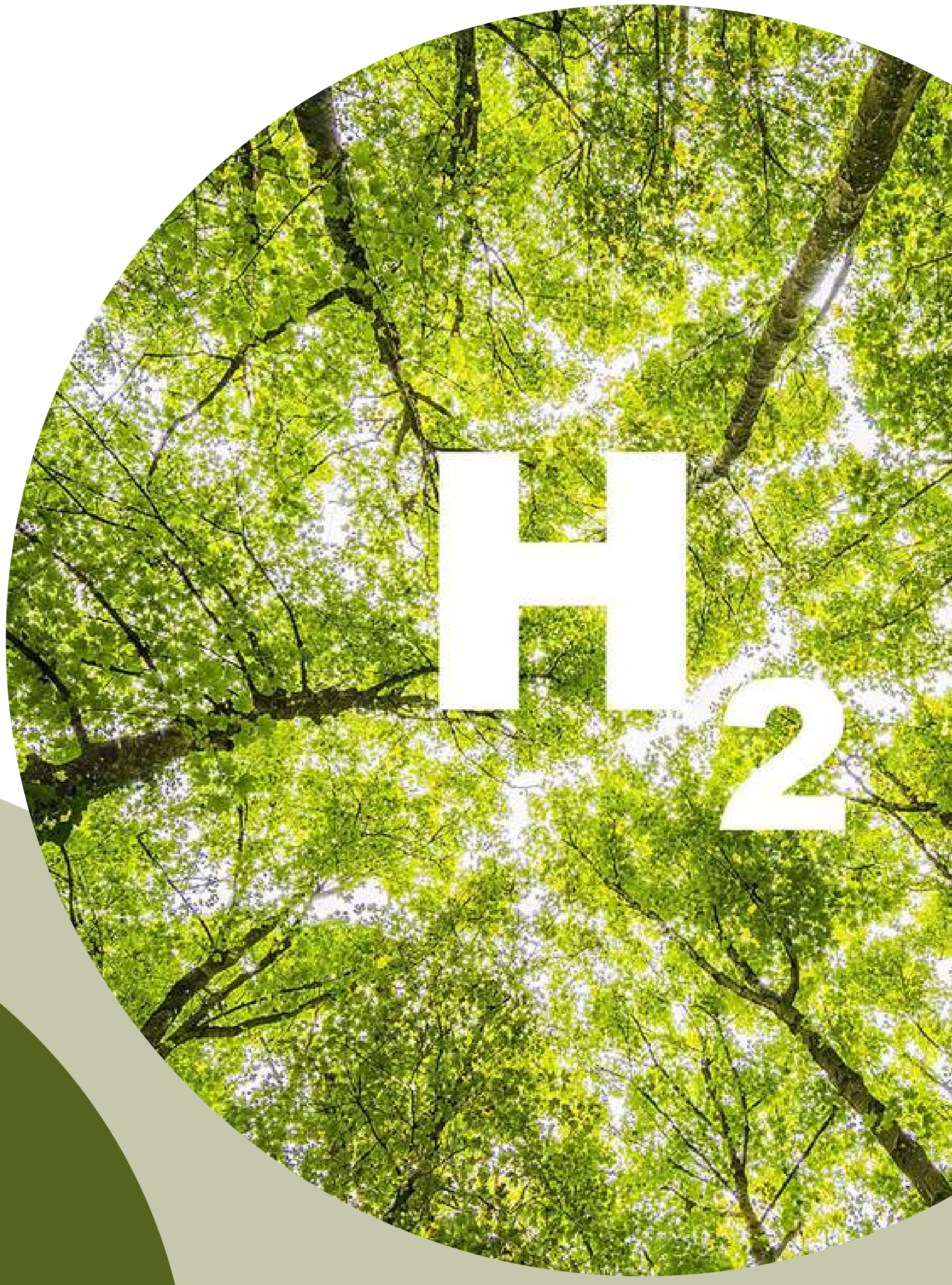
European Hydrogen Valleys

An energy security perspective

July 2023



Anniek Reitsma - S5348811

Supervisor: *dr. Agha Bayramov*

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ABSTRACT

Worldwide, hydrogen is considered the answer to climate and energy security challenges. The European Union (EU) regards hydrogen as an effective solution for boosting European energy security. In light of the Russian-Ukraine conflict, the EU has set a target of producing 10 million tonnes of domestic hydrogen to safeguard the European energy supply. In reaching EU objectives Hydrogen Valleys play a vital role. Hydrogen Valleys refer to a locally integrated (green) hydrogen ecosystem encompassing the entire value chain, from generation and storage to utilisation. EU energy policy assigns an important role to Hydrogen Valleys. However, research has not yet been conducted on the contribution of Hydrogen Valleys to European energy security. Therefore, this thesis examines how Hydrogen Valleys contribute to EU energy security and what the challenges are. To answer the research question, a thorough analysis was conducted, utilising both content analysis and case study analysis. The study investigated two examples of Hydrogen Valleys, the HEAVENN project in the Northern Netherlands and the HyBalance project in Denmark. The two case studies were analysed using a modified version of the Four A's Energy Security Framework, called the Renewable Energy-Focused Four As Framework. The Renewable Energy-Focused Four A's Framework comprises four dimensions (affordability, availability, accessibility and acceptability) and 12 indicators. The research showed that the Danish and Dutch Hydrogen Valleys have the potential to contribute to European energy security, but the current contribution is limited. The green hydrogen generated in the Dutch and Danish Hydrogen Valley faces challenges when it comes to competing with low-cost energy sources and the reliance on raw materials exploiting countries. Furthermore, unclear policies and the environmental impact on mining countries add to the Hydrogen Valleys' contribution obstacles. The potential of Hydrogen Valleys for energy security is evident in their contribution to Co2 reduction in the respective country and the commitment of the Danish and Dutch governments and the European Commission to hydrogen, reflected in the development of a wide range of policy options. Further development of unambiguous policies is crucial to address the challenges and fully realize the potential of Hydrogen Valleys in contributing to European energy security.

