Renewable hydrogen in Dutch built environment and the impact on energy security

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October 2020

Abstract: The field of energy security is dominantly filled with concepts and frameworks built on the characteristics of traditional fossil fuel energy systems. Increasing penetration of renewable energy sources in the energy system brings about novel implications and challenges in the field of energy security. Hydrogen is an increasingly popular option to decarbonize hard to abate sectors or parts of the heating system. The Netherlands has a favourable position and infrastructure for large scale hydrogen roll-out. The objective of this research is to explore how hydrogen utilized in the Dutch built environment affects energy security performance. Moreover, what geotechnical characteristics of hydrogen are responsible for a change in energy security performance. A framework for analysis is constructed and applied to the current Dutch energy system as a reference case and two future energy scenarios. The data requirements are retrieved through desk research and interviews with stakeholders and experts in the field. The research concludes that hydrogen positively affects future energy security performance. The geotechnical characteristics of hydrogen can explain the differences between the results of the scenario. These emphasize a shift in energy dependencies, global hydrogen markets, increased diversity due to the broader system role of hydrogen and efficiency reductions. Future research should focus on different hydrogen production pathways and reassessing the concept of energy security given renewable energy carriers and geopolitics.

Keywords: energy security, scenarios, hydrogen, built environment, geotechnical characteristics

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1. Introduction

To decarbonize energy demand and reduce carbon emissions, countries are required to 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. However, growth in renewable electricity production can be distinguished.

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 the use of natural gas 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 create opportunities for renewable hydrogen 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 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 electrolysis of water 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 has effects on 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 the geographic dependency of RES 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 rise new dependences in comparison with 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 has to consider the accumulation of rare metals that are essential in decarbonization technologies that can become critical drivers for technology prices and diffusion (Hache, 2018; Scholten, 2018). This confirms different implications for energy security with different renewable energy sources or energy carriers, such as hydrogen.

Overall, renewable energy carriers for heating is 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. Also, social acceptance for hydrogen implementation is expected to be higher as it is less of a radical adjustment compared to 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 compared to 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 and research question

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 to increase flexibility, gaseous energy carriers ought to be integrated next to electricity. In the built environment, hydrogen can provide substantial greenhouse gas reductions and provide heating demand for homes that are hard to electrify. 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. From this problem statement, the main research question is formulated in the following way:

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

2. Literature review

The origin of the literature review 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. However, 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 to remove irrelevant aspects of the analysis. Considering the specific scope for this research, this allows removing certain aspects of the framework to comply with the time constraints this research is bound to. The second paper that is evaluated into more detail is the paper from Scholten (2018). This paper allows for creating 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 a change in the energy security of a country is caused by specific differences between current and future energy system.

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. 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 economic and social developments of a nation. Short-term energy security deals with the ability of an energy system to handle sudden changes in supply/demand balance appropriately (IEA, 2019). This is also highlighted in the article of 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 the security of supply. Another interesting comment in the work from Radovanović et al. (2017) is that creating a unique methodology applicable for all countries is not possible. 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 rather than a strategy or policy. They also argued that measuring or improving energy security requires a clear understanding of the perception of energy security. Moreover, the definition is highly contextual and of polysemic nature, which is, in line with the opinions of other authors (Azzuni & Breyer, 2018; Radovanović et al., 2017; Winzer, 2012). There is much misconception between energy security and security of supply. Where some authors argue that it is paramount importance to include the complete energy supply chain in energy security analyses, others focus more on energy security of supply. The main reason for this misconception is that authors do not fully identify the actual implication of energy supply. 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 that is using the concept and to what end. It can be concluded that energy security is dynamic, polysemic and multi-dimensional by nature. Literature reveals energy security as highly context dependent and bound to change or evolve over time. Therefore, in this research, energy security is defined as "a sustainable uninterrupted availability of energy sources, free from any threats in all its relevant dimensions".

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 in those who aggregate a specific number of indicators and those who do not (Valdés, 2018). Azzuni & Breyer (2018) argue that every dimension that has a relationship with energy security should be addressed based on the argument of Yergin (2006). 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).

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. The selection criteria are usually not well explained and transparent (Månsson et al., 2014).

2.2 Energy security in a renewable world

Until now, 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). The majority of literature, as delineated in the section before, examines the effects of energy security indicators on renewable energy deployment using import dependence on other countries as the significant proxy for renewable energy implications for energy security (Valdés Lucas et al., 2016). Renewable energies have a complicated relationship with energy security. The 2030 Climate and energy framework sets three main targets: research for energy efficiency and mastering the energy demand, diversifying the provision of energy and reaching independence by increasing the share of 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 bring 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 end 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 is required to 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 the geopolitics of renewables 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.

