicated in the table above. The data for this dimension is gathered from the scenario and interviews with stakeholders and experts in the field.

Energy use per capita

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. The Netherlands' final energy demand is decreasing (figure 19), and the total population will increase over the years. This indicates a decrease in energy use per capita. The energy use in the built environment decreased the least in relative terms compared to other sectors. However, the relation of hydrogen in the built environment is positive in terms of this indicator. Therefore, this indicator is given a positive score.

Air transport, passengers carried per capita

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. There is no relation between this indicator and hydrogen in the built environment distinguished. Hence, this indicator is awarded a neutral score.

Awareness of climate change and knowledge of the technology

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. For the current Dutch energy system, this indicator was measured with the expert interviews where interviewees were asked to score this indicator from the second parameter from 1 to 10. There is a great deal of effort and resources mobilized to create more awareness among citizens considering climate change and the implications of different renewable technologies. Interesting is that multiple stakeholders mentioned the ease of implementation of hydrogen in the built environment. Dutch citizens are used to burning gaseous energy carriers in households to satisfy heat demand and cooking utilities. Hence, the knowledge of the incumbent technology of hydrogen combustion is well developed. Though there is no clear relation between climate change awareness and hydrogen in the built environment, it does contribute to easier knowledge diffusion of the incumbent technology. Hence, this indicator is awarded a positive score.

Fairness of the decision-making process

The fairness of the decision-making process is based on how citizens perceive the fairness and transparency of the decision-making process regarding renewable energy projects and decarbonization efforts. The international scenario 'imports' its decarbonization efforts, for the most part, that leaves transparency and fairness of these processes in the hands of renewable energy carrier exporters. It is challenging to understand how these fuels are extracted, especially for biomass originating from Northern America (interview TNO, Gasunie). It is expected that Russia aspires to sustainable hydrogen from gasification combined with CCS when there is demand in Europe. However, this stipulates the same problem: it remains ambiguous whether these sources are sustainable (interview Gasunie). Therefore, this indicator is given a negative score.

Overall evaluation of costs, risks, and benefits of technology

This indicator is not affected by differences in the scenarios; hence the same description is used for the national scenario. This effect of hydrogen in the built environment was rated outmost positively by different interviewees (interview Stedin, Enexis, Gasunie, EBN, NVDE, TNO). However, some improvements concerning the communication of costs ought to improve (interview NVDE). Due to the Netherlands' gas background, risks and benefits of the technologies that hydrogen in the built environment necessitate are regarded as common knowledge. For this reason, many district and regions in the Netherlands are even hesitant for other heating solutions like district heating. They feel more familiarised with gaseous energy carriers. As a result, this indicator is allocated a positive score.

Local context (NIMBY)

This indicator is substantial concerning the two different scenarios. The interviewees expressed the potential NIMBY challenge when hydrogen is produced from purely domestically generated renewable energy sources (interview Enpuls, NVDE). In the international scenario, the hydrogen demand for the built environment is imported across the border. This reduces the need for installed renewable capacity and storage, which is reflected in this scenario's costs distribution (figure 23). For these reasons, this indicator is awarded a positive score.

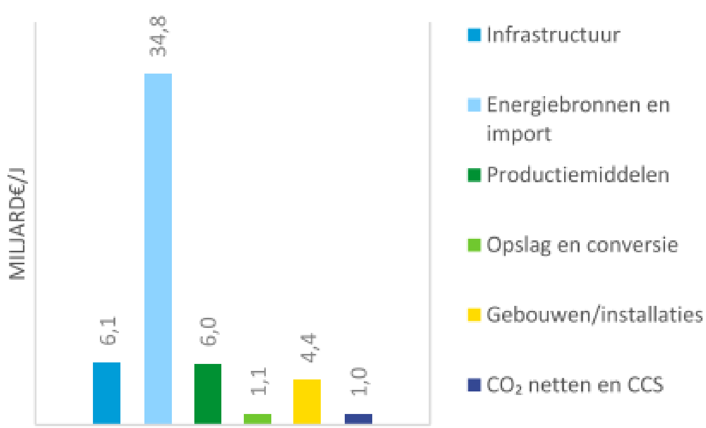


Figure 23: Energy system cost distribution in Dutch *(Afman & Rooijers, 2017)*

Trust in decision-makers and other relevant stakeholders

This indicator is closely connected to the fourth indicator. According to interviews with experts in the field, acceptance of hydrogen in the built environment is more straightforward than other heating solutions due to the background of Dutch society. This has been mentioned before and is a critical aspect of the success and acceptability of hydrogen in the built environment. The relation of hydrogen in the built environment for the international scenario and trust in decision-makers is threefold. First, hydrogen in the built environment is expected to experience the least resistance compared to other solutions. Therefore, trust in contractors and decision-makers is relatively positive (interview Enexis, TNO, EBN, Enpuls). Second, trust in decision-makers is based on their historical performance, and considering gas infrastructure stakeholders, their trustworthiness is credited and embroidered in Dutch society (interview NVDE). Third, it is more complicated considering the relationship with countries exporting the renewable energy sources for Dutch demand. In a scenario where approximately all hydrogen demand for the built environment is imported cross-border can create dependencies on cheap Russian or Saharan hydrogen (interview TNO, Gasunie, Stedin). Regarding sustainability efforts and hydrogen in the built environment, this can facilitate a debate between society and decision-makers, decreasing trust in their sustainability efforts. Hence, this indicator is awarded a negative score.

6.3.8 Policy

	Indicators	Score
Policy	Subsidies and other transfers (percentage of expense, subtracted from unity)	+
	Regularity indicator for sustainability (RISE)	+

The policy dimension is constituted from one parameter with two indicators. Data for this scenario is retrieved from expert opinions on renewable energy policy. The second indicator is more extensive, reviewing the policy indicators that make up the regularity indicator for sustainability. The overview for these metrics is presented in Appendix E

Subsidies and other transfers

Currently, renewable energy production is bound to subsidy support to be profitable. The levelized cost of electricity for both wind and solar technologies is decreasing. Giant offshore wind parks will not be needing any subsidy anymore from five years onwards (interview Enpuls). However, hydrogen developments and implementation in the built environment are not ready before 2025 (Gigler & Weeda, 2018). This implies that the starting point for hydrogen implementation in the built environment requires government subsidies or investments.

Nevertheless, in the international scenario, hydrogen demand for the built environment is imported. This means that any transfer or subsidies for its production are not under domestic regulation but depend on the exporting country. Moreover, the existing gas grid (with minor alterations) can transport hydrogen to the places of demand in the built environment (interview Gasunie). For that reason, utilizing hydrogen in the built environment distributed by the existing gas grid improves this indicator. Hence, a positive score is awarded.

Regulatory indicator for sustainability (RISE)

The regulatory indicator for sustainability is subject to change when examined from the international scenario point of view. The indicator assesses a countries' regulatory and policy support given the three pillars of sustainable energy: 1. Access to modern energy, 2. Energy efficiency, and 3. Renewable energy. The framework is designed to assess policy standards, regulations, and procedures from a domestic point of view. Regarding access to modern energy, the first theme has the same implications as for the national scenario. Interviewees expect no risks regarding policymaking and providing energy access in the coming years. This is and will be, the first priority (interview Gasunie, Enexis, Enpuls). Even more so, the international grid is not restricted by grid expansions compared to the national scenario with a focus on domestic renewable energy generation.

The second theme, energy efficiency, requires coherent policy providing incentives for consumers, financing mechanisms, carbon pricing, and performance standards. From the international perspective, hydrogen in the built environment will not require drastic changes to policy frameworks. Integrating hydrogen in the energy system implies more losses in the energy system. *"If you look at the whole hydrogen chain, there will be more losses in the energy system when we introduce hydrogen. However, when we look at hydrogen from renewables this is still favourable, even though on an energetic level, it will be less efficient. For the built environment, it would be more efficient compared to P2G to electricity." – Interview, Enexis.*

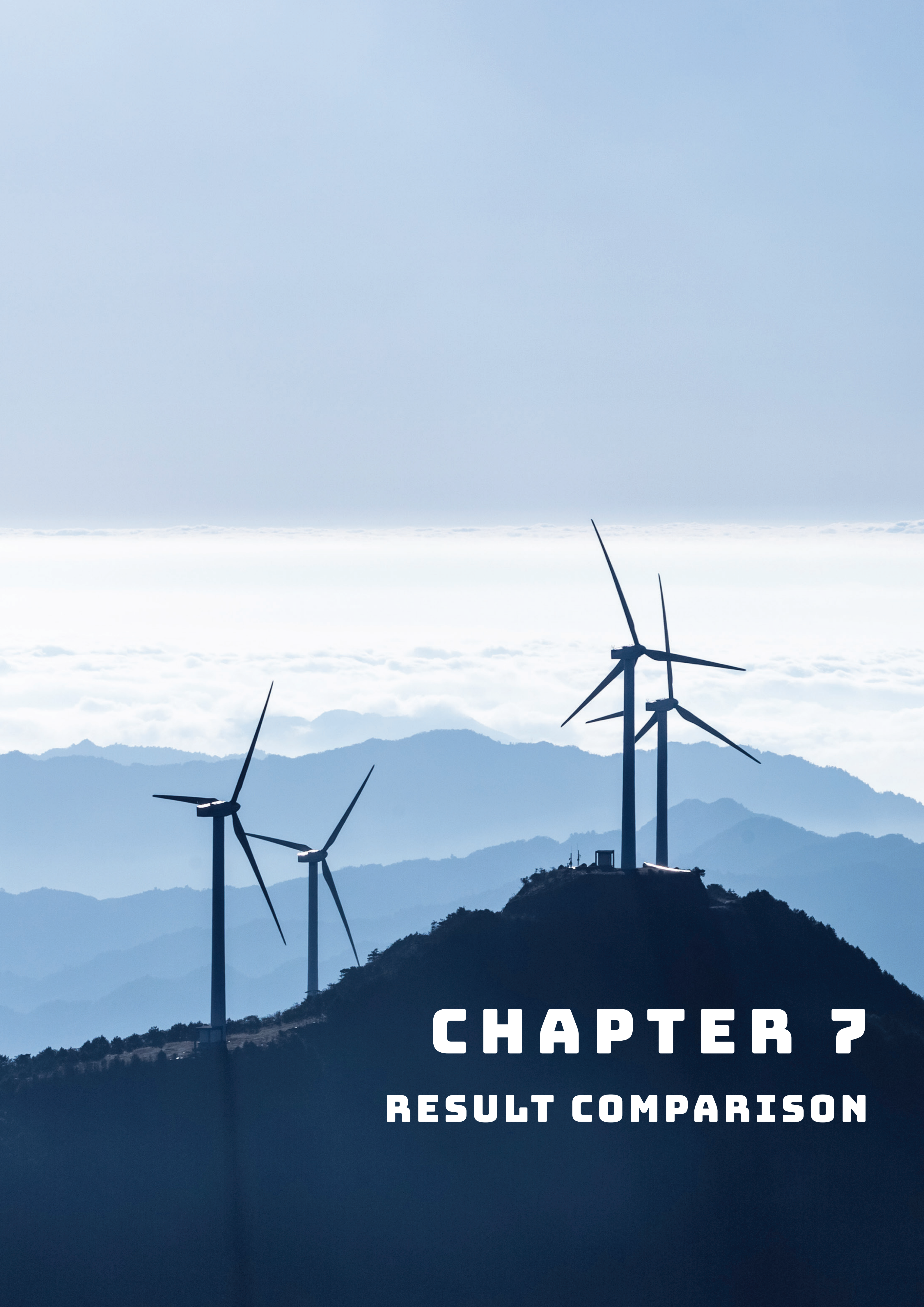
The third theme, renewable energy, is subject to change in comparison with the reference case. In this scenario, the Netherlands is depicted as prosperous and intensely global orientated. However, renewable energy capacity is restricted in this area, hindering new projects providing sufficient domestic capacity. In the context of hydrogen in the built environment, clear legislation necessary for the distribution of hydrogen and end-use appliance standards has to be created. Multiple interviewees indicated that future legislation regarding hydrogen in the built environment would provide sufficient incentive for implementation and coherent network connection and access (interview Gasunie, Stedin, Enexis). For these reasons, this indicator is awarded a positive score.

6.4 Summary of energy security dimensions for the international scenario

Dimensions	Availability	Diversity	Cost	TE	Location	Environ.	Culture	Policy
Impact	- O +	O + + -	- +	+ - O	- + + -	+ + + +	+ O + - + + -	+ +

Table 7: Summary of energy security dimensions for the international scenario.

The summary of the effects of hydrogen utilization in the built environment on different energy security dimensions for the international scenario has been presented in table 6 above. The green colour coding indicates a positive correlation, yellow a neutral impact, and the red colour (not present) expresses a negative impact of hydrogen in the built environment on that dimension. In general, hydrogen in the built environment expresses positive effects on the energy security dimensions compared to the reference case. A comparison of these results with that of the national scenario is made in the next chapter.



CHAPTER 7

RESULT COMPARISON

7. Result comparison of the reference case and hydrogen scenarios

The following chapter is dedicated to comparing the results that have been presented in chapter 5 and chapter 6 and intend to answer sub-question 4:

What geotechnical characteristics of hydrogen are responsible for the change in future energy security performance compared to the reference case?

Chapter 6 has been written carefully in the reflection of the reference case. The following sections aim at delineating the expected change in energy security when introducing hydrogen in the built environment. With the help of the theoretical implications of chapter 2, it is demonstrated how different characteristics of hydrogen are responsible for the examined developments in the possible scenarios. Moreover, lessons learned from these results are discussed shortly after introducing the discussion chapter after these sections.

7.1 Differences between the national and international scenario

Both scenario analyses have been performed based on the reference case of the current Dutch situation, outlined in chapter 5. This section will focus on putting both scenario outcomes next to each other to distinguish differences and explain these differences. The outcomes of both scenarios are given in the table below. Each dimension that is different for the two scenarios is discussed.

Dimensions	Availability	Diversity	Cost	TE	Location	Environ.	Culture	Policy
Impact	+ O +	O + + -	- +	- - O	+ + - +	+ + + -	+ O + + + - +	- +

Table 8: Summary of energy security dimensions for the national scenario.

Dimensions	Availability	Diversity	Cost	TE	Location	Environ.	Culture	Policy
Impact	- O +	O + + -	- +	+ - O	- + + -	+ + + +	+ O + - + + -	+ +

Table 9: Summary of energy security dimensions for the international scenario.

Every dimension is subject to some change in the indicators, except for the diversity and cost dimension. Therefore, these dimensions are not discussed in this section. The other dimensions are subject to change and thus explored independently.

7.1.1 Availability

The national scenario exercises positive effects on the availability dimension from the perspective of hydrogen utilization in the built environment. The international scenario exerts a neutral effect on this dimension. The first indicator is the reason for the difference in the overall effect on this dimension. The existence of resources indicator examines the availability of renewable resources and its exploitation. The international scenario depends on international energy imports to meet national demand and thus does not utilize the available renewable resources any close to its potential. This implies the role of hydrogen (in the built environment) to extract renewable energy sources and convert it into an energy carrier that can be stored and distributed over long distances.

7.1.2 Technology and efficiency

The national energy scenario has adverse effects on the technology and efficiency dimension, while the international scenario is neutral concerning energy security. The main difference between the two scenarios is energy efficiency. Introducing hydrogen in the energy system has consequences in terms of energy efficiency, as demonstrated by different interviewees. The international scenario relies more on the balancing game between energy demand and international supply. This match is less challenging and requires less flexibility and storage capacity to cope with the intermittency of renewables.

7.1.3 Location

Only the second indicator is the same for both scenarios for the location dimension. The national scenario is built on energy autonomy, resulting in the domestic hydrogen supply chain, decreasing the distance between production and consumption. The central nature of this supply chain increases the distance compared with other heating solutions that can be fed with local renewable energy, but overall, this indicator improves significantly. However, a domestic hydrogen supply chain implies a decrease of total renewable surface water, which is not the case in the international scenario. Finally, the international scenario fails to exploit new business opportunities that the potential hydrogen supply chain would bring when domestically organized.

7.1.4 Environment

The only difference in this (rather obvious) dimension is the water stress indicator for both scenarios. The national scenario relies on large quantities of domestically produced hydrogen for the built environment, while the international scenario imports this sector's demand.