DECLARATION BY THE CANDIDATE

I hereby declare that this thesis, *"European Hydrogen Valleys: an energy security perspective",* is my own work and by my own effort and that it has not been accepted anywhere else for the award of any other degree or diploma. Where sources of information have been used, they have been acknowledged.

Name: Anniek Reitsma

Date: 08 – 07 – 2023

Signature:

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List of abbreviations

Abbreviation	Definition
ALK	Alkaline
APERC	Asian Pacific Energy Research Centre
DEI+	Energy Innovation Demonstration Scheme
EHB	European Hydrogen Backbone
EU	European Union
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GO	Guarantee of Origin
IEA	International Energy Agency
IPCEI	Important Projects of Common European Interest
IRENA	International Renewable Energy Agency
LCOH	Levelized Costs of Hydrogen
PEM	Polymer Electrolyte Membrane
PGM	Platinum Group Metal
RED II	Renewable Energy Directives II
REE	Rare Earth Elements
RES	Renewable Energy Sources
SDE++	Sustainable Energy Production and Climate Transition

INTRODUCTION

In the world we live in today, we face air pollution, climate change, and energy security issues in combination with an increase in energy demand. The generation of hydrogen energy is considered the way to address these challenges (Kovac et al., 2021; Dincer & Aydin, 2023; Van Renssen, 2020; Olabi et al., 2023).

Hydrogen is an energy carrier that can be produced from a variety of energy sources (Noussan et al., 2020; Ajanovic, 2020; Parra et al., 2019). Fossil fuels can be utilised to generate hydrogen (grey hydrogen) with the possibility of capturing the released emissions (blue hydrogen). However, Renewable Energy Sources (RES) such as wind and solar power can also be used for generating hydrogen, also known as green hydrogen. Hydrogen can thus be generated with lower emissions or even without, which benefits climate, environment and air quality (IEA, 2019).