2.3 The geotechnical characteristics of renewable energy systems

The previous section discussed how RES substantially could improve energy security in the long run. However, there is 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). 9Moreover, most authors do not separate between 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 is applicable to all countries. Each country has different resources, wealth, economic growth, climate conditions and the likes (Radovanović et al., 2017).

Integration of hydrogen in energy systems

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. On an economic scale, this would hamper investments needs for a new hydrogen infrastructure in the Netherlands considering their enormous gas infrastructure. Countries with significant natural gas infrastructure have the means to leverage these pipelines for hydrogen, as well as acting as large 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 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 to 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).

The following section will discuss the methods applied in the research, consecutive steps and the rationale.

3. Methods

The objective of this research is to understand how hydrogen utilization in the Dutch built environment potentially affects energy security performance of a future energy system, given its geotechnical characteristics. To understand potential changes in a future system, a reference case is necessary to compare the future situation with the present. The present energy security performance can be measured with one of the available energy security indices, presented in the previous section. Desk research and interview with an expert in the field facilitated the knowledge and arguments for choosing and shaping an energy security index that is applicable on the Dutch energy system, more specifically, on the heating sector. The index proposed in Azzuni & Breyer (2018) is used for this analysis. However, the framework must be simplified and adjusted to conform to time constraints and the Dutch contextualities. The original framework considered 15 dimensions. The adapted version has eight dimensions: availability, diversity, cost, technology and efficiency, location, environment, culture and policy. The final index is presented in Appendix A. Its original maker validated this adjusted framework.

Since there is no real data for future energy systems, there is a need to find realistic and relevant energy system scenarios that integrate hydrogen for heating. First, an understanding of the current natural gas supply chains is necessary. After this, possible hydrogen supply chains are outlined discussing the differences based on the geotechnical characteristics of renewable energy systems (Scholten, 2018). Possible hydrogen supply chains are explored, examining scenario literature that is available (Detz et al., 2019; Gasunie & TenneT, 2019; Gigler & Weeda, 2018). Based on the geotechnical characteristics of hydrogen in potential future energy systems, its lesser geographic boundaries call examining the implications of national and international orientated future Dutch energy systems. Therefore, two scenarios from CE Delft are deemed most suitable for applying the framework on (Afman & Rooijers, 2017).

There is no real data available for the indicators to measure the energy security performance of the future hydrogen scenarios in literal terms. However, with the help of experts in the field, each indicator can be compared with the reference case to see how hydrogen implementation affects each indicator. The logic developed in the theoretical background offers the tools to reflect on the differences between the national and international orientated scenario based on the geotechnical characteristics of hydrogen. The primary data sources to create the reference case was desk research. For the future system assessment,

the scenarios are a result of supply chain analysis through desk research and expert interviews helping to find the effects on each indicator in the framework.

Desk research

Data requirements for the reference energy security case are collected through extensive desk research. The qualitative data requirements were gathered from the Central Bureau for Statistics (CBS), the culture dimension from expert interviews and data on other countries from the supplementary excel file provided by Azzuni & Breyer (2018). The scenarios are a result of supply chain analysis from the desk research. The logic that empowers a narrative to reflect on the results and the implications of the geotechnical characteristics of hydrogen on energy security are also explored with this method.

Expert interviews

Several interviews with experts in the field have been conducted. An overview of the list of interviewees is presented in table 1. The first interview was with the creator of the original framework. While the index choice was based on comprehensiveness, the original index was too extensive to fit in the limited time frame of this research. Following dr. Azzuni, several dimensions were removed, which were considered less relevant in the scope of this research. Next, removing obsolete indicators and adding new elements in the culture dimension was validated with dr. Azzuni in future correspondence. This led to the final framework for analysis, as presented in Appendix A.

The next seven interviews were conducted with stakeholders and experts in the field of hydrogen in the Netherlands. The pool of interviewees can be divided into TSO/DSO, Research institutes, and energy advisory organizations. While the availability and diversity dimension are satisfied with data from the scenarios, the effect of hydrogen in the built environment on the other dimensions (and their indicators) is evaluated through interviewing these key stakeholders. The

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

interviews were informal and semi-structured. This format allows an open discussion on the different themes without forcing answers into a direction. All the interviews were recorded and summarized for each dimension. It was tried to ask each question in the same tone to prevent biases or misdirection. The summaries of the interviews provided the narrative to score the indicators in comparison with the score of the reference case. Arguments in the result section are based on distinguishing the variables in the different interviews to formulate critical takeaways.