7.1.5 Culture

The scenarios both have an equally positive effect on the culture dimension in comparison with the reference case. However, some interesting differences have to be distinguished. The main differences between the two scenarios are located in the local context and the dialogue between society and decision-makers. Large quantities of hydrogen demand in the built environment require hefty renewable capacity, considering overall electricity demand or dedicated energy parks solely for hydrogen production. Both solutions can encounter resistance from the public. However, on the contrary, energy carrier imports (especially hydrogen due to the different production pathways) can decrease decision-maker trust when their origin is poorly communicated and ambiguous. The uncertainty of hydrogen quality and production methods brings upon transparency issues when imported from countries Russia.

7.1.6 Policy

The main difference in the policy dimension between the two scenarios is the dependence on governmental subsidies. The national scenario relies on domestic hydrogen production for demand in the built environment, and that requires a complete hydrogen supply chain in the Netherlands. Subsidies for these technologies to make hydrogen solutions in the built environment competitive against other possibilities for heat demand.

7.2 Effect of hydrogen on energy security

This section will focus on clarifying the effects of hydrogen on energy security. This section builds on the comparison of the different results from both scenarios in the previous section. The differences from these scenarios aids in formulating a more generic description of hydrogen's effects in the built environment on energy security in the future.

As indicated, the overall effects of utilizing hydrogen in the built environment are positive. The availability dimension improves significantly in the future energy system with domestic hydrogen production. Hydrogen makes it possible to harvest more renewable energy while coping with intermittency due to the storage possibilities (Azzuni et al., 2020; van de Graaf et al., 2020). The difference between the scenarios indicated the importance of domestic hydrogen production. Next, hydrogen increases system diversity as well. Electricity is dominantly portrayed as the future energy carrier, emphasizing the need to electrify the energy system. However, in terms of energy system security, a more diversified energy portfolio is favourable.

The existing Dutch gas infrastructure gives the Netherlands a good position in becoming a frontrunner in building a hydrogen supply chain. This can dampen the costs for decarbonizing certain sectors like the industry or the built environment significantly. However, the levelized cost of hydrogen depends on the levelized cost of electricity. For example, this implies that countries with cheap renewable solar electricity can become net exporters of hydrogen and hinder domestic production (Scholten, 2018; van de Graaf et al., 2020).

Considering energy system efficiency, integrating hydrogen will have adverse effects on the energy security of the system. The differences between the scenarios emphasized this notion. While integrating hydrogen in the energy system improves resource extraction, hydrogen is an energy carrier that requires conversion (van de Graaf et al., 2020). Each conversion step affects energy efficiency negatively. As demonstrated in multiple interviews, the conversion of hydrogen to electricity is unfavourable for these reasons. However, economic efficiency can overrule energy efficiency when there is an insufficient energy supply to meet demand.

Domestic hydrogen production decreases the distance between energy production and consumption, improving energy security, and prevents new dependencies (Hache, 2018; Scholten, 2018; van de Graaf et al., 2020). The industrial benefits for domestic hydrogen production are significant, while large-scale import of hydrogen can impair the Netherlands' frontrunner position. On the contrary, domestic production can have significant adverse effects in an environmental or social context. There is a fine line between negative new dependencies and distrust in decision-makers due to massive hydrogen imports on one side and social dilemmas like NIMBY when aiming for energy autonomy. However, the actual hydrogen constitution in the future is greatly affected by renewable energy policy and subsidies. Also, the extent of governmental involvement in the early stages of the hydrogen supply chain rollout is paramount to implementation success, as demonstrated in the interviews.

Previous paragraphs demonstrated the effects of hydrogen in the built environment in a nutshell; the following chapter will go into more detail these insights. The discussion chapter will reflect on the results for practice in light of the theory, and reflect on this study (and limitations) in more detail.

7.3 The geotechnical characteristics of hydrogen in light of energy security

To refrain from a regular energy security assessment, this research intends to shed light on how hydrogen's geotechnical characteristics affect the different dimensions of energy security of two realistic future energy systems. The insights from section 3.2 can now reflect on the results of both scenarios and tackle perceived change not only from an energy security analysis perspective but, moreover, examine these future changes from a sources, generation, and distribution perspective. Ultimately, these implications make it possible to examine the dimensions in a sensitivity discussion that allows us to understand how different indicators are subject to change when the hydrogen supply chain transforms from the perspective of sources, generation and distribution.

There are different production pathways for hydrogen, of which green hydrogen is produced with electricity from renewable energy sources. This means that the potential for hydrogen production in the Netherlands depends on the renewable energy source capacity. Moreover, this relationship works both ways because hydrogen is an energy carrier that is easily stored and distributed. At the same time, renewable energy sources are intermittent and require large capacities to provide sufficient supply at peak hours. However, a considerably large capacity of renewable energy sources is bound to curtailment when demand is low. To that sense, large scale hydrogen implementation for the built environment requires revamping the existing gas grid, creating coherent (seasonal) storage, and preventing curtailment of renewable energy sources. This means, from a sources perspective, the actual and realistic potential of renewables increases with the integration of hydrogen in the energy system.

Compared to natural gas supply for heating demand, hydrogen is very similar. However, the Groningen gas fields are ramping down, increasing the dependence on natural gas sources outside the Netherlands. Green hydrogen is produced for renewable energy sources and can be produced everywhere across the globe. The Netherlands faces a make or buy decision, where it either produces hydrogen domestically or imports it from other countries, increasing diversity of the Dutch energy mix compared to complete electrification. Hydrogen is less geographically bound than natural gas, increasing the probability for competitive markets with a more diverse pool of potential suppliers.

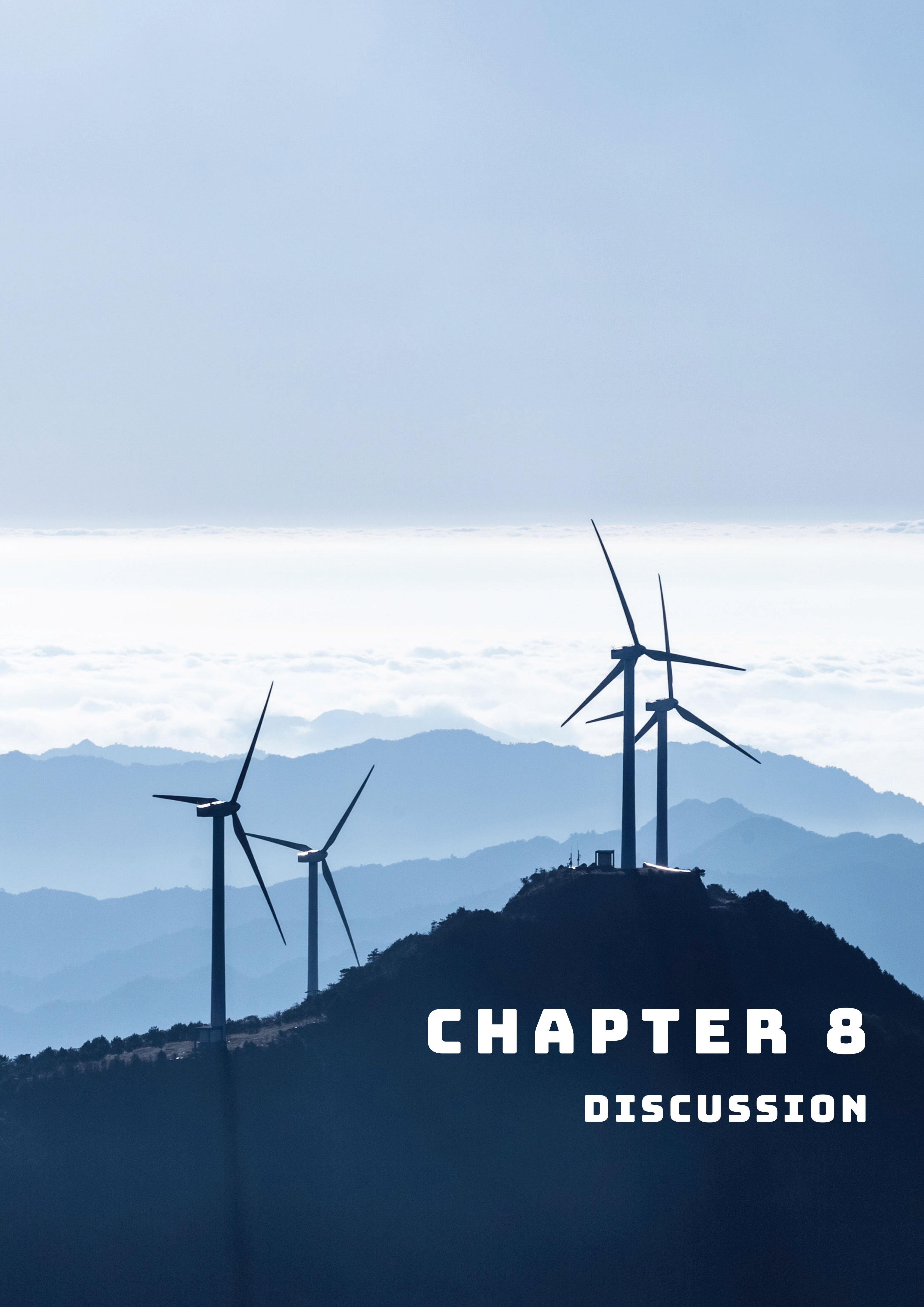
From a generation point of view, this research's scope examined the integration of green hydrogen in the energy system. Nevertheless, other hydrogen production pathways are likely to gain a significant foothold towards 2050. Blue hydrogen could potentially diversify the playfield even more. The Netherlands' potential feasibility to import cheap blue hydrogen from either the Middle-East or Russia can shift the make or buy decision more to an import-orientated Dutch hydrogen supply chain. This debate of on-site location dramatically affects the location dimension of energy security for the future Dutch system. Decreasing the distance between production and consumption is favourable; however, site location depends on where hydrogen is produced most economically. When large quantities of cheap cross-border hydrogen are available for import, domestic facilities' construction is not encouraged. Still, moving away from energy dependencies is advantageous and should be accounted for at the end of the investment balance.

Moreover, hydrogen as an energy carrier is produced most economically in extensive central facilities. These hydrogen production facilities are well connectable to large offshore wind parks, decreasing societal resistance for more renewable energy sources and improving the culture dimension. Also, as demonstrated, the Netherlands has a gas culture. Citizens are used for cooking and heating with natural gas. Hydrogen is a gaseous energy carrier, like green gas, that can expect the least resistance from a societal perspective compared to other heating solutions. However, green hydrogen is produced through electrolysis. Considering this research's scope, only green hydrogen is integrated into the energy system to supply the built environment. Electrolysis of freshwater is most mature but still an expensive solution for hydrogen production. These costs are translated into energy prices for consumers.

From a distribution perspective, the existing natural gas grid provided an opportunity for introducing a novel, renewable gaseous energy carrier in the energy system. It would make no sense to simply remove the gas grid and electrify the energy system from an economic, societal, and environmental perspective. Hydrogen allows for transport over greater distances, just like natural gas, compared to electricity without significant energy losses. This characteristic creates the opportunity to interconnect different countries to a future hydrogen grid more easily, refraining from a more local market for energy to a potential world market for hydrogen trade. Scoping down to the Netherlands' distribution, the existing natural gas grid provides a coherent incentive to find some novel gaseous energy carrier. Moreover, the distribution of green hydrogen in the existing gas grid provides large energy storage, which affects the availability dimension to the extent that the potential of renewable energy sources can be extracted more efficiently, preventing curtailment and overcapacity.

CHAPTER 8

DISCUSSION



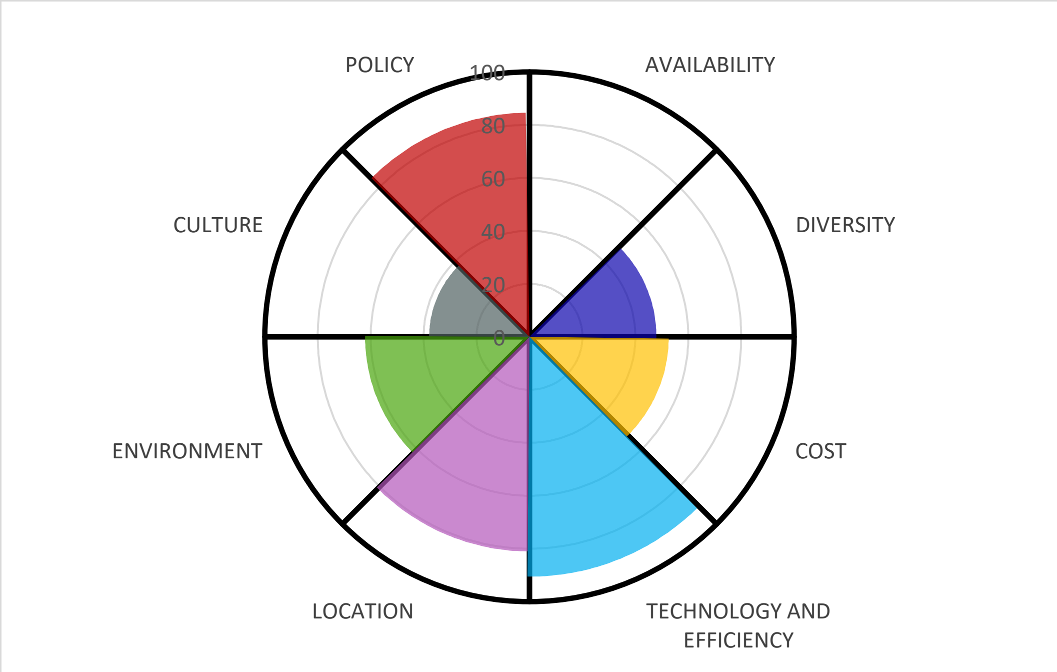
8. Discussion

The following chapter will further delineate the result section into two parts, summarizing the results and discussing them. First, the results are discussed for practice demonstrating how hydrogen affects energy security, compared to possible scenarios. Secondly, the results are discussed in light of theory and relates the findings to other research results. After this comprehensive result analysis, a reflection is written based on this research approach, and limitations of the framework are evaluated.

8.1 Results from the practical perspective

This research project incorporated several research activities to explore the effects of hydrogen on future Dutch energy security when utilized in the built environment. At the centre of this research process was the energy security framework adapted accordingly to be adequate for future analyses of the Dutch energy system. This suggested that there is no real data available for different future pathways of the Dutch energy system. The reasoning was created to understand the implications of renewable energy systems and hydrogen in the context of energy security. There was a need to develop a logic that guides the analysis of the future energy system and gives reasoning for the possible differences in such an energy system compared to the status quo in the Netherlands. The data-driven analysis of the current system could then be compared to different scenarios for hydrogen implementation in the built environment, and a dialogue is developed for the expected change in the different dimensions.

For structure purposes, several figures from the results are copied to this section to create an exact representation of the system's differences now and the possible system in the future in the light of hydrogen. The figures below illustrate the current level of energy security in the Netherlands, given the eight different dimensions, and below that are the two tables representing positive or negative effects of hydrogen in the built environment on the specific indicators and dimensions.



National scenario:

Dimensions	Availability	Diversity	Cost	TE	Location	Environ.	Culture	Policy
Impact	+ O +	O + + -	- +	- - O	+ + - +	+ + + -	+ O + + + - +	- +

International scenario:

Dimensions	Availability	Diversity	Cost	TE	Location	Environ.	Culture	Policy
Impact	- O +	O + + -	- +	+ - O	- + + -	+ + + +	+ O + - + + -	+ +

The following paragraphs will discuss all the results in light of the reference case of the Netherlands. The results are reflected on the literature review that formed to the backbone for this narrative. Recommendations for actors in the field can be based on the aspects of the energy security spectrum that will improve or deteriorate when hydrogen is implemented in the built environment.

Before reflecting on the two scenarios' results, reflection on the reference case given the approach and results is necessary. The outcomes of the reference case were based on real data retrieved from different sources. This resulted in quantitative results in comparison with the qualitative assessment of chapters 6 and 7. However, the quantitative results did reveal each dimension's performance in the energy security framework compared to other countries in the world. The reference case analysis helped to understand the strong and weak points of the current energy system given the geotechnical characteristics of fossil fuel dominated energy system. This contributed to developing a feeling to what extent hydrogen could influence the different parameters in the framework. Therefore, reproducing the same numbers is not desirable or necessary, but they serve as a guideline to understand what dimensions are prone to change or less easy to alter.