Green hydrogen can especially be used in sectors where it is difficult to reduce emissions using electricity applications. These sectors range from shipping, aviation, steel production, and long-distance road transportation to building heating in densely populated areas (IEA, 2019; Hermesmann & Müller, 2022; Osman, 2021). Globally, hydrogen strategies are, therefore, formulated in which green hydrogen is described as the energy source that can replace fossil fuel use in transport, heavy industries and heating (Moradi & Groth, 2019). Frontrunners in writing these hydrogen plans are the governments of Japan, China, South-Korea, the United Sates and countries on the European continent but also organisation such as the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and the European Union (IEA, 2022a; IRENA, 2022; World Economic Forum, 2022).

The European Union (EU) is one of the organisations primarily focusing on hydrogen. Formulating hydrogen energy strategies stems not only from the negotiated targets in the Fit-For-55 package, aiming for a 55% reduction in carbon dioxide emissions by 2030, or the Green Deal Industrial Plan to create a more conducive environment for the expansion of net-zero technologies (European Council, 2023; European Commission, 2023a), but is also a response to the war in Ukraine that causes high oil and natural gas prices, showing EU's energy dependence on Russia. The production of hydrogen is considered one of the main ways to increase European energy security in the 27 EU countries (including Switzerland and Norway) and the United Kingdom (Prisecaru, 2022; EHB, 2022; Surwillo, 2020).

The EU defines energy security as *''a stable and abundant supply of energy''* (Russels, 2022, p.1). The reduction of energy supply is recognised as one of the primary threats to European security due to the high dependence of the EU on non-European countries for energy. In 2020 57,7% of the total energy used in the EU was imported from non-European states (Russels, 2020; Surwillo, 2020; Eurostat, 2022). In the REPowerEU plan, the EU, therefore, expresses its goal of producing 10 million tonnes of European hydrogen by 2030 to secure the European energy supply through domestic production of energy. In addition to in-region hydrogen production, the EU promotes the European Hydrogen Backbone (EHB). The EHB network, consisting of hydrogen pipelines, connects European hydrogen hubs creating a 53,000 km European hydrogen infrastructure by 2040. This EHB allows a flow from areas of high hydrogen supply to areas of hydrogen demand, creating more energy resilience within Europe and leading to a rise in energy security (Weichenhain, 2022; EHB, 2022).

One of the key steps in achieving the goals of EU hydrogen infrastructure and domestic production is doubling the total number of Hydrogen Valleys (European Commission, 2022, p.8; Clean Hydrogen Joint Undertaking, 2022; Concas et al., 2022).

Hydrogen Valleys consist of a defined area (city, industrial area, region) with a locally integrated hydrogen ecosystem for regional economic growth and climate change mitigation, often in connection with national and international regions via roads and waterways (Weichenhain et al., 2022). Within the hydrogen ecosystem, Hydrogen Valleys span a significant portion of the value chain, from hydrogen generation, transportation and storage to its final application in diverse industries (see Figure 1). End-users include the industry business, heating facilities and fuel stations (Weichenhain et al., 2022). To generate green hydrogen, RES such as wind and solar power are used for the electrolysis process (Petrolesse, 2022). On the European continent, 24 initiatives to develop Hydrogen Valleys have been launched in recent years (Weichenhain et al., 2022).

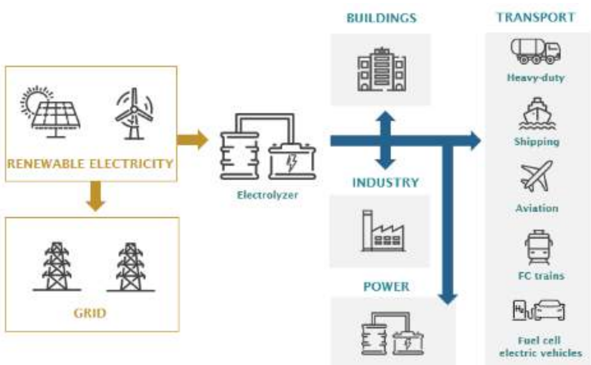

Figure 1: Schematic representation of a Hydrogen Valley (Sandarova, 2022)