4. Results

The first part of the analysis entailed analysing the energy security performance of the current Dutch energy system to serve as a reference case. Each indicator was scored in comparison with other countries in the world. The highest value was awarded 100% and the lowest at 0%. Then, the effects of hydrogen utilization in the built environment could be explored through expert interviews and comparing the key insights with the current system. From here, it could be argued whether hydrogen positively or negatively contributes to the individual indicators. The main aim is to understand what geotechnical characteristics of hydrogen account for a particular change in the energy security performance of a future Dutch energy system.

4.1 Dutch energy security

Each dimension was scored by summing the individual scores of each parameter and dividing by the total amount of parameters. Each parameter score is compared with other countries in the world with data retrieved from the supplementary datasheet from dr. Azzuni. The total aggregated score for the Netherlands is 57.145%. The scores for each dimension are crucial in determining how hydrogen can potentially improve or decrease the score based on its geotechnical implications. 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.

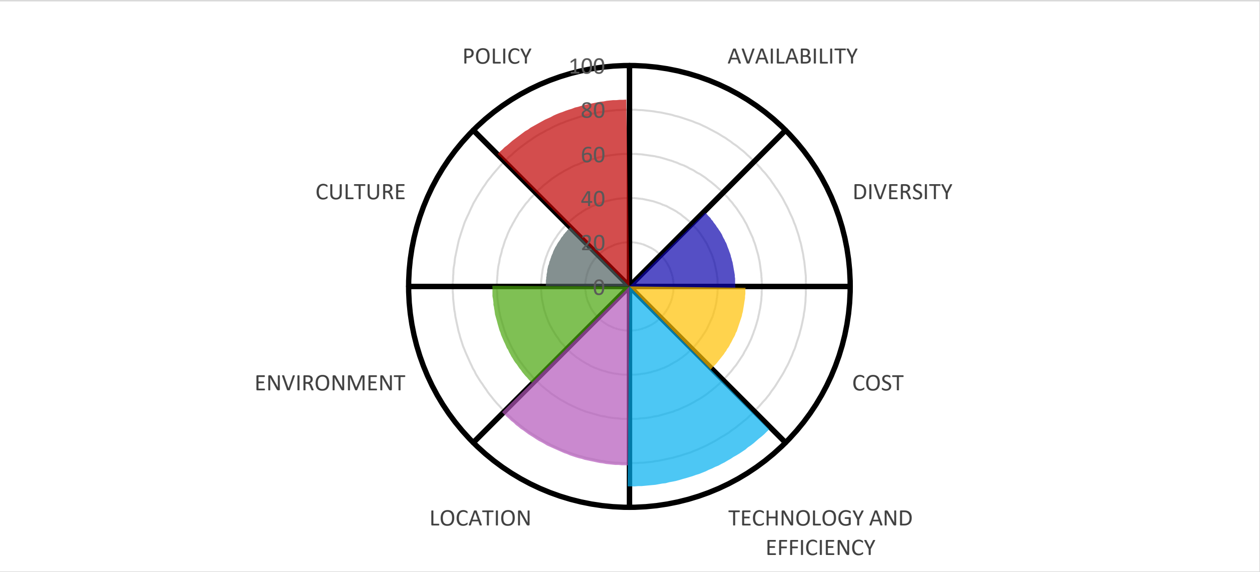

Figure 1: Dutch energy security score for each dimension.

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

Table 2: Hydrogen effects on energy security performance, national scenario.

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

Table 3: Hydrogen effects on energy security performance, international scenario.

4.2 Scenario results

Given the boundaries of both scenarios, each dimension of the energy security framework was examined by knowledge retrieved from the expert interviews data from the scenarios themselves. This led to insight on how each scenario has different effects on the individual indicators concerning utilizing hydrogen in the built environment. The effect of hydrogen utilization in the built environment is scored positive, negative or neutral for every parameter in each dimension. The colour code represents the total effect of hydrogen for that dimension, where red is negative, green positive and yellow is a neutral effect. The results are presented in tables 2 and 3 above.

There are six noticeable differences between the scenarios:

- 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.

4.3 The geotechnical characteristics of hydrogen in light of energy security

There are several differences between the scenarios, as indicated in table 2 and 3. These similarities and differences can be explained in light of the geotechnical characteristics of hydrogen from a sources, generation and distribution perspective.