8.1.1 Effect of hydrogen on the energy security dimensions

Implementing hydrogen in the built environment significantly improves the availability dimension of energy security. However, this effect on energy security is only achieved in an energy system that incorporates large quantities of renewable energy sources and hydrogen production. Energy imports create new energy dependencies and decrease the self-sufficiency of the Netherlands. The interviews and scenarios gave clear implications on the benefits of integrating some sort of domestic hydrogen supply chain. The availability dimension demonstrated strong relationships with the other dimensions from the perspective of hydrogen utilization in the built environment. A more extensive domestic hydrogen supply chain implies consequences for system efficiency, the distance between producer and consumer, water stress, social challenges, and reliance on governmental support. This relationship works both ways, and this exposes the interconnectedness of energy security dimensions and the urgency to include as many dimensions/indicators as possible for a holistic analysis (Azzuni & Breyer, 2018). Hydrogen in the built environment makes an excellent business case for storing the surplus of renewable energy combined with dedicated renewable energy farms exclusively generating electricity for hydrogen production. This helps to harvest more renewable energy from the total potential and is substantially beneficial for Dutch energy security. Hydrogen in the built environment can improve the availability dimension to a large extent. However, the availability dimension is somewhat arbitrary due to the method of analysis. This limitation is discussed in the section of this chapter.

While other scenarios or visions place hydrogen less prominently in the energy system, it is capable of diversifying the energy system considerably. The diversity dimension analysed energy system diversity based on four indicators: diversity of sources, diversity of energy carriers, diversity of technology, and diversity of consumers. Examining each indicator's scores in the current Dutch energy system, hydrogen in the built environment can improve three of the four indicators significantly while potentially decreasing the fourth indicator. There was no relation between the diversity of energy sources and hydrogen in the built environment due to the scenario assumptions. However, the Netherlands relies increasingly on energy imports now that domestic gas extraction is forced to certain limits. Large scale hydrogen production for the built environment can saturate this void and improve the ratio between energy imports and domestic energy production. Likewise, hydrogen in the built environment can improve energy carrier diversity, even more so when large scale centrally orientated hydrogen production facilities deliver large capacity to produce hydrogen for other synthetic renewable fuels or industry feedstock. The scenarios and interviews demonstrated that the Netherlands should be divided into energy districts, applying the most cost-efficient solution to specific regions. Hydrogen in the built environment can be integrated employing different technologies, generally some type of hybrid heat pump, diversifying means of delivering low-temperature heat across the Netherlands. The final indicator is potentially negatively affected by integrating hydrogen in the built environment. The final energy demand of the two scenarios decreases; however, the share of energy demand in the built environment decreases significantly less than other sectors decreasing the diversity of energy consumers.

The cost of the energy system neither positively nor negatively affected when utilizing hydrogen in the built environment. The energy prices are not determined by hydrogen alone but are all the efforts to decarbonize the energy system. This implies an increase in energy prices since the endeavours for sustainable low-temperature heat are translated into energy prices. This applies both ways, domestically producing hydrogen and for importing hydrogen demand. The levelized cost for hydrogen will gradually decrease with technology advancements in general. However, the levelized cost of hydrogen is closely affiliated with the costs of electricity production. Hence, the location of hydrogen production depends remarkably on the location of cheap electricity production. Nevertheless, international hydrogen imports require an extensive infrastructure that is currently lacking. This must be included in the levelized cost for non-domestically produced hydrogen and allows indigenous organizations to be a front runner in the Netherlands.

Overall, energy system efficiency is subject to losses due to curtailment and increased energy conversions. In particular, a domesticated hydrogen supply chain for the built environment entails efficiency losses due to increased renewable energy source capacity, additional hydrogen storage, and further utilization of hydrogen for grid support. Hydrogen imports are based on energy demand instead of the balancing game between supply/demand and backup capacity in a more energy-autonomous system. Of course, on the premise that hydrogen is broadly available for import at competitive prices. Concerning energy diversity, energy import and domestic production should be balanced, especially considering hydrogen production for the built environment.

The location of hydrogen production and utilization is an essential aspect of its effect on energy security. The Netherlands has a strong position regarding industry and infrastructure to reap the benefits of a domestic focussed hydrogen supply chain. Its extensive infrastructure and ports allow becoming one of the frontrunners of a future hydrogen supply chain, increasing industrial output, decreasing the distance between hydrogen production and consumption in the built environment, and allow to decarbonize hard to abate sectors in the process. However, large scale domestic central hydrogen production increases the water footprint of production regions but not to the extent of scarcity in the Netherlands.

Furthermore, dealing with environmental aspects of energy security and hydrogen utilization in the built environment, green hydrogen production contributes substantially to a fast-paced energy transition and a decreased carbon footprint. However, there are no standards for hydrogen, yet considering quality, source, and carbon abatements. This is critical in a future system that is supplied by blue (or green) hydrogen imports. The source of hydrogen should comply with environmental standards to assure hydrogen supply free of emissions.

Gaseous energy carriers are embroidered in Dutch culture, giving hydrogen in the built environment tremendous leverage compared to other low-temperature heating solutions. Simultaneously, this is the major pitfall for hydrogen utilization in the built environment. Hydrogen is not the most cost-efficient solution in all Netherlands' districts, as demonstrated in the interviews and scenarios. Even these high hydrogen scenarios share the playfield with all-electric or district heating solutions. There is a need for dialogue between society and actors that deal with the transparency of risks and benefits and the incumbent technologies' costs to avoid resistance. Another key finding is that hydrogen imports inhibit distrust from society dealing with the source of hydrogen in GHG emissions and dependence on other countries. Domestically produced hydrogen for the built environment increases these aspects of culture by facilitating a dialogue that accounts for import source and hydrogen standards. Based on the reference case of the current Dutch system

This firmly relates to the policy dimension of energy security. The level of governmental involvement is critical for infrastructure development, import standards, subsidy requirements, and a strong early position of the Netherlands in the future hydrogen market. It has been demonstrated that Dutch culture, infrastructure, and knowledge leverage a strong starting position for hydrogen utilization in the built environment. The current Dutch political landscape established a strong constitution of regulation and policy for the fossil fuel-based energy system. Interviews with key stakeholders in the fields acknowledged no threats in future hydrogen policy, standards, and trade agreements. However, it is paramount that the government takes an early role in facilitating hydrogen infrastructure and role distribution for existing actors in this new energy system concerning hydrogen.

8.1.2 Recommendation for actors in the fields

Based on the critical findings from section 8.1.1, recommendations can be made towards actors in the field. Whereas the recommendations are either economic, technical, and political, society's recommendations are not part of this section but discussed concerning the other actors. The recommendations for actors in the field provide business value for key stakeholders. Recommendations are made for DSO's and TSO's in the Netherlands.

Dutch DSO's

The focal point for the DSO's in the coming years should be on the *location, technology and efficiency, and culture dimension*. From the location perspective, it is expected that the distance between energy production and consumption will decrease and that the future energy system will not wholly decentralize. There is a need for new infrastructure and reinforced existing infrastructure in an energy system where hydrogen will have a dominant energy system position. Moreover, the DSO is responsible for the distribution system. This part of the supply chain is susceptible to embrittlement and leakage when hydrogen is transported. DSO's should provide necessary distribution infrastructure in districts that will be supplied with hydrogen for heating demand. Looking at the technology and efficiency dimension, DSO's face the responsibility to inform and lobby for the use of hydrogen in the built environment. This is closely related to the culture dimension. The Netherlands ought to be divided into different districts, each with other needs for heating demand. Districts further from the Randstad make an interesting business case for hydrogen in the built environment. As demonstrated, there is substantial leverage for hydrogen utilization in the built environment. However, hydrogen must not be considered a panacea for decarbonizing the built environment. There is a need for transparency of the different heating solutions' risks and benefits to ensure trust in decision-makers. This ought to be organized together with the government. Next to this, DSO's should decide where to implement hydrogen for heating the built environment in terms of electricity grid congestion prevention. Likewise, the location for generation and production should be in tune to prevent conversion losses. An overview of the recommendations is presented in figure 24.

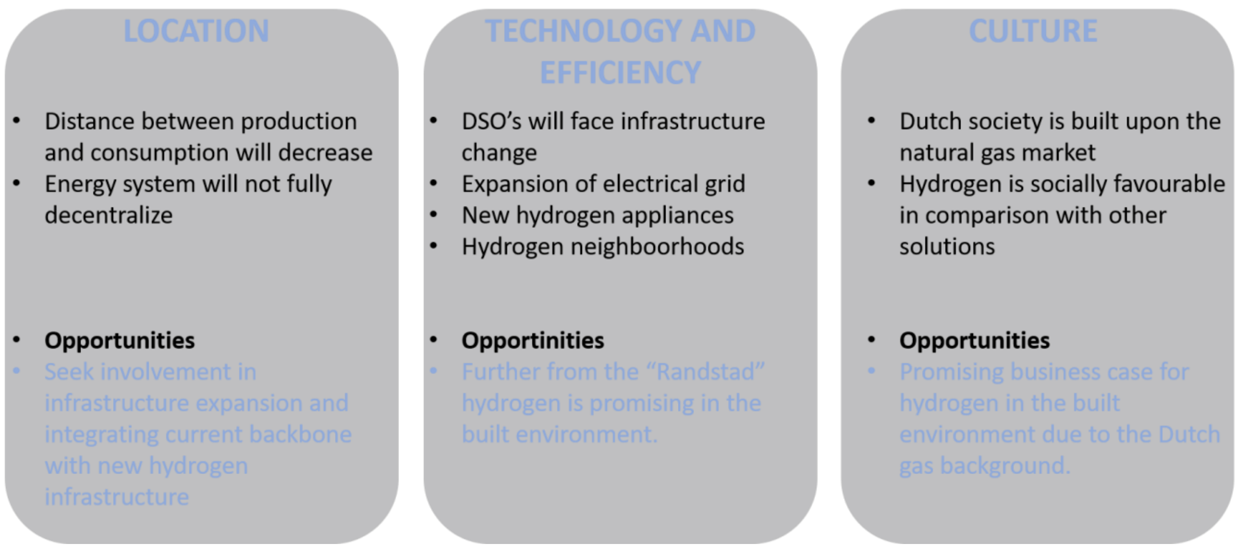


Figure 24: Overview of recommendations for Dutch DSO's.

Dutch TSO's

All recommendations are from a 'gas perspective'. The transmission system operator should focus on the location, policy, and diversity dimension. It is critical for the location dimension to seek close contact with potential hydrogen producers and provide coherent hydrogen infrastructure. The distance between production and consumption of energy will decrease in terms of hydrogen in a future energy system. This implies that there is a need for extensive infrastructure. The existing infrastructure can be revamped for hydrogen transport, but new infrastructure is necessary at centralized hydrogen production facilities. Together with governmental support, there is a need for early infrastructure development. Next, the Dutch TSO should seek partnerships with neighbouring countries for rolling out a hydrogen infrastructure due to the high potential of an interconnected hydrogen market. The strong position of the Netherlands due to its infrastructure and industry calls for early investments to grasp the opportunities from the developing hydrogen market. Looking at the diversity dimension, hydrogen will have a crucial role in diversifying the energy mix not only in the built environment but throughout other sectors as well. The system role of hydrogen is vital for the Dutch TSO as hydrogen demand will cover the built environment and the industry and transport sector. More on the system role of hydrogen will be discussed in the next section. An overview of the recommendations for the Dutch TSO is presented in figure 25.

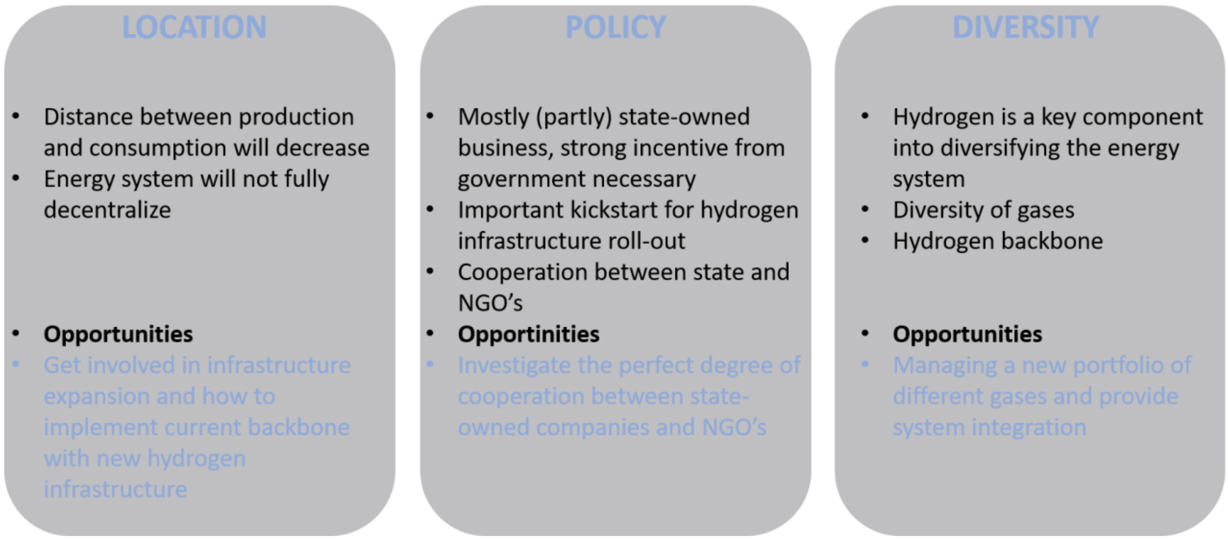


Figure 25: Overview of recommendations for the Dutch TSO.

Government

The government's role concerning the success of hydrogen in the Netherlands is firmly based on extensive involvement. In the current energy system, the government has a distant relationship with other actors in the energy system to inhibit market dynamics and competition. It has been demonstrated that the government should become involved in the early stages of hydrogen integration and decide which actor has what roles in the total system. Together with the DSO's, a dialogue with society is crucial to prevent resistance towards other promising technologies for heat demand in the built environment. The lock-in of hydrogen due to the extensive gas infrastructure is a blessing and curse in that hydrogen supply for the built environment pushes other cost-efficient technologies. Thus, the government must create a heatmap that indicates different heating sectors in the Netherlands and the most cost-efficient heating solution for the different sectors. Next to this, there is a need for a comprehensive hydrogen gas law that incorporates gas standards.

8.1.3 Placing this research in the broader perspective

While this research focused on the effect of hydrogen utilization in the built environment, the framework can be used for other applications. This research specified on one role of hydrogen in a future energy system, meeting a share of Dutch heating demand in the built environment. However, as the desk research and expert interviews indicated, hydrogen will not only be used for heat supply in the built environment. Even more so, hydrogen will probably have no role in the built environment for the coming decade and will only gradually be implemented from 2030 onwards when the prices for technology and hydrogen can compete with other solutions. Satisfying heating demand is one of the many roles hydrogen will have in a future energy system. Hydrogen will have a significant role in the chemical industry and industry that requires some form of high-temperature heat. These sectors are hard to decarbonize through electrification. The role of renewable gasses in the energy transition is indisputable, whereas hydrogen proves to be one of the most versatile solutions applicable to multiple sectors at once. This framework is easily utilized to examine other roles of hydrogen in the energy system. The framework is not applicable to be applied to other energy carriers or renewable energy sources yet. The method of choosing indicators and leaving out dimensions has to be redone to include all dimensions and indicators that measure and explain the perceived observations. The framework is also applicable to find energy security implications of hydrogen in other countries' built environment. However, besides Germany, only a few countries make a compelling business case for hydrogen utilization in the built environment. Still, the framework can evaluate other roles of hydrogen and its effect on energy security in other countries, like industry or transport.

8.2 Comparison with other results

In light of the theory and compare the findings with other literature results discussing academic relevance and learnings. The results can be compared to literature that discusses the implications of renewables on energy security, geopolitical characteristics of hydrogen, and cases with similar approaches.