EU policy thus shows that since the start of the Fit-For-55 programme in 2021 (followed by the REPower EU plan in 2022 and the Green Deal Industrial Plan in 2023), Hydrogen Valleys have been given an important role in the European Commission’s energy strategy (European Council, 2023; European Commission, 2023a). However, where research has been conducted on the role of hydrogen in energy security (Shah, 2020; Pareek et al., 2020; IEA, 2022; Ren et al., 2014; He et al., 2020), this has not yet been done for Hydrogen Valleys specifically despite its key role in European hydrogen policy. Therefore, this thesis examines Hydrogen Valleys’ contribution to European Energy security.

The study is conducted based on the combination of the qualitative research methods content analysis and case study analysis with a focus on two case studies, HEAVENN (H2 Energy Applications in Valley Environments for Northern Netherlands) and HyBalance. HEAVENN and HyBalance are two large-scale Hydrogen Valley projects in the Northern Netherlands and Denmark. HEAVENN was the first Hydrogen Valley project to receive funding from the EU-supported Clean Hydrogen Partnership, and the HyBalance project was one of the first projects to be fully implemented in 2020 (European Commission & CORDIS, 2022; HEAVENN, n.d.; HyBalance, n.d.).

The two projects differ in degree of development, production methods, storage facilities and end-users[1]. Due to the differences between the HEAVENN and HyBalance projects, an analysis of both covers Hydrogen Valley development variations and provides a clear impression of the EU as a whole (Weichenhain, 2022). This is why two Hydrogen Valleys were selected instead of one.

To explore the contribution of Hydrogen Valleys to energy security, an updated version of the Four A's Energy Security Framework of the Asian Pacific Research Centre (APERC, 2007) and Kruyt et al. (2009) has been applied. The four A's Framework consists of four pillars: affordability, accessibility, availability and acceptability. The framework of APERC (2007) and Kruyt et al. (2009) is considered the most suitable theory because it incorporates economic, geological, social, geopolitical and environmental aspects, allowing a complete picture to be described. The corresponding criteria of the four dimensions, however, have been adapted, extended and replaced in this thesis based on energy security research on RES (including hydrogen) and traditional energy security literature to be suitable for analysing renewable energy sources such as green hydrogen. From the amalgamation of literature, the Renewable Energy-Focused Four A's framework has been developed.

By analysing the two Hydrogen Valleys using the Renewable Energy-Focused Four A's framework, the thesis aims to identify the contribution and challenges of Hydrogen Valleys to European energy security. This has resulted in formulating the following research question: **how do Hydrogen Valleys contribute to European energy security, and what are the challenges? A case study on the HEAVENN and HyBalance projects.**

To answer the main question, the following sub-questions are formulated:

1. How can energy security be defined?
2. How can the HEAVENN and HyBalance projects be described?
3. How do HEAVENN and HyBalance contribute to energy security looking from an affordability perspective?
4. How do HEAVENN and HyBalance contribute to energy security looking from an availability perspective?
5. How do HEAVENN and HyBalance contribute to energy security looking from an accessibility perspective?

[1] The HyBalance project was finalised in 2020 and is therefore labelled fully implemented. The HEAVENN project, on the other hand, is in the implementation phase. It is expected that the project will be completed in 2025. The HyBalance project, furthermore, uses a PEM electrolyser to produce green hydrogen, stores the produced hydrogen in cylinders and transports it via pipelines and trucks to the end-users, the mobility and industry sector. On the contrary, in the Dutch Hydrogen Valley, PEM and Alkaline electrolysers are used for production, storage takes place in caverns, and hydrogen is transported to the end – users (mobility, industry and energy sector) via pipelines, trucks and ships (Weichenhain, 2022).