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 of the existing gas grid, creating coherent (seasonal) storage, and prevent curtailment of renewable energy sources. However, seasonal hydrogen storage affects energy system efficiency negatively. Therefore, the difference between the national and international scenario is distinguished. Also, from a sources perspective, the actual and realistic potential of renewables increases with the integration of hydrogen in the energy system. However, as indicated in the international scenario, a decrease in availability performance is perceived when relying on large scale energy imports.

Domestic production of hydrogen can inhibit environmental concerns as well, dealing with water stress when large scale hydrogen production facilities are constructed to meet hydrogen demand in the built environment.

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 for both scenarios. Hydrogen is less geographically bound than natural gas, increasing the probability for competitive markets with a more diverse pool of potential suppliers. This can potentially lead to a decrease in the performance of location in the international scenario when there is the abundant availability of cheap hydrogen elsewhere. This is examined more closely in the following paragraph dealing with generation.

From a generation point of view, the scope of this research 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 potential feasibility for the Netherlands 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 performance of 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, construction of domestic facilities is not encouraged. Still, moving away from energy dependencies is advantageous, and should be accounted at the end of the investment balance.

Moreover, hydrogen as an energy carrier is produced most economically in large central facilities. These hydrogen production facilities are well connectable to large off-shore wind parks, decreasing societal resistance for more renewable energy sources, 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 the scope of this research, only green hydrogen is integrated into the energy system supply the built environment. Electrolysis of freshwater is most mature, but still, an expensive solution for hydrogen production. These costs are translated into the 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 point of view. Hydrogen allows for transport over greater distances, just like natural gas, in comparison with 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 distribution in the Netherlands, the existing natural gas grid provides coherent incentive to find some novel gaseous energy carrier. Moreover, 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.

5. Discussion

This section reflects on how the results of this study contribute to field and reflect on the quality of the research.

5.1 Learnings for the field of study

In more general terms, the results of this research demand for 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. 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. From the 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 wholly appreciated by this type of approach. Moreover, energy security is hugely country-specific. There is no one generic framework that fits all; this seems even more true in 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.

5.2 Reflection on research approach and methods

This section reflects on the research approach and the methods. It is crucial to critically assess the research approach and methods to understand how limitations in the research framework potentially affected the results.

The energy security framework

From the original framework, eight dimensions were picked with adjustments in the indicators according to 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 grasp the importance of the culture dimension completely. With this final set of parameters and indicators, the first analysis of the current Dutch energy system 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 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 system. 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. A recommendation for this dimension would be to altogether remove it from studies that compare current energy systems with future scenarios. Studies focussing solely on the implications of future renewable energy systems can incorporate a more extensive policy dimension.

Case selection and biases

The literature and cases used in section 8.2 to reflect on the results are partly applied in 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 in creating the final energy security framework. The purpose of including this literature was to structure the place of hydrogen in a possible future energy system and what implications different hydrogen supply chains have in comparison with the traditional Dutch energy system. Next, arguments in other studies are not necessarily focussed on the Netherlands, but more frequently made on a global level. 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 context of the Netherlands. Nevertheless, the researcher acknowledges this potential bias problem and that argues that the reflection of the results in light of theory is carried out carefully and holistic at all times.

6. Conclusion

The objective of this project is 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, to explore 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 on how hydrogen could potentially affect the eight dimensions in the framework. 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, potentially induces increased energy prices. Due to characteristics of hydrogen gas, 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 especially favourable in the built environment from a societal point of view. For both scenarios, hydrogen in the built environment improves the culture dimensions significantly.

Future research should focus on updating the energy security definition in a more renewable context. The current energy security frameworks are built on the premises and characteristics of fossil fuel-based energy systems. Moreover, the results demonstrated different implications of hydrogen as a novel energy carrier in the system in comparison with traditional fuels. These geotechnical characteristics should be expanded into market dynamics of renewable energy systems and interstate energy relations concerning hydrogen. Finally, the implications of different hydrogen production pathways and their effects on energy security should be explored.

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Appendix

Appendix A: the final energy security framework

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	Total renewable surface water	m^3/(year*km^2)	Dividing by the maximum
	Lo_4	Industrial added values	USD/km^2	Dividing by the second highest
Environment	E_1	Ecological footprint (number of earth required)	Number	Max-min
	E_2	CO_2 intensity	Kg per kWh energy use	Dividing by the maximum in the world
	E_3	Total GHG emissions excluding land-use change and forestry per GDP	$MtCO_2$/USD	Dividing by the highest in the world
	E_4	Water stress	Percentage	Normalized

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 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: Percentage 2: Percentage 3: Percentage 4: Percentage 5: Percentage	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