The first step is to examine how this research's results relate to the work from Scholten (2018). The paper from Scholten (2018) introduces a set of expectations evaluating the geographic and technical characteristics of renewable energy systems compared to traditional fossil fuel energy systems. The first set of expectations discusses the shift to more competitive energy markets, moving away from fossil fuels' oligopolistic markets. Traditional energy markets are built around finite and geographically concentrated fossil fuels that result in an energy market with a few well-endowed net exporters of energy sources that dominate the global market. On the contrary, renewable energy is abundant and evenly spread across the globe, which creates possibilities for countries to extend their portfolio, diversify their energy mix, and become more self-sufficient in their energy needs. This allows countries to produce a larger share of their energy demand domestically and diversify their energy mix, which lowering their import-dependence. In terms of this research, the above arguments have demonstrated to contribute to Dutch energy security, mostly when renewable electricity is utilized to produce hydrogen, diversifying the energy portfolio even more.

The second set of expectations envelops the decentralized nature of energy production in comparison with the more centrally focused energy system currently prevailing. Decentralized energy production brings forth a new varied set of local actors, enabling new business models in the process. However, analysis of the scenarios and interviews demonstrates a trend towards ample centralized energy production facilities to decrease the costs and incorporate economies of scale dynamics. Moreover, considering hydrogen production for the built environment, large centralized facilities, and international orientated distribution system is favourable. With increasing interest in hybrid heating solutions for sectors that are challenging to electrify, a larger share of hydrogen in the energy mix is expected. Central production and distribution is economically favourable in the Netherlands and contributes to energy security, especially when there is a healthy balance between domestic production and hydrogen import. This does not imply that novel business models are obstructed. Local empowerment will see less leverage, but the industry has significant opportunities concerning a domestic hydrogen supply chain.

The third expectation concerning the geographic and technical characteristics of renewable energy systems concerns technology knowledge and the competition for rare earth materials. The interviews' analysis demonstrated a strong position for the Netherlands to integrate hydrogen in the built environment. There is much knowledge based on the gas culture and extensive infrastructure. Therefore, the Netherlands has a strong position for a domestic hydrogen supply chain, especially supplying the built environment and industry. Considering competition for rare earth materials, there is much discussion on the matter at hand. Scholten (2018) and Hache (2018), among others, argue that an increase in renewable energy production creates new dependencies on countries that mine rare earth materials. In line with these arguments, these dependencies were also highlighted in the interviews with stakeholders and experts in the field but, not as significant as existing literature expects. However, in a recent paper from Overland (2019), it is argued that this geopolitical rally over control of these rare earth materials is not necessarily inevitable. These materials can be seen as just another commodity that cannot defy the realities of trade, economics, and innovation.

The final set of expectations surrounds the electrification of future energy systems. The paper from Scholten (2018) distinguishes different challenges that countries face growing shares of electricity in the energy mix. This research indicated undoubtedly the growing share of renewable electricity in the energy mix from different sources. However, supply the built environment with renewable green hydrogen mitigates the negative consequences of energy system electrification while simultaneously contributing to national energy security. Hybrid heat pumps can solve grid congestions at peak moments, and the hydrogen infrastructure can act as extra storage capacity in times over demand.

Moreover, electrification of heat on the local level is not always possible, and here, hydrogen poses a great opportunity. Next to this, the electricity grid faces the challenge of long-distance transport losses. Hydrogen, on the other hand, is transported over long distances without any significant losses. This could create a more global orientated market for energy trade when hydrogen becomes a commodity for heating and industry instead of regionalization.

A recent study by van de Graaf et al. (2020) discusses the geopolitics of hydrogen in light of international governance. The paper argues that it is challenging to achieve deep decarbonization without some form of climate-neutral molecules like synthetic fuels, biogas, or hydrogen, especially for sectors like metallurgy, long-haul transport, and chemicals (van de Graaf et al., 2020). Different hydrogen value chains suggest different pathways for hydrogen production, handling, and its applications. These paths involve a mix of different choices for technologies or locations for consumption and production. Technological leadership will be necessary for countries that aspire to gain significantly. Interesting is that this paper makes a critical statement regarding domestic production or hydrogen imports. Countries need to weigh the costs of large scale hydrogen imports against the costs and benefits of domestic production of hydrogen. This study demonstrates how neither scenario (energy-autonomous or full energy import) is desirable and that a balance between domestic production and imports is favourable. Results exposed the probability of hydrogen to create new dependencies on countries that produce cheap hydrogen. However, hydrogen trade will not be so asymmetric as traditional fossil fuels. Hydrogen can be produced practically anywhere globally and is easily stored, making it almost impossible for exporters to abuse market dynamics and for importers to be trapped in a small cartel of hydrogen suppliers. Moreover, international hydrogen trade improves the energy security of importers by providing a backup for the energy system.

Looking more closely at these geo-economics of hydrogen offers opportunities for petrostates integrating segments of the fossil fuel industry and large scale centralized hydrogen production and distribution. The oil and gas exporting countries in the Middle East have several advantages like abundant availability of low-cost solar power, underground storage for CCS, and a geographic location that can serve both Asian and European markets. However, the potential of these regions can be undermined by the availability of freshwater. This study indicates the environmental concerns for water stress, especially for countries with lower amounts of annual precipitation. These challenges can drive up the costs for hydrogen production in these regions.

The oil and gas sectors are championing hydrogen because this allows for re-utilizing existing natural gas infrastructure, especially by pipelines distribution companies (van de Graaf et al. 2020). This is reflected in the results of this study and even goes beyond DSO's and TSO's. In the Netherlands, there is enormous leverage for hydrogen utilization in the built environment from society. Gaseous energy carriers are embroidered in Dutch culture, empowering the business case for hydrogen in the built environment.

Moreover, 19 frontrunner countries have been distinguished that recently published hydrogen strategies or roadmaps. These publications have different national strategies regarding hydrogen productions and utilization (van de Graaf et al., 2020). The paper motivates a need to standardize gas quality and international rules and certification to identify hydrogen quality or carbon content of derivate fuels. This research results in line with these statements, but add to this argument that there is a strong wish and need for government involvement in these early stages of integrating renewables in the energy system and refrain from the classic Dutch setup where the government is more market-orientated.

Finally, results are reflected in comparison with a case with a similar research method. This research is built on the assumption that the future energy system is supplied with green hydrogen from domestic or imported renewable energy sources. However, there are different pathways possible for (sustainable) hydrogen production, and each separate pathway has potentially different consequences for the energy security of a country (Ren et al., 2014). The paper examines the effect of different hydrogen production pathways on the overall energy security of a nation. The case study focuses on China and Denmark by investigating the inferiorities and superiorities of the different hydrogen pathways that help determine the best possible pathway that contributes the most to energy security. Hence, it is interesting to understand the implications of different hydrogen pathways compared to this research's results to determine what dimensions are susceptible to change with different hydrogen production pathways. According to their results, electrolysis from wind power scores the best in the availability dimension, followed by gasification of biomass, biomass pyrolysis, and electrolysis by solar power. According to the energy scenarios, wind energy will occupy a large share of the total energy mix. Comparing Denmark and the Netherlands geographically, both countries have substantial potential for renewable wind power. Therefore, the paper from Ren et al. (2014) can be considered applicable to the Dutch situation as well. This comment is discussed in more detail in the section considering future research possibilities.

Finally, while some of these cases are used in developing the narrative for scenario analysis, it is paramount to reflect on how this potentially affected the results. This is done in section 8.4.2.

8.3 Energy security: time for an update

In more general terms, the results of this research demand critical reflection on how they relate to the field of energy security and renewables. Energy security in literature has always been surrounded by the pre-assumptions and geopolitics of fossil fuel-based energy systems. The current energy security framework does not grasp a future energy system to its full extend. Analysing two future energy systems with existing frameworks. This need for an update was expressed in the challenge of different dimensions to find its value in the future energy system. Whereas Azzuni & Breyer lobby to include all dimensions related to energy security in the analysis, it is experienced that for analyses that consider future energy systems, this is not necessarily the case. From a geopolitical perspective, there is an enormous shift in energy dependencies, moving towards fully renewable energy systems. Implications of new markets, international hydrogen trade, and its effects on national energy security, is not entirely appreciated by this type of approach. Renewable energy systems and scenario analyses are complex, dynamic processes that need to be reviewed from different perspectives. Moreover, energy security is hugely country-specific. There is no one generic framework that fits all; this seems even more accurate for the analysis of future energy systems. In the field of energy security and future energy systems, there is a need to include the complexity of renewable energy systems and new geopolitical dependencies they bring, especially when analysing possible future energy systems. Lastly, energy security frameworks are built on the premises of fossil fuel energy carriers. The geotechnical characteristics of renewable energy carriers, hydrogen in this, are different from traditional fuels, bringing other complexities that energy security frameworks should aspire to touch upon.

8.4 Reflection on research approach and methods

This final section of the chapter reflects on the research approach and the methods. It is crucial to critically assess the research approach and methods to understand how the research framework's limitations potentially affected the results.

8.4.1 The energy security framework

This section will reflect on the energy security framework that has been adapted from Azzuni & Breyer (2018) and how it was applied in this research. The original framework comprised 15 dimensions, 50 parameters, and 76 indicators. An interview was conducted with dr. Azzuni, discussing the application of this energy security framework, to the scope of this research and time constraints. His recommendations were to eliminate certain dimensions that are less relevant for the Dutch energy system regarding hydrogen utilization in the built environment. Eight dimensions were picked with adjustments in the indicators according to the literature review to fit the Dutch context. This was validated with dr. Azzuni. After this, the culture dimension was enriched with new indicators, whereas the first set of indicators did not completely grasp the importance of the culture dimension. With this final set of parameters and indicators, the current Dutch energy system's first analysis was performed.

The indicators from the availability dimension were scored in comparison with the total availability of sources in other countries in the world. For that reason, this dimension was an outlier that affected the energy security score negatively. In the future, this can be abated by dividing the total available energy sources by the total area of each country. That creates an energy potential per square kilometre for all the countries making it more relevant to compare the availability dimension with other countries.

The environment dimension turned out too obvious for an interesting analysis of potential future energy systems. It is irrelevant to examine total GHG emissions in energy systems are nearly carbon-free. However, the water stress indicator is relevant for hydrogen-based energy systems. This dimension can be fixed by incorporating parameters that measure rare earth material stress and rogue carbon emissions from blue hydrogen or other carbon abatement efforts.

Interviews with stakeholders and experts in the fields demonstrated the importance of hydrogen policy and governmental involvement as a kickstart for a potential hydrogen supply chain. However, the policy dimension of the framework did not grasp this critical part of policymaking for future scenarios. Especially given the difference between the national and international scenarios, there is a need for a more in-depth analysis of the policy implications. The regulatory indicator for environmental sustainability was handy for analyzing the current policy dimension but hard to apply to future scenarios. A recommendation for this dimension would be to altogether remove it from studies that compare current energy systems with future scenarios. Studies focusing solely on the implications of future renewable energy systems can incorporate a more extensive policy dimension.

8.4.2 Case selection and biases

The literature and cases used in section 8.2 to reflect on the results are partly applied in the theoretical section to create an understanding and narrative of the relation between renewables and energy security. This can create biases in the results, especially reflecting on the results with the same literature. However, the literature reviewed in chapter 2 that concerns geopolitics and energy security of renewables was not adopted in the energy security framework. The claims of these papers did not have any influence on creating the final energy security framework. This literature aimed to structure the place of hydrogen in a possible future energy system and what implications different hydrogen supply chains have compared with the traditional Dutch energy system. Next, arguments for the results in this research are not necessarily in line with other literature claims, as demonstrated in section 8.2. Next, arguments in other studies are not necessarily focused on the Netherlands, but more frequently made globally. In some instances, arguments from this research and other literature are in line with each other. This does not indicate a biased result but confirms the statement also in the Netherlands' context. Nevertheless, the researcher acknowledges this potential bias problem and argues that the reflection of the results in light of theory is carried out carefully and holistic at all times.

8.5 Reflection on research relevance

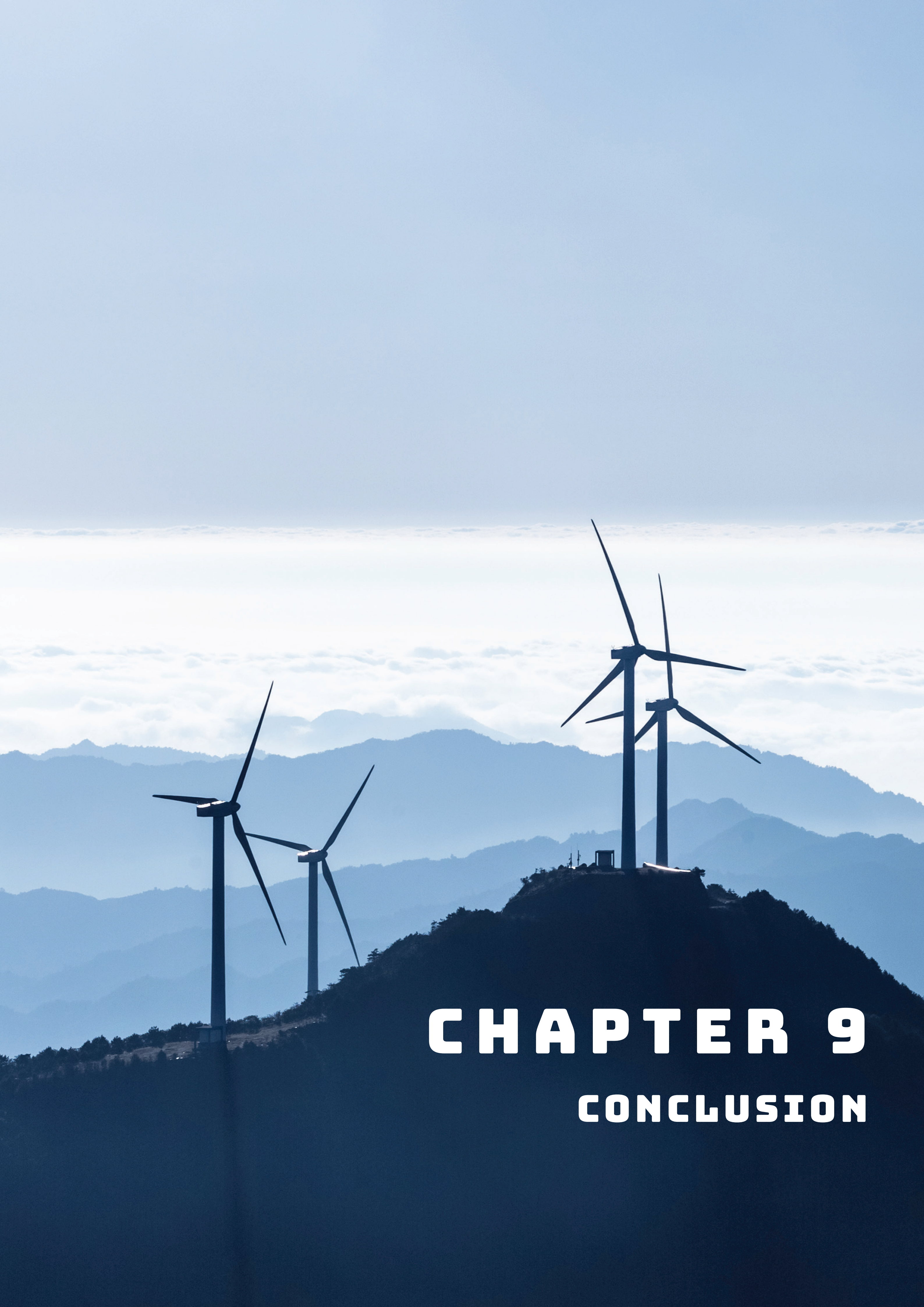
Reflection on this project results gives more insight into how these results are relevant to the academic and practical level. The following paragraphs will discuss the relevance of research outcomes in light of the researched field and on a more practical level.

8.5.1 Academic relevance

The discussion section shortly touched upon several elements of the results that indicated some sort of update current literature in the field of energy security. While most energy security literature is strongly biased by the premises of fossil fuel energy systems and the geotechnical characteristics of fossil fuels, renewable energy systems will probably be dominated by sustainable energy carriers. As demonstrated, the economic, societal, and environmental consequences of renewable energy systems compared with traditional systems require different perspectives to cope with the complexities they entail. First of all, an update of energy security literature in light of renewable energy carriers is desirable. Literature review and applying the framework indicated that different dimensions do not fully grasp the underlying assumptions future energy system analyses contain. The shift in interdependencies between states and the transfer of geopolitical power and societal implications of renewable energy systems are overly mentioned to affect future energy security significantly. Current energy security indices are not designed to touch upon these complex changes or are exceedingly holistic and fail to distinguish future energy systems' deeper complexities and uncertainties. There is a need for new indices designed to evaluate the effects of different energy scenarios on energy security performance compared to a reference case. The results, and reflection on results, depicted opportunities for more coherent frameworks purely designed for renewable energy system analyses.