6. How do HEAVENN and HyBalance contribute to energy security looking from a social acceptability perspective?

The paper is outlined as follows to answer the sub-questions and main research question. After the introduction, the energy security theory and the Renewable Energy-Focused Four A's Framework are explained, followed by the methods and methodology of the thesis. Thereafter, chapter 1 describes the HEAVENN and HyBalance case studies before the analysis of the case studies starts in Chapters 2 (affordability), Chapter 3 (availability), Chapter 4 (accessibility) & Chapter 5 (acceptability). The study's results, recommendations and implications are addressed in the discussion, followed by an answer to the main question in the conclusion.

ENERGY SECURITY THEORY

This chapter outlines the theoretical framework of the thesis. The theoretical framework applied in this thesis is the Renewable Energy-Focused Four A's Framework, an energy security model. To properly describe the theory, first, the concept of security is introduced, after which energy security and the pillars and indicators of the Renewable Energy-Focused Four A's Framework are explained. Additionally, sections describing the criticism of energy security theory and the application of the theory have been added.

Security & Securitisation

The notion of security is an important theme and always has been. The literal meaning of security, as defined by Meerts (2018, p.1), is *''a state of being free from danger or threat''*. Within this, the meaning of security consists of an objective and subjective part. From an objective point of view, security refers to security dangers (i.e., threats, risks, vulnerabilities) in a specific security dimension (political, social, economic, military or environmental) involving a referent object (human, national level or international level). However, a security danger essentially does not exist (Balzacq, 2010). The intersubjective understanding of a security issue arises from a social construction through discursive interaction between people within a community. The social construction of the security issue leads the community to understand the security problem as an existential threat to the referent object's life that requires and justifies extraordinary measures to address these threats (Brauch, 2008; Heinrich & Szulecki, 2018). This is also known as the securitisation process (Balzacq, 2010; Heinrich & Szulecki, 2018).

In the social construction of security, context and value systems play an essential role. They influence the perception of a securitising actor on an issue and affect the audience's opinion about recommended extraordinary measures. A change in the context and value systems after 1990 has resulted in the securitisation of new issues and thereby led to the widening of the security meaning (Brauch, 2011; Heinrich & Szulecki, 2018).

The classical focus of security in the discourse of International Relations is on the nation-state and its protection of territory and sovereignty through military means (Rothschild, 1995; Baldwin, 1997). However, several factors have caused the securitisation of other matters after the 1990s, widening the security concept. The ending of the Cold War, first of all, played a major role in the reconceptualization of security due to the increase in military security, allowing space for economic and social security concerns (Ballin et al., 2019; Rothschild, 1995). Additionally, globalization has shifted the focus to the international level as a referent object instead of the nation-state. This not only created a higher responsibility for international organisations to enhance security but also generated new threats due to the increased interdependence of countries (Brauch, 2011).

The 2008 financial crisis, moreover, showed the impact of financial fragility on security, creating more awareness of the importance of the economic dimension of security (Brauch, 2011; Ballin et al., 2019). Lastly, in response to the Brundtland report (1987) on environmental matters, more and more attention emerged on the effects of ecological and environmental concerns (e.g., climate change, resource depletion, energy source reduction) on security. The four events have changed the context, resulting in the construction of new referent objects (e.g., the international level, the environment), new dimensions (e.g., economic, social, political and environmental), and associated new threats (e.g., climate change, financial crisis) that require measures (Rothschild, 1995; Brauch, 2011; Brauch, 2008, Ballin et al., 2019). The concept of security and the type of security concerns has thus expanded as compared to pre-1990.

One of the security issues that already received more attention due to circumstances in the 20th century but has been enhanced by the widening of the security concept is energy security (Brauch, 2011; Kruyt et al., 2009). Also, within energy security, security is not an objective part of the energy system but rather a socially constructed phenomenon (Heinrich & Szulecki, 2018; Wilson, 2019).

Energy Security

The concept of energy security has been an important issue since Winston Churchill's (head of the navy) decision during World War I to replace the British Navy's fuel with oil instead of coal, making England dependent on other countries for energy supply. From this day one, energy became part of national security due to the construction of oil as an essential energy system resulting in the securitisation of energy (Yergin, 2006; Heinrich & Szulecki, 2018). The importance of energy security in the 20th century was, however, not only recognised in both World Wars but also due to the indispensable role of oil in the industrialisation of the economy worldwide (Cherp & Jewell, 2011). The theory of energy security started with a sole focus on avoiding oil disruptions to secure the energy supply (Mouraviev & Koulouri, 2018).

The limited focus on oil stemmed from the high demand for this energy type as a feedstock for many industries, such as manufacturing, transport, and electricity (Mouraviev & Koulouri, 2018). Fluctuating oil prices and the push for a reduction of carbon dioxide emissions in the late 20th century and early 21st century created a renewed interest in energy security. The rising oil prices and the subsequent economic crisis, in combination with the pressure to reduce emissions, made it evident that other factors, like climate, political circumstances and affordability of energy, are equally important for energy security than just securing the energy supply (Kruyt et al., 2009; Cherp & Jewell, 2014). In the years that followed, more indicators were added to the definition of energy security, including environmental, political and economic elements (Kruyt et al., 2009; Mouraviev & Koulouri, 2018). The energy security definition expanded.

The shift towards a broader definition of energy security is evident in the various conceptualisations developed at the beginning of this century (Šumskis & Giedraitis, 2015; Mouraviev & Koulouri, 2018). Bollen (2007) and Jansen (2004), for example, came up with ways to measure energy security which resulted in the establishment of the Shannon index and the *''willingness-to-pay"* (Bollen, 2007, p.27) principle. The Four A's Framework of the Asia Pacific Research Centre (APERC) was the first energy security framework to move away from the classical dimensions of affordability and availability by merging them with the concepts of acceptability and accessibility. Prominent articles that followed, such as the articles of Kruyt et al. (2009) and Sovacool & Mukherjee (2011), took the Four A's Framework as the foundation for their theories (Cherp & Jewell, 2014).

The Asia Pacific Energy Research Centre (APERC) defines energy security as *''the ability of an economy to guarantee the availability of energy resource supply in a sustainable and timely manner with the energy price being at a level that will not adversely affect the economic performance of the economy"* (APERC, 2007, p.6). To evaluate the energy security of a country, region or the world, four pillars are identified by Kruyt et al. (2009) and the APERC (2007): Affordability, Accessibility, Availability and Acceptability. Within Kruyt et al.'s (2009) Four A's Framework, each pillar has corresponding indicators (see Figure 2). The framework thus combines various elements and indicators from a wide range of energy security studies providing a comprehensive theoretical background. Furthermore, the theory addresses a broad variety of dimensions (economic, geological, political & environmental), compared to other energy security theories that focus only on one dimension, such as Bollen's (2007) theory, which only addresses economic content. These characteristics make the Four A's Framework a useful theory for energy security research (Kruyt et al., 2009).

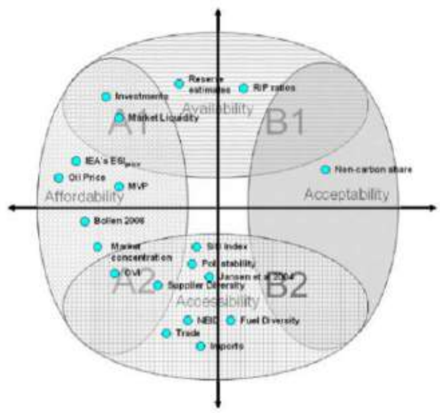

Figure 2: Energy Security Framework (Kruyt et al., 2009, p.2171)

Therefore, in this paper, the theoretical focus will be on the Four A's Framework defined by the Asia Pacific Energy Research Centre (2007) and Kruyt et al. (2009). However, the clearness of the framework has been criticised and using the indicators in place has its limitations due to the changing nature of energy systems (Cherp & Jewell, 2014; Narula & Reddy, 2016). Therefore, this thesis extends the theoretical model of Kruyt et al.'s and the APERC by including the critical points through the addition, replacement and modification of indicators.