8.5.2 Practical relevance

This project and its results demonstrated several implications and recommendations for the actors in the field on a practical level. The analysis of the two different scenarios helps policymakers understand how energy imports and production potentially create energy security challenges Differences between the national and international scenarios presented hidden pain-points from an energy carrier perspective. This helps policymakers to steer the energy transition and integration of hydrogen in the energy system accordingly, ensuring improvement energy security. Ensuring a coherent vision for the future helps the government distribute facilitating roles in this novel energy system among key actors. Finally, on the end-use site of hydrogen utilization in the built environment, stakeholders should focus on transparency, education, and communication of developments in this new energy system.



CHAPTER 9

CONCLUSION

9. Conclusion

This chapter aims at concluding and answering the research questions. The first part of this chapter is dedicated to answering the research questions, and the final sections will include recommendations for further research and a reflection on the relevance of this project.

9.1 Main research question

This project aims to explore how hydrogen, as an energy carrier, affects Dutch energy security when decarbonizing the built environment given its geotechnical characteristics. This objective led to the formulation of the research questions that form the foundation of this research. The main research question was dissected into smaller, workable research problems that collectively work towards answering the main research challenge:

How will decarbonization of the Dutch built environment through hydrogen affect national energy security in the long-term?

The objective is directly recognized in the main research question itself: exploring how hydrogen as an energy carrier affects future Dutch energy security. This research demonstrated how hydrogen potentially affects energy security in the Netherlands, given eight different dimensions. This study created an improvement energy security framework applicable to the Dutch context and possible future energy systems. Two scenarios have been chosen based on their assumptions and high hydrogen penetration in the built environment. The national scenario is built on the assumption of a future energy-autonomous energy system. The international scenario assumes an international orientated energy systems with major energy imports. Other variables in these future energy systems are primarily constant. The framework is applied to both scenarios and the current system as a reference case. Interviews with stakeholders and experts in the field gave insights into how hydrogen could potentially affect the framework's eight dimensions. In general, the effect of hydrogen in the built environment on energy security performance is positive. Significant improvements in the availability, diversity, and culture dimension are recognized for both scenarios. Domestic hydrogen production for the built environment significantly improves both the availability and location dimension. However, it potentially induces increased energy prices. Due to hydrogen gas characteristics, it is likely to become a global trading commodity, creating competitive markets, decreasing hydrogen prices, inhibiting less incentive for large-scale domestic production. This would increase the dependencies between countries and is unfavourable for energy security concerning the availability dimension. Hydrogen is favourable in the built environment from a societal point of view. For both scenarios, hydrogen in the built environment improves the culture dimensions significantly.

9.2 Sub research questions

The main research question was dissected into multiple smaller research problems that collectively helped answer the main research question. These sub research questions allow adding a little more detail into the subsequent steps that led to answering the main research question.

What can theories and/or concepts be used best to capture energy security in a renewable world?

The first research phase's start required a deep dive into literature to understand what different models, frameworks, and theories were available in the energy security domain. Energy security demonstrated to be an exceptionally well-covered theme in literature. Moreover, the contextual differences between previous research resulted in various available energy security indices to perform an analysis. Due to this research's contextuality and specific scope, the choice was made to find an index that provided a holistic overview and includes as many dimensions as possible. That would allow further specifying the framework and excluding or including different indicators to make the framework applicable to the Dutch energy system. Next, the literature on the energy security of renewables and geopolitics of future energy systems was necessary to understand the possible implications of novel energy carrier in the system. Also, this created a narrative for analysing the current Dutch heating system and future supply chains. This led to the choice of an index that is presented and substantiated in section 2.4. Section 2.5 and 2.6 provide the researcher with the knowledge and tools to analyse the implications of hydrogen in the built environment and the effects on energy security.

What does the system integration of hydrogen as an energy carrier imply for heat supply chains in the Netherlands; what are the most realistic and relevant hydrogen penetration scenarios towards 2050?

Chapter 3 analysed the current Dutch heating system based on the narrative created at the end of chapter 2. This same approach was applied to a possible hydrogen supply chain from the sources, generation, and distribution perspectives. Examining the current heat supply chain with the future hydrogen supply chains, the distribution will not change. Hydrogen production is mainly done centrally and can be transported into the existing gas grid. From a sources point of view, the most significant change is expected. Hydrogen is an energy carrier in contrary to natural gas, which is a fuel. That means it is produced from another energy source, in this case, renewable electricity. This energy source is abundantly available and geographically less restricted than fossil fuels. This makes hydrogen production possible everywhere in the world. From a generation perspective, hydrogen production technologies require rare earth materials that potentially create new dependencies. Based on the literature review and the supply chain overview, two hydrogen scenarios stand out. Both scenarios integrate hydrogen in large quantities for the built environment while leaving other aspects nearly constant, making them incredibly applicable for an energy security analysis. One scenario assumes an autonomous energy system, and the other is more internationally orientated, relying on massive energy imports to meet demand.

How can the initial framework from the first sub-question be improved?

The first sub-questions energy security framework is updated with knowledge from chapter 3 and an interview with the creator. Due to the time constraints of the research, not all fifteen dimensions of the framework can be examined. Next, the culture dimension did not grasp the implications of renewable energy carriers in future energy systems for society sufficiently. For these reasons, eight dimensions were kept with adjusted indicators. The culture dimension was given another parameter consisting of five indicators. The adjustments were validated with the creator of the original framework. The final deliverable was an operationalized, workable framework applied to both the current energy system and the two future scenarios.

What geotechnical characteristics of hydrogen are responsible for the change in future energy security performance compared to the reference case?

After analysing the current system and the future energy systems in light of the reference case, some differences can be distinguished. Based on the geotechnical characteristics of hydrogens, these can be discussed. This also provides a sensitivity discussion on how different indicators are prone to change when the hydrogen supply chain changes or other aspects of the environment. First, hydrogen gas is easily stored in either dedicated vessels or the existing Dutch natural gas grid after minor changes. The only cost-efficient possibility for implementing hydrogen in the built environment is by distributing hydrogen through pipelines. The Netherlands makes an interesting case considering the extensive existing natural gas infrastructure. This network can provide substantial amounts of hydrogen storage, making it possible to extract more renewable energy sources and convert them into hydrogen. Hydrogen utilization in the built environment gives considerable incentive to revamp the existing grid that would otherwise be obsolete, preventing hefty investments for grid expansion and electrification. Next, the capability to store hydrogen opens up the potential for a future global hydrogen market, inhibiting competitive hydrogen prices and potentially lowering energy prices. There are different production pathways for sustainable hydrogen, increasing the spatial distribution of potential production countries, and supporting the petrol states to become players in this new market. On the societal level, hydrogen as a gaseous energy carrier can expect superb reception for sustainable home appliances due to Dutch culture. This Netherlands is accustomed to legislation regarding gasses; hence, integrating hydrogen in the built environment from a political perspective should not face any serious challenges.

9.3 Recommendations for future research

Recommendations for future research are mainly adapted from the academic learnings that the results of this project presented. The field of energy security is still built on the characteristics of traditional fossil fuel energy systems. Many parameters surround the idea of fossil fuels and traditional geopolitical environments. This makes room for interesting future research that updates the notion of energy security in a more renewable context—with that, developing a framework that surrounds the definition and incorporates dimensions that can evaluate shifts in the geopolitical environment.

Interviews demonstrated the significance of policy dealing with renewable energy carriers, role distribution in a novel energy system, and the extent to which the government should be responsible for the execution of projects. The framework in this project was somewhat limited in its policy analysis. This opens up the opportunity for future research to inspect the policy implications for successfully integrating hydrogen for the Netherlands' built environment.

Next, on a geopolitical level, this research examined the geotechnical characteristics of hydrogen and how this affects energy security in two different scenarios. As section 2.6 indicated, there are more dimensions to renewable energy geopolitics than treated in this research. Interesting would be to investigate further geopolitics' implications and the shift in interdependencies when moving towards a renewable energy system with hydrogen as the second dominant energy carrier.

A final recommendation for future work is based on the case comparison in the final paragraph of section 8.2. This research was built on the assumption that only green hydrogen is either produced or imported in a future energy system. However, different hydrogen production pathways can be promising for the Netherlands in light of different aspects. The case study was performed for Denmark and China; interesting would be to do the same for the Netherlands.

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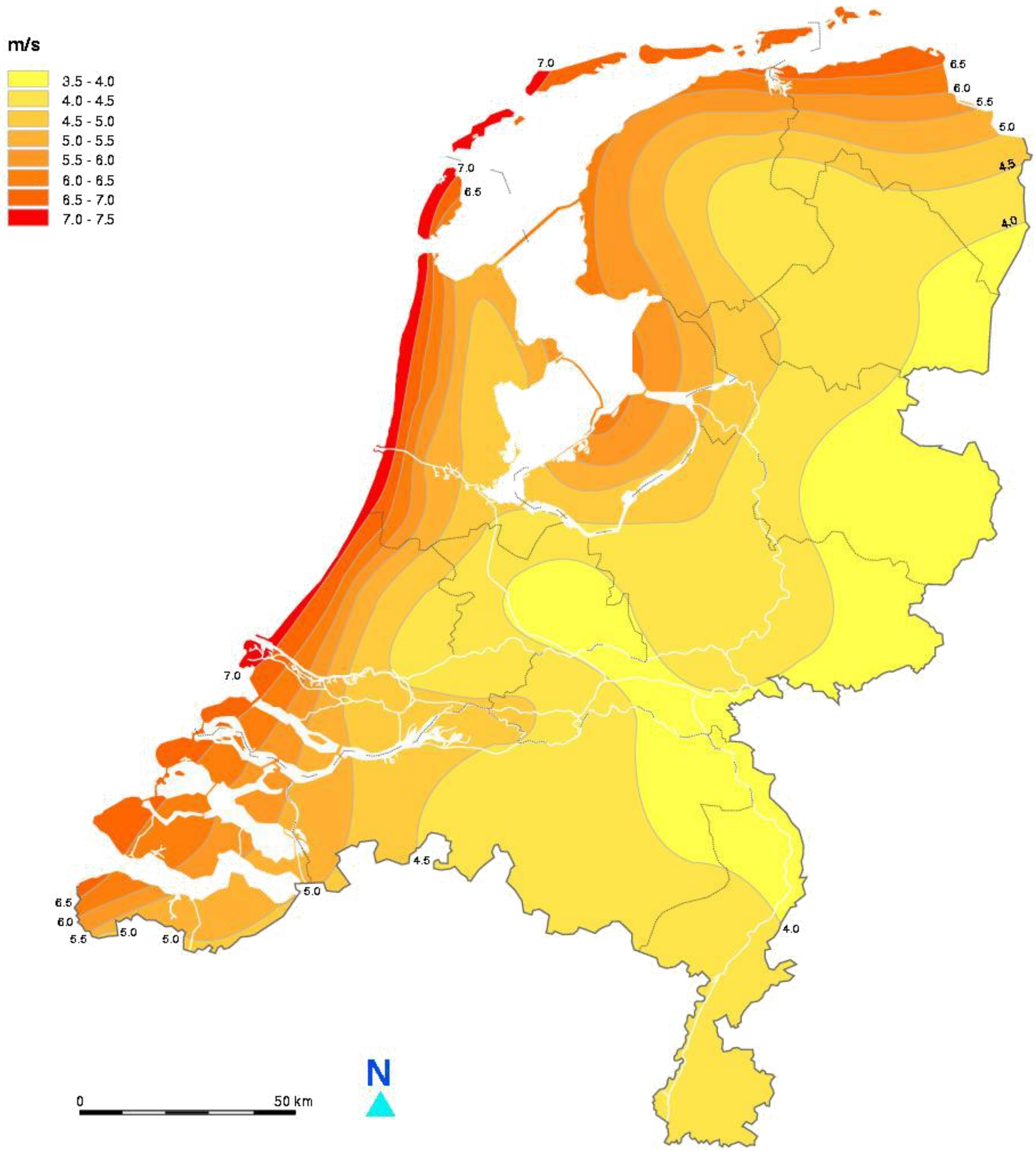
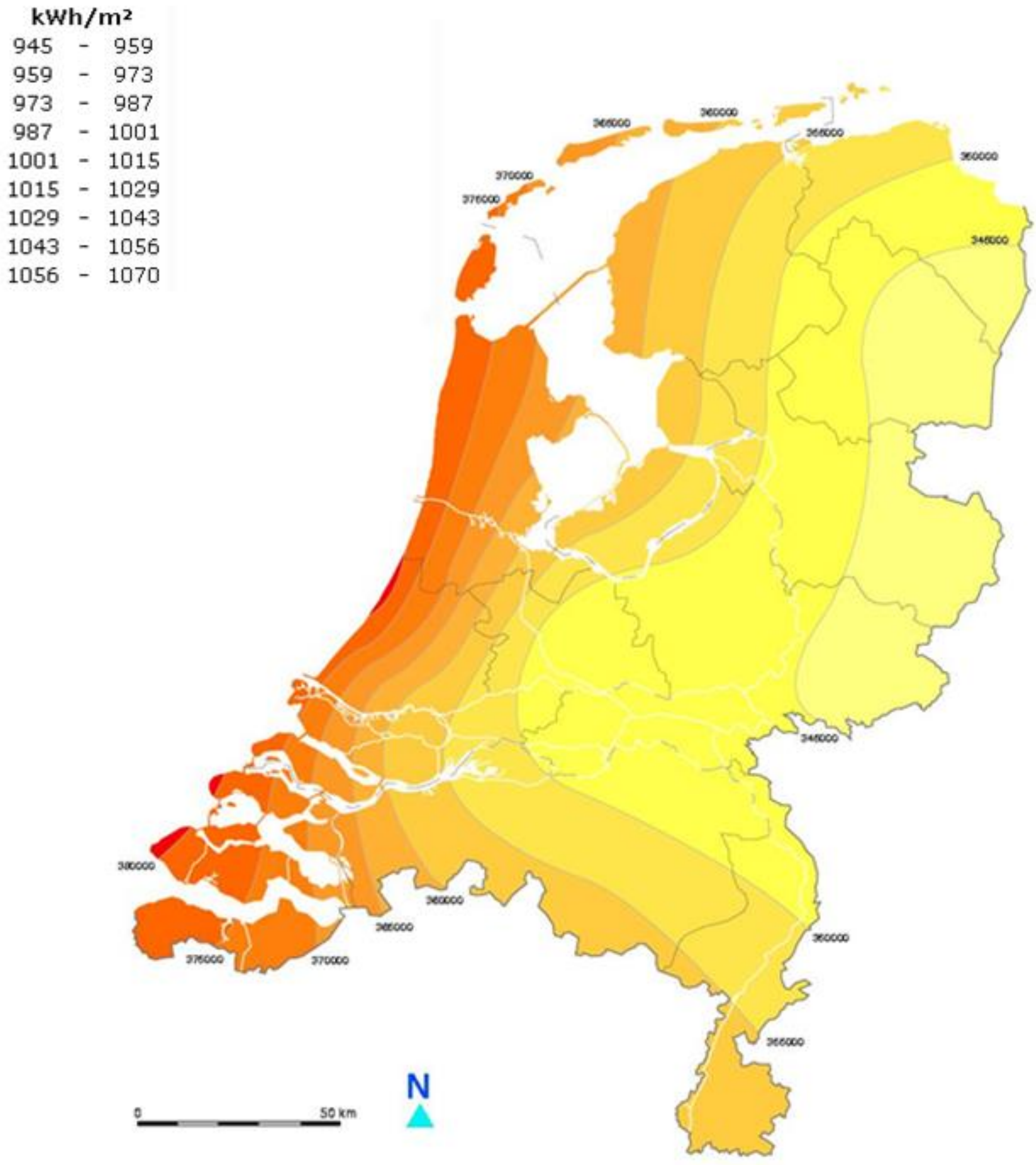
Appendix

Appendix A: Average wind speeds in the Netherlands



Source KNMI

Appendix B: Average solar irradiation in the Netherlands



Source KNMI

Appendix C: Interview questions in English and Dutch

Interview questions per dimension English:

1. Availability: NO QUESTIONS, DATA/REPORTS
2. Diversity: NO QUESTIONS, DATA/REPORTS
3. Cost:
    a. What are your expectations regarding future energy prices in a future energy system with hydrogen as second energy carrier?
    b. LCOE for green hydrogen will follow the same trend solar PV and wind power generation as 70-80% of the costs of hydrogen is due to electricity generation. How do you expect the Netherlands will position itself in the hydrogen market? What factors will be our advantage or disadvantage? SKIP?
    c. What role will hydrogen have in price stability/volatility?
4. Technology and efficiency:
    a. Which technologies for hydrogen production, distribution and consumption can we expect to be dominantly used in the Netherlands in a future renewable energy system?
    b. Currently we face high energy losses in thermal plants, resulting in a rather low “efficiency” (input/output ratio). Introducing renewable energy production improves efficiency, but what happens to efficiency when the Netherlands starts producing hydrogen from this electricity?
    c. How can hydrogen contribute to energy demand reduction?
5. Location:
    a. Dependence on Russian gas and Saudi oil will deteriorate with introduction of renewables, these “producing countries” can be seen as losers of the energy transition. Will hydrogen create new dependencies in the Netherlands? Or will we be one of Europe’s exporters in the near future?
    b. How could central hydrogen production pose any threats to energy security in terms of system failures? How is this related to the uneven distribution of the Dutch population?
    c. What is your perspective of NIMBY regarding hydrogen production facilities, huge wind farms and storage facilities? (link to culture)
6. Environment:
    a. What are the consequences for the environment with large scale hydrogen production for example in terms of pollution, water use, etc.?
7. Culture:
    a. How do you think hydrogen implementation should be promoted to prevent adversity towards hydrogen realization?
    b. How will the Dutch society look towards hydrogen utilization, especially as gas for heating?
    c. Scores
        i. Awareness of climate change and technology
        ii. Transparency of the decision-making process
        iii. Communication of benefits, disadvantages and costs
        iv. Local context, NIMBY
        v. Trust in decision-makers
8. Policy:

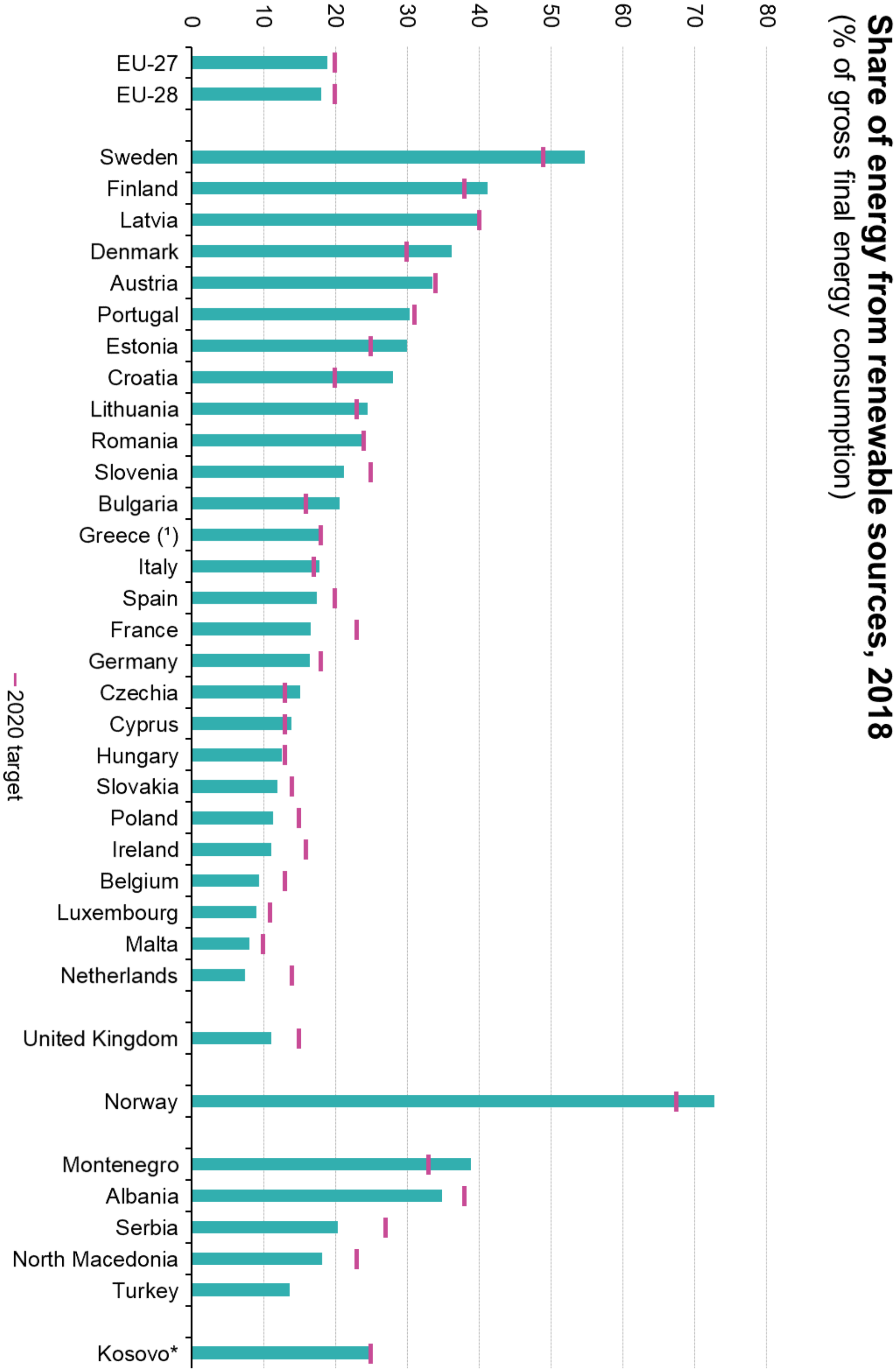
a. On regulatory level, do current regulations provide sufficient incentive for developing a hydrogen supply chain? What regulatory pitfalls can be distinguished and what is necessary to cope with them?
b. How can cooperation between government and hydrogen initiatives best be organized? To what extent should the government be involved/responsible?

Interview questions per dimension Dutch:

1. Toegankelijkheid: geen vragen
2. Diversiteit: geen vragen
3. Kosten
    a. Wat zijn uw verwachtingen betreft de energie prijzen in een toekomstig energie systeem met waterstof als tweede energie drager?
    b. Welke rol gaat waterstof spelen voor stabiele prijzen en tegen prijs volatiliteit?
4. Technologie en efficiëntie
    a. Welke technologieën voor waterstof productie, distributie en consumptie kunnen we verwachten een dominante plek aan te nemen in het Nederlandse energie systeem?
    b. Momenteel staan we voor het probleem veel energie te verliezen in warmtekracht centrales dat resulteert in een betrekkelijke lage energie efficiëntie. Hernieuwbare energie zou dit kunnen oplossen, maar wat gaat er gebeuren met de efficiëntie wanneer waterstof als tussendrager wordt toegevoegd aan de keten? Is dit probleem kleiner wanneer waterstof direct wordt gebruikt als warmte bron?
    c. Hoe kan waterstof bijdragen aan verminderde vraag naar energie?
5. Locatie
    a. De afhankelijkheid van Russisch gas en olie uit Saudi Arabië zal afvlakken wanneer hernieuwbare energie meer draagvlak krijgt in het energie systeem. Zal waterstof juist weer nieuwe afhankelijkheden creëren in Nederland? Hoe kan dit eruit gaan zien?
    b. “Er is veel onderzoek naar de voordelen van decentrale energie productie ten opzichte van centrale productie waarin vaak de voorkeur gaat naar een toekomstig decentraal systeem”. Hoe kan het centraal produceren van waterstof problemen opleveren voor grootschalige systeem falen?
    c. Wat is uw perspectief op het NIMBY principe omtrent waterstof productie faciliteiten, grote wind farms en bijvoorbeeld opslag?
6. Cultuur
    a. Hoe denkt u dat waterstof implementatie gepromoot dient te worden om afkeer tegen deze energie drager te voorkomen (denk dus ook weer aan dat NIMBY principe)?
    b. Hoe denkt u dat de maatschappij zal kijken op waterstof als energiedrager voor warmte in de gebouwde omgeving?
    c. Scores:
        i. Besef van klimaatverandering en nieuwe energie innovaties in de Nederlandse samenleving
        ii. Transparantie van decision-makers
        iii. Communicatie van voordelen, nadelen en kosten van renewables
        iv. Lokale context: NIMBY problemen
        v. Vertrouwen in beleidsmakers

7. Milieu
    a. Wat zijn de consequenties voor het milieu als we het hebben over grootschalige waterstof productie met betrekking tot vervuiling, water gebruik, etc.?
8. Wet en regelgeving
    a. Is de huidige wet en regelgeving voldoende om een waterstof supply chain in de hand te werken? Welke valkuilen moeten nog overkomen worden en hoe kan dit het beste gedaan worden?
    b. Hoe kan de samenwerking tussen de overheid en het bedrijfsleven het beste georganiseerd worden? Tot welke hoogte moet de overheid betrokken/verantwoordelijk zijn?

Appendix D: Share of energy from renewable sources, 2018



** This designation is without prejudice to positions on status, and is in line with UNSCR 1244/1999 and the ICJ Opinion on the Kosovo declaration of independence.*

(¹) Estimate.

Source: Eurostat (online data code: ilc_lvho05a)

Appendix E: RISE indicators – scored and non-scored (World Bank, 2016)

	Policies and Regulations			Administrative Procedures*
Energy Access	• Existence and monitoring of officially approved electrification plan • Scope of officially approved electrification plan	• Framework for grid electrification • Framework for minigrids • Framework for stand-alone systems	• Consumer affordability of electricity • Utility transparency and monitoring • Utility creditworthiness	• Establishing a new household grid connection • Permitting a new minigrid
Energy Efficiency	• National energy efficiency planning • Energy efficiency entities • Information provided to electricity consumers • Incentives from electricity rate structures	• Mandates & incentives: large consumers • Mandates & incentives: public sector • Mandates & incentives: utilities • Financing mechanisms for energy efficiency	• Minimum energy performance standards • Energy labeling systems • Building energy codes • Carbon pricing and monitoring	• Securing energy efficiency appliance standards certification
Renewable Energy	• Legal framework for renewable energy • Planning for renewable energy expansion	• Incentives & regulatory support for renewable energy • Attributes of financial and regulatory incentives	• Network connection and access • Counterparty risk • Carbon pricing and monitoring	• Permitting a new renewable energy project

Source: RISE database, World Bank.
*Not scored

Appendix F: Data overview for the diversity dimension

Diversity of sources (production and imports)

Local production		Imports		Total		SIDI
ktoe	%	ktoe	%	ktoe	%	1-∑x^2
58528	*22.94*	*196650*	*77.06*	*255178*	*100*	***0.354***

Diversity of carriers of total final consumption

Coal		Crude oil		Oil products		Natural gas		Nuclear	
ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
704	*1.60*	*3155*	*7.15*	*22364*	*50.69*	*17900*	*40.57*	*0*	*0*

Continued;

Fossil fuels		Hydro		Geothermal, solar		Biofuels and waste		Renewable fuels	
ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
44123	*77.76*	*0*	*0*	*63*	*4.95*	*1209*	*95.05*	*1272*	*2.24*

Continued;

Electricity		Heat		Total		SIDI
ktoe	%	ktoe	%	ktoe	%	1-∑x^2
8740	*15.40*	*2605*	*4.59*	*56740*	*100*	***0.369***

Diversity of technologies

Gas		Oil		Coal		Nuclear		Solar PV	
ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
20977	*63.68*	*117.15*	*0.36*	*5839*	*17.72*	*482*	*1.46*	*1050*	*3.19*

Continued;

Solar CSP		Wind		Biogas		Biomass		Geothermal	
ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
0	*0*	*2985.6*	*9.06*	*243.57*	*0.74*	*1212.3*	*3.68*	*0*	*0*

Continued;

Hydro RoR		Hydro reservoir		Ocean		Total all tech.		SIDI
ktoe	%	ktoe	%	ktoe	%	ktoe	%	1-∑x^2
11.824	*0.04*	*25.476*	*0.08*	*0*	*0*	*32944.41*	*100*	***0.55***

Diversity of consumers

Industry		Transport		Residential,		Commercial and public services		Agriculture and forestry	
ktoe	%	ktoe	%	ktoe	%	ktoe	%	ktoe	%
13181	*23.23*	*10280*	*18.12*	*9120*	*16.07*	*6326*	*11.15*	*3382*	*5.96*

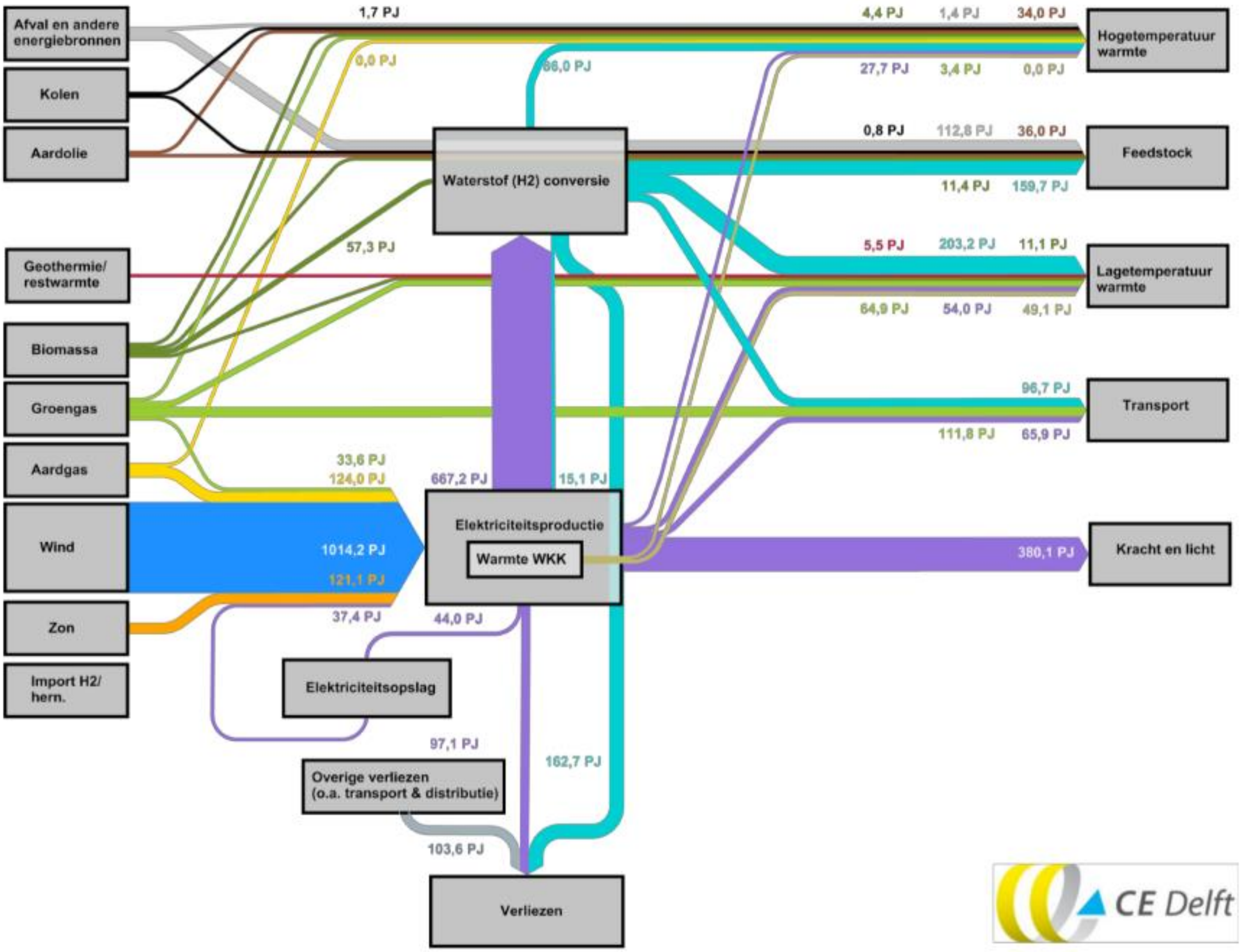
Continued;

Fishing		Non-specified		Non-energy use		Total		SIDI
ktoe	%	ktoe	%	ktoe	%	ktoe	%	1-∑x^2
164	*0.29*	*101*	*0.18*	*14186*	*25*	*56740*	*100*	***0.809***

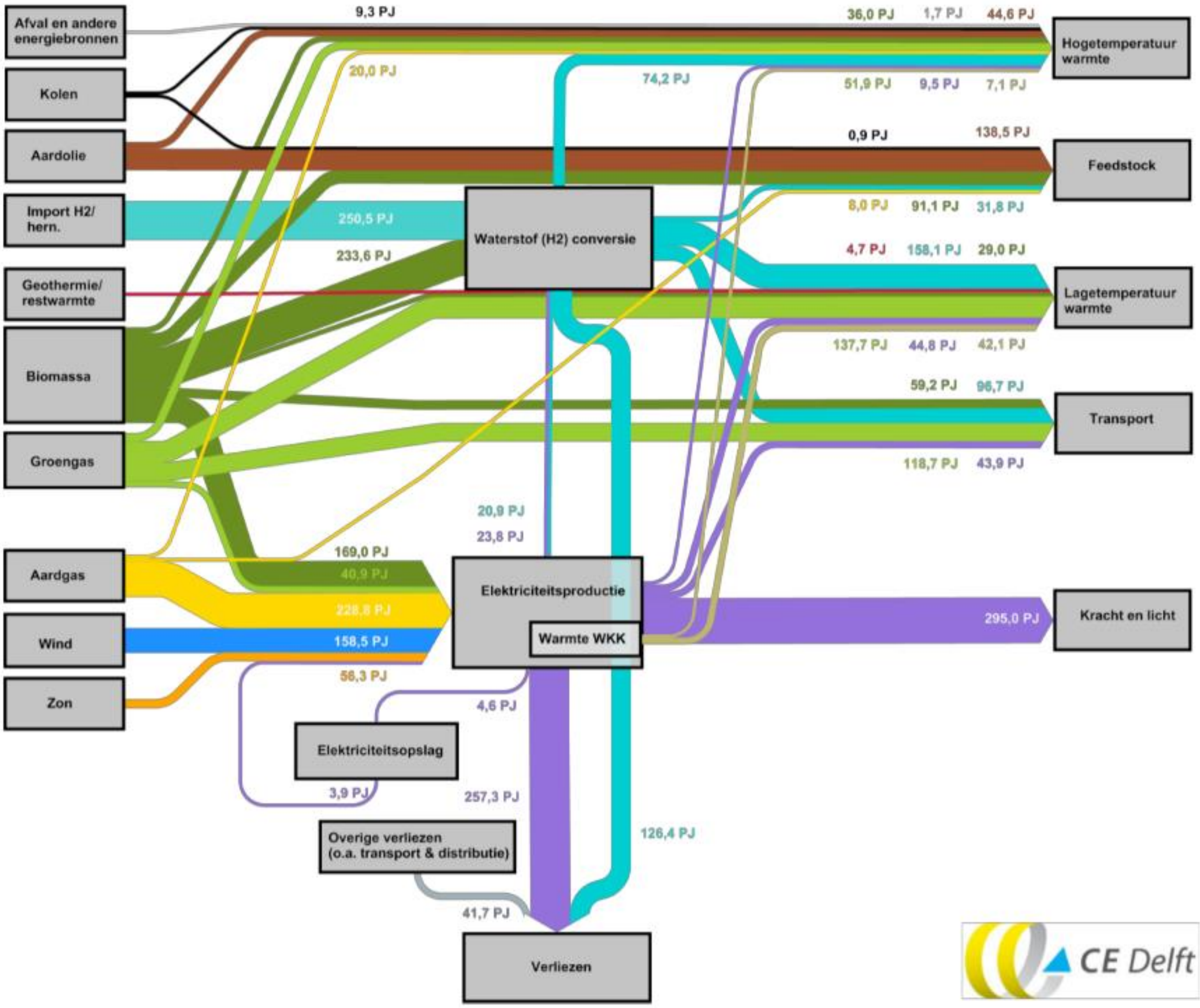
Appendix G: Main characteristics of the future energy scenarios

	Local	National	International
Power & Light	25% base-load savings through more efficient appliances. Substantial electrification of industry	25% base-load savings through more efficient appliances. Substantial electrification of industry	25% savings through more efficient appliances
Low-temperature heat	High penetration of heat grids and all-electric (restrictions on green gas, no H_2 distribution) Savings: 23%	High penetration of hybrid heat pumps burning H_2 (and green gas) (restrictions on green gas) Savings: 23%	High penetration of hybrid heat pumps burning H_2 and green gas (mild restrictions on green gas). Savings: 12%
High-temperature & feedstock industry	Circular industry and ambitious process innovation: 60% savings 55% electrification 97% lower CO_2 emissions	Circular industry and ambitious process innovation: 60% savings 55% electrification 97% lower CO_2 emissions	Biomass-based industry: 55% savings 35% biomass 14% electrification 95% lower CO_2 emissions
Passenger transport	100% electric	75% electric 25% hydrogen	50% electric 25% green gas 25% hydrogen
Freight transport	50% green gas 50% hydrogen	50% green gas 50% hydrogen	25% synthetic fuels 25% green gas 50% hydrogen
Renewables generation	84 GW solar 16 GW onshore wind 26 GW offshore wind	34 GW solar 14 GW onshore wind 53 GW offshore wind	16 GW solar 5 GW onshore wind 6 GW offshore wind
Conversion and storage	75 GW electrolysis 60 GW battery storage	60 GW electrolysis 50 GW battery storage	2 GW electrolysis 5 GW battery storage
Hydrogen	100 TWh domestic generation	158 TWh domestic generation	73 TWh import 4 TWh domestic generation
Methane	23 TWh domestic biomethane 35 TWh imported natural gas	46 TWh domestic biomethane 55 TWh imported natural gas	24 TWh domestic biomethane 72 TWh imported natural gas
Biomass			28 TWh import

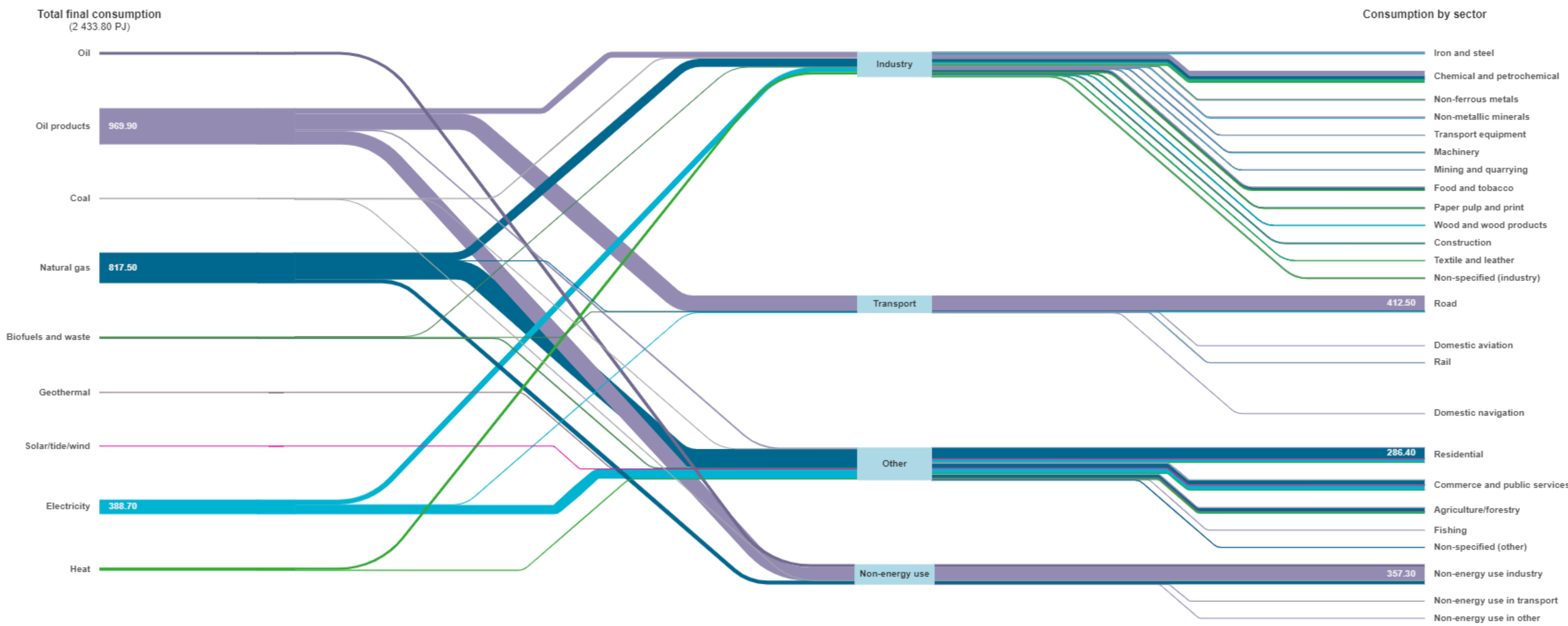
G.1 Sankey diagram of energy flows national scenario PJ/y (in Dutch)



G.2 Sankey diagram of energy flows international scenario PJ/y (in Dutch)



Appendix H: Sankey diagram of final total final consumption (PJ) in 2018 (IEA, 2018)



Appendix H: Summary of each interview

H.1 STEDIN

1. **Costs**

- With high share of renewables we need to work on either demand-side, storage or supply-side management. Demand side management will be interesting, however, curtailment is something that will also happen at a certain moment. Hydrogen makes it possible to store this energy, but to what extent is the question. Storing energy has consequences on the energy price.

2. **Technology and efficiency**

- Hydrogen will have several roles, feedstock, non-energetic and of course in the energy system, built environment and mobility. Until 2030, hydrogen will not be used in the built environment on a large scale. In the beginning of the energy transition you want to make big CO2 reductions. For this reason, the industry will be the first sector that is supplied with renewable hydrogen.
- Hydrogen will not be the only solution to the problem.
- Upcoming years will not see any large hydrogen facility yet, probably from 2030 onwards.
- Look at system level what is needed! Before deciding where to develop the hydrogen supply chain, it is necessary to look at the system needs. What is the most economic location for hydrogen production and storage.
- No direct relation between reducing energy demand and hydrogen. However, we need to look at efficiency when it comes down to hydrogen for electricity use.
- Will green hydrogen be cheap enough when produced during peak hours? You would want to have electrolysers to run at full load constantly. Therefore, again, we need to look at the complete system. How can we integrate hydrogen in such a way that we can satisfy the built environment, industry and keep the electrolysers running at full load to prevent high hydrogen prices.

3. **Location**

- A lot of future predictions regarding climate and energy were wrong, so I like to think in scenarios on how the future can look like with regard to hydrogen.
- Energy is actually a lot of politics and in the Netherlands a lot of policy is driven through Groningen and the earthquake challenges.
- If we extract less gas, we need more import! So that means more LNG or gas from Russia that gives more footprint.
- Do we want green hydrogen immediately, or is blue hydrogen also a good option?
- I think we need a pathway towards green hydrogen, with first blue hydrogen.
- Question is: do we want to be self-sufficient? We have never been self-sufficient, so why be now? Why not do this on European level?
- Probably we will not be able to produce all the hydrogen ourselves, so we need to import. The question is, how will the shift occur in dependencies? This implies that a new energy carrier create new dependencies. One, from the technology perspective where large scale hydrogen production requires rare earth materials, two, dependence on cheap hydrogen from places where electricity production much cheaper than in the Netherlands.
- The strength of the Netherlands lies within their vast gas infrastructure that can be revamped to transport hydrogen. The transport of gases is easier and better to store. This way we can use the gas grid to ease the energy transition.

- Large scale production has it benefits when we talk about gas quality and gas standards. Makes it easier to change appliances on large scale which is more efficient
- We should think about dividing the Netherlands in compartment and understand what districts need what solutions for heating.
- The complexity of central hydrogen production and distribution is limited. There are plans for making it happen.
- How will the Netherlands position itself? We have a lot of knowledge and infrastructure (gas roundabout). If it possible somewhere, than it should be in the Netherlands (koppelen met gasunie studie vergeleken met Duitsland)

4. **Culture**
    - Hydrogen can expect to be accepted easily, especially here in the Netherlands
    - People don't want to change all their appliances to electric for example.
    - Production will always be an issue when considering the need for more renewables
    - The hydrogen infrastructure is much easier adaptable the current system.
    - A lot of industrial clusters can provide place to produce and store hydrogen
5. **Environment**
6. **Policy**

- Current gas law is not sufficient. The question is, who is accountable for what? These questions should be the first concern for the government.
- DSO's should be responsible for hydrogen distribution.
- Last decades we had quite a neo-liberal government, looking at markets. We see now that, especially with COVID, that this is back casted to the society. This raises the question whether the government should maybe get involved more. I believe that they should. More and more public parties join in this initiatives and I believe that this is interesting and good.

H. 2 GASUNIE

1. **Costs**
2. **Technology and efficiency**
3. **Location**
    - System failure: decentral is not really economic. More than 60% of the energy demand will be satisfied with molecules. So I believe that we need the big projects, and keep it central. So how robust is this system? Another question would be, how robust is this compared to decentral. We expect, that the most part of molecule supply will be central. This is the most efficient way and also more robust than the smaller projects. In the same system, storage can be integrated that adds to this robustness of the system that can be compared to the robustness of the system.
    - Import dependence: OPEC is not as powerful anymore. Russia is an important player, and will remain one probably. But there is not a dependence on one country, there is diversification of the supply already. For hydrogen I think that there is a lot of local production, but still, trade will happen. I suspect to have North European market for hydrogen. Maybe we also will see cheap hydrogen from the north of Africa. So first, upscaling nationally, then in Europe and maybe at the end intercontinental.
    - Geographic location Netherlands: good position! This is of course due to our gas infrastructure. We have a good geographic position for logistics and storage, and of course, production of

hydrogen due to the North Sea. Considering transportation and distribution we have our ports that makes future hydrogen trade easier.

4. **Culture**
   - There is a lot of leverage for hydrogen! Compared to other heating solutions hydrogen. Especially, due to the fact that we can re-use the infrastructure and that people are used to cook and heat on natural gas.
5. **Environment**
6. **Policy**
   - Currently nearly no legislation. Politics, ministry, are responsible for sustainability. I believe that there is not really a risk for the lack of legislation in the future.

SIDE NOTES:

- At first, industry will be supplied and afterwards mobility. The specific solution for heating depends on the district or location.
- After 2030 we will see opportunity for hydrogen in the built environment.
- Gasunie project is busy with making a closed chain of hydrogen, so that means production of renewable energy until the end use appliances (industry feedstock first).

H.3 ENPULS

1. **Costs**

- Hydrogen will dampen the peaks of electricity prices.

2. **Technology and efficiency**

- Technologies: production, will be namely electrolysis. However, we also see interesting developments in super critical water gasification. A reason for this is the drop in prices for renewable electricity from wind and sun. Distribution: In the Netherlands we already have a hydrogen backbone. But, we also have a coherent gas infrastructure for natural gas, that can be utilized for hydrogen. On regional level, there is research on distribution of hydrogen with the existing grid to houses, and that seems very promising. Consumption: built environment, fuel cell but also boilers that can be adapted to combust hydrogen. This is especially interesting when we talk about a hybrid system. The benefit of this system is that nearly every house in the Netherlands can be heated this way, whereas, some houses would use more electricity and the older houses would utilize more gas. This gas can either be hydrogen, but also towards the full transition we will probably see a mix of gas that step-by-step is changed to hydrogen or mixed with biogas. Benefits are, less insulation, less stress on the grid, utilize the gas grid, and less resistant from society.
- Efficiency: It would be inefficient to convert hydrogen to electricity, you want to avoid this conversion processes. At some points, it might be energetically inefficient to do some conversions, but economically favourable. You can expect this to happen when there is an enormous surplus of renewables. This would be a very hard calculation. However, energetic efficiency is one variable. There is also the economic factor. This would be the end sum, simply a numbers game.

3. **Location**

- It is possible to produce all the hydrogen domestically. This is also the same for electricity production. I do not expect that we won't import hydrogen. That is very expensive, and that means that we need a lot more renewables. I expect that there will be an European or even world market for hydrogen, and we might be importing hydrogen from places that can generate electricity for low prices. At the moment, we only generate around 8% energy ourselves, from renewables, if we drop our gas extraction. However, I do expect that our dependence will be lower. But, 30-40% of our energy demand will be satisfied from molecules, and I do not expect that we can produce every last of them domestically for a cheap price. So there will be a shift.

- There are already studies on how much it will cost to produce hydrogen at places that need grid expansion. The cost of green hydrogen is threefold that of imported grey hydrogen. But, there are saved costs for grid expansion, but still this would not make a business case, yet.
- I expect that we first satisfy the industry hydrogen needs and afterwards, from 2030 onwards, look at the built environment.
- Central/decentral: I don't think you should rely on just one point of hydrogen production. There is a lot of opportunity for more local electrolysers at places of renewable electricity production. The electrolysers have three functions: 1. Of course, the production of hydrogen, 2. Less stress on the grid and 3. Flexibility.
- We are experiencing that solar parks and wind parks will not be needing any subsidy in five years.

4. Culture

- How to promote hydrogen? I don't think that this is really necessary in the Netherlands. We are so used to cook and heat with natural gas. The culture is pro-gas. There is a lot of lobby for hydrogen in the built environment, to the extent that district heating systems are delayed because of potential for hydrogen on those regions. However, safety will stay be an issue. District heating will see a lot more resistance.
- NIMBY: should not be a big problem, especially when we use the existing pipelines. However, if we decide to produce all hydrogen domestically than we can get that NIMBY problem, because we need a lot more solar power and wind power.
- Awareness: I believe the majority of Dutch citizens is educated, but not enough. I score this a 6
- Transparency: I score this with a 7
- Communication of benefits and costs: This is given a 4
- Local: I score this with a 7
- Trust: Trust in decision-makers really depends on the type of project. Regarding hydrogen, people are familiar with gasses so I give this an 8.

5. Environment

- Every form of energy production has negative consequences on the environment. However, if we compare the current way of energy extraction with hydrogen production this is an incredible improvement. Material problem, because we need rare earth material for the electrolysers. This can also become a problem with the hydrogen market and trade, more dependence on Africa for these materials. I believe green hydrogen has an incredible low impact on the environment.

6. Policy

- According to the gas law, hydrogen is not a gas. So, there is a lot of work to do on the legislation side. At the moment, distribution is not a regulated task. I believe that this should be regulated for the DSO's. Enexis advocates this idea as well. Especially, when we will use hydrogen for the built environment and use the existing gas infrastructure.
- The government will be the kickstart of proper legislation, transport and distribution will be a regulated task. Production will be more commercialized

H.4 EBN

1. **Costs**

- Energy price is not determined by hydrogen in the future. The energy price is constituted by all the efforts we make to decarbonize our energy needs. An example, all the efforts we make to reduce demand and increase efficiency in the built environment are costly. So what are the costs in whole chain? The question is, to what extent is hydrogen beneficial? Because, hydrogen is very expensive at the moment. These costs will be translated to some extent in the energy price, so I believe that this price will grow.
- Stability/flexibility: I think that hydrogen will have an enormous role for price stability and flexibility, especially, with storage. We, as Dutch inhabitants, are used to having and using a gas like substance. That makes hydrogen so promising. There are also parties that believe that this extra conversion of energy is very inefficient. Why not use this energy immediately. But this means that we should cope with this intermittency in the industry for example. This would be extremely complex compared to utilizing hydrogen. On system level, I believe that creating hydrogen from this electricity because the costs of finding flexibility elsewhere outweigh the efficiency losses of hydrogen production from renewable energy production.

2. **Technology and efficiency**

- If we use hydrogen for the built environment, efficiency problems will be less compared to other solutions.
- In the Netherlands, we need the big projects at the start. In this way, the flywheel will start spinning. But we will see more and more small scale projects, to prevent congestion and find solutions for region specific problems. But this will not solve the national demand, especially, considering that this would imply grid expansions and this is something that TenneT wanted to prevent.
- Energy demand: hydrogen will not really reduce energy demand I believe. This is in close relation with the energy price. When there is low priced hydrogen, people will simply insulate their homes less. But what we will see that maybe this price will be reflected by the sustainability.
- With a backbone, you will be amazed how much hydrogen will applied in the built environment, I believe even more than current scenario's depict.
- Transition towards hydrogen: I believe that we will see a gradual shift towards green hydrogen. Blue hydrogen is simply a lot cheaper in the beginning, but as soon as the technology improves and economies of scale improve, green hydrogen can be a good possibility.

3. **Location**

- Dependencies: yes we will see other dependencies, because we probably cannot produce the cheapest hydrogen in the Netherlands. Hydrogen can become a commodity that will create new markets and new dependencies with other countries. However, this will improve as we will be less bound a few countries because more countries can produce hydrogen in comparison with the amount of gas exporting countries.
- Geographic location: we a have a lot of sea and shore, so I expect that we can produce a great deal of hydrogen ourselves. But we think that wind on sea will be more expensive than solar and for that reason I believe that we import a lot of hydrogen as well.

4. **Culture**

- I believe that producing hydrogen on large scall will cause less problems compared to more decentral systems. Transport will not cause a lot of trouble.

- Hydrogen is explosive, but natural gas is the same. We are used to natural gas, so hydrogen should not be an incredible problem. An issue is, that citizens see that hydrogen is coming to the built environment and for that reason do not want to consider heating networks or electric heating. This is very dangerous of course, since these options are very promising for the majority of the built environment. Especially, on energetic level.
- Awareness: I give a 4
- Transparency: I give a 7
- Communication of benefits and costs: I give this a 6
- Local: Hydrogen will be received with ease, I give this an 8
- Trust: Trust can improve, especially considering contracts with other countries and dependencies. I give this a 7.

5. Environment

- I believe that water use will not be a real problem. The vast amounts of water needed, for example in Groningen, will be extracted from the sea and from the clean water supply.

6. Policy

- The government should be completely involved with rolling out this hydrogen infrastructure and market. The government should indicate who has what role, this is very important. Private parties do not have the power to really get things done in the beginning.
- Some big projects, like highway 27 are very costly, but are necessary. This is something that must be financed by the government without even knowing their return on investment.

H.5 ENEXIS

1. Costs

- Energy prices: solar and wind energy prices will become lower. When we would electrify the system completely, we would have two problems. First, it is not always available when we need it and second, the costs for grid expansions and preventing congestion are enormous. Therefore, the route of gasses is inevitable. However, these technologies are expensive as well. But in the energy system we will see many cost inducing components.
- LCOE: if we look at how the prices are set now for renewable energy, this depends a lot on the supply and demand at that particular moment in time. Conversion to hydrogen can help flatten out these prices.

2. Technology and efficiency

- Production: first we will see blue hydrogen, but we want to move to green hydrogen as soon as possible.
- Distribution: there is need to adapt the existing gas infrastructure. But the costs are limited and we can profit a lot from our existing infrastructure. There is a lot of knowledge and experience with gasses, this helps us a lot.
- Efficiency: if you look at the whole hydrogen chain, there will be more losses in the energy system when we introduce hydrogen. However, when we look at hydrogen from renewables this is still favourable, even though on energetic level it will be less efficient. For the built environment would be more efficient compared to P2G to electricity.

- Demand: this really depends on the whole supply chain. This is a matter of costs. As soon as renewable hydrogen will be cheap, maybe we will that it is less economic to insulate houses and increase demand. So that is an interesting question. But there is need to find balance in this, insulating and utilizing hydrogen.

3. Location

- Dependencies: really depends on how the supply chain will look like, where will the hydrogen come from? I think that in the Netherlands hydrogen production might be a little expensive, but that there will be a world market for hydrogen. The more countries are connected to this market, the less dependent we will be on specific countries. When there is a world market for hydrogen, dependencies will decrease
- Geography: The Netherlands has a favourable position for hydrogen production and our gas infrastructure makes it even more interesting to look at hydrogen possibilities.
- Central/decentral: regarding hydrogen, we need to go towards large scale production and distribution. Especially, considering moving towards green hydrogen, to make it more economic. However, there is great supporting base for more electricity production in the North Sea, or with large solar parks instead of the decentral production. Naturally, regarding hydrogen production, you will move towards central production at places where this electricity is generated. Otherwise, you need to expand the grid and have to deal with transportation losses. That would make no sense at all.
- As a DSO, location for generation and production of hydrogen for example, you want make the right decision on where to do that. The conversion process should take place there where the costs for conversion are the lowest.

4. Culture

- NIMBY: hydrogen is perceived as dangerous and explosive. So, there is some improvement to be made here. We need to start with pilots in the built environment, to see how this unfolds. Also, to understand how society would react on hydrogen implementation.
- The hydrogen production facilities will have enough support
- Society on hydrogen for built environment: people are not too familiar with hydrogen. We probably will see first that the industry hydrogen demand will be satisfied and afterwards the built environment. In the future, we will not see hydrogen in new buildings.
- Awareness: I score this a 6
- Transparency: I give this an 8
- Communication of benefits and costs: There is a lot room for improvement for this, I give this a 5
- Local: Hydrogen is easily accepted and integrated from a societal point of view. I give this an 8
- Trust: I give a 7

5. Environment

- I believe that the amount of water we need for electrolysis will not be in competition with the water we consume.

6. Policy

- Current legislation: not sufficient at the moment. Hydrogen is seen as feedstock now, not as a gas for the built environment. There is need for an updated legislation. We see that the pilots we want to do cannot be done under Enexis, but we need to do this through a public organization. At the moment, hydrogen is not seen as a gas, so we need to see hydrogen as the energy carrier it is.

- There should be a separate law for hydrogen and prevent to ‘update’ the existing gas law.
- We need the government to direct the hydrogen transition. Especially on the location dimension and to decide who is responsible for certain parts in the supply chain.
- Due to COVID we see that government sometimes need to take a more prominent role in certain initiatives. I believe that this should also be the case for hydrogen. If this happens we can also expect hydrogen to be available in the built environment once the existing grid is utilized for hydrogen transport.
- There is some failure in coordination between the different energy carriers. This means that when we want to introduce hydrogen on large scale we need more coordination between energy carriers.

H.6 TNO

1. **Costs**

- Energy price: electricity prices regarding renewables will become lower. At the same time, projections show an increase in electricity price. How does this happen? We will still need gases, like hydrogen, these solutions can become the price setting technologies. To analyse the future we can also use the past, and extrapolate this to the future.
- LCOE: What will be the price of hydrogen? This really depends on the LCOE of electricity from renewables. This can also create new dependencies! Hydrogen LCOE will depend on how hydrogen is used for creating energy.
- Intermittency: hydrogen will not be the number one solution for short term intermittency issues. On the long-term you want to introduce hydrogen for this because the amount of renewables grows.
- Flexibility: I don’t believe that hydrogen will have an enormous role in flexibility, but more on seasonal storage.
- If you need hydrogen to balance the electricity system, than we will see an increase of electricity price at those moments.

2. **Technology and efficiency**
3. **Location**

- If we look at electricity demand and hydrogen demand in applications like the built environment, if we add those demand numbers than we would have the potential in the Netherlands to satisfy those demands. At the moment we would also try to satisfy demand on transport fuels and for the industry we need to import.
- Output economics: We have Rotterdam, so there is a lot of potential to export these kind of products. Will this increase economic output, that is the question, I believe so yes. The difference with oil and hydrogen is their energy density and transportation commodity. This implies that the output will change over the years when their output products will change from fossil to renewables.
- Energy intensity: hydrogen has a lot of dimensions. When we use hydrogen in industry, there are some differences with energy intensity compared to utilizing fossil fuels for feedstock. In this sense, nature has already done part of the job in these energy intense conversion processes. As soon as we introduce hydrogen and other renewable carriers, there is an extra part of conversion that would increase energy intensity. However, when hydrogen is introduced in the built environment you might encounter positive effects on energy intensity because there are less conversion needs.

4. **Culture**

- Awareness: I believe that Dutch citizen are aware of climate change, as long as it won't cost more. I score this with a 6
- Transparency: Communication could be better to the society. The subject of hydrogen is new, and even in expert groups there not enough unambiguity yet to communicate this to the Dutch society. But for sustainability we see a lot of public participation, especially in the built environment. But there is an understanding that before we can make homes more sustainable there are insulating needs etc. If we look at hydrogen, people are positive about using it but when asked what their opinion is on a wind mill next to their home, they are hesitant. People are not informed enough about the complete hydrogen chain and what that means to them. I score this with a 7
- Communication: I give this a score of 7
- Local: If it would be as simple to just substitute natural gas for hydrogen, people are positive. However, it is not that simple. But people are really willing to use hydrogen for heating appliances. I give this an 7
- Trust: I give this an 8.

5. **Environment**

- I don't think hydrogen will be in competition with our water demands. A few other aspects, like resources to make the appliances and technologies can become a challenge. Rare earth material are critical the upcoming years. This can also create dependencies!
- When you burn hydrogen you will see chemical reactions that create NO_x. But this is already regulated with natural gas. So this should pose any new problems or challenges.

6. **Policy**

- The current regulations are based on natural gas and oil. So, there is need to change this to more renewable. Especially, hydrogen must be recognized as a fuel not only as a feedstock.
- In all cost structures hydrogen does not fit yet. So maybe more subsidies are necessary.
- Relation government: the government should create the boundaries and the rules of the game. Private parties should play the game within these boundaries. The government should also be responsible to get everyone in the same direction.
- Infrastructure: at this moment we have hydrogen infrastructure, but this is private. The question is for whom the hydrogen will be. If this will be for society and the built environment than the government is responsible as well.

SIDE NOTES:

If you want to use all the potential for renewable electricity, there is need to differentiate from only electric solutions due to grid issues and high costs. Hydrogen is simply the second carrier in line. This implies that hydrogen can inhibit more renewable energy extraction from the total national potential.

H.7 NVDE – Marc Londo

1. **Costs**

- There are a lot of studies that sustainability efforts for the Netherlands are not that much more expensive than doing nothing. From all option, hydrogen will not be cheapest but inseparable in the Dutch energy transition
- Stability: there are many solutions to cope with intermittency, and hydrogen is one of these possibilities.

2. **Technology and efficiency**

- If we look towards 2050, there is some discussion. Of course we want to move to green hydrogen, but blue hydrogen is really necessary towards green hydrogen.
- Energy intensity: if the end use appliances remain the same, integrating hydrogen will be more energy intensive because that requires more conversion steps.
- Energy use/ km2: final energy use should go down, if we want to meet our climate goals. Hydrogen can help with respect to final energy use. Especially when you integrate hydrogen for the built environment or industrial processes

3. **Location**

- Dependencies: depends on how we produce hydrogen. Green hydrogen would have the least dependencies. Import dependency we will always have. How these dependencies will shift depends

4. **Culture**

- Awareness: there is still a lot of energy illiteracy. But this is a global problem so I score this a 5
- Transparency: The Netherlands has a good participation culture, compared to other countries I would give it a 7
- Communication of benefits and costs: no we are not transparent enough. 4
- Local: most districts even wait for hydrogen, people are hesitant on other solutions for the built environment. Hence I score this with an 8.
- Trust: Your reputation among your stakeholders really shapes the trust people have when we consider sustainability projects and hydrogen in the built environment. So, one example on small scale, if you as a housing corporation have a bad reputation regarding solving other issues, then resistance towards these kind of projects is large. For this reason I would score this with a 6.

5. **Environment**

- If it possible to build electrolysers in the dessert, than it should also be possible to get this working in the Netherlands.
- For rare earth materials this could get critical once the world produces hydrogen on large scales.

6. **Policy**

- A lot of work needs to be done regarding regulation of hydrogen. Especially, looking at the current gas legislation. Maybe it would be even better to create a complete new hydrogen instead of adapting the current natural gas laws.
- The government got used to leaving the market as it is and inhibit competition. But this old way might not help us through the energy transition. We might want to reconsider the relation between the market and the government to kickstart certain events.
- The government should reconsider their role within the transition. They should get more involved with the market.
- I believe that the government should interfere especially in the beginning of the transition to inhibit competitive markets but also lead the way in which direction the Netherlands is going is now important when dealing with hydrogen and the many different system roles it has.