Criticism

Besides the theoretical advantages of the Four A's Framework, it has also been criticised. According to Cherp and Jewell (2014), it is unclear in the Four A's Framework who needs to be protected (referent object) from what risks or threats and in what kind of energy system. As a result, the framework is not well embedded in the objective meaning of security as described above in this chapter, which deteriorates energy analysis. While the security danger, the referent object and the security dimension were evident in the traditional oil industry this is no longer true for new energy industries (such as renewable energies). In the new energy systems, there is a rising influence of non-state actors, non-oil countries, social values and the role of resilience. Different values, entities and threats/risks are thus attached to these new energy systems (Cherp & Jewell, 2014). Therefore, these three points should be better defined in the framework to properly access contemporary energy security, according to Cherp & Jewell (2014).

Moreover, there is an increasing focus within energy security on climate change, energy emissions and environmental issues. According to Narula & Reddy (2016), these emerging notions are not yet reflected extensive enough in the Four A's Framework, which leads to a reduction in the relevance of existing indicators.

To cope with the criticism, indicators are replaced, added and adapted in this research to make the Four A's Framework appropriate for analysing one specific energy system, that of renewable energies. This differentiation from other energy systems ensures a better assessment of the system by the Four A's Framework, according to Cherp & Jewell (2014). In addition, the development of the Four A's Framework specifically for renewable energies provides the opportunity to analyse the environmental, economic, political and physical vulnerabilities, threats and risks of this energy system specifically. The inclusion and reflection of risks, threats and vulnerabilities are accomplished by adding and adjusting indicators within the framework. The scope of the study focused on the European Union, moreover, provides a clear answer to the question of energy security for whom? Lastly, three new indicators have been added under the acceptability dimension: water, emissions and natural resource depletion. The addition of these indicators improves the inclusion of the environmental dimension (Narula & Reddy, 2016). By doing so, the thesis incorporates the criticisms that have been made of Four A's energy security framework.

The expansion of the theory is accomplished by combining energy security research on Renewable Energy Sources, hydrogen (Al Mufachi & Shah, 2022; Steinberger-Wilckens et al., 2017; Stuchtey & Below, 2015; Rybak et al., 2022; Narula & Reddy, 2016; Azzuni & Breyer, 2018; Hydrogen Council, 2020; Ren et al., 2014; Ali et al., 2021; Ren & Sovacool, 2014) and traditional energy security literature (Kruyt et al., 2009; APERC, 2007; Bollen, 2007; Jansen, 2004). The renewed Renewable Energy-Focused Four A's energy security framework is outlined below.

The Renewable Energy-Focused Four A's Framework

The Renewable Energy-Focused Four A's framework applies the four dimensions described by the APERC (2007) and Kruyt et al. (2009): Affordability, Availability, Accessibility and Acceptability. These four pillars address the economic, geological, political and environmental factors that are of importance to energy security (Kruyt et al., 2009). However, as Narula & Reddy (2016) point out in their article, the right indicators are needed for accurate energy security analysis and are a prerequisite for formulating the correct energy policy. Therefore, to make the corresponding indicators of these pillars appropriate for temporary renewable energy system analysis, the indicators of the four dimensions have been adjusted. Adapting the indicators using academic energy security and renewable energy literature has provided the following indicators (See figure 3): Affordability: *Price, Willingness to pay, Cost competitiveness;* Availability: *Renewable energy sources, Raw materials, Infrastructure*; Accessibility: *Policy, Knowledge & Information, Versatility of energy source*; Acceptability: *Resource depletion, Water, Emissions.* I am aware that more indicators could be added to the framework. However, these 12 indicators are selected since extensive literature research shows that these indicators are mentioned most often in combination with the energy security of renewable energy systems and, additionally, provide an answer to the theory criticism. Furthermore, the decision was made to include three indicators for each dimension to ensure the framework is balanced, with each dimension being equally important (Ren & Sovacool, 2014). The 12 indicators are outlined in the next paragraphs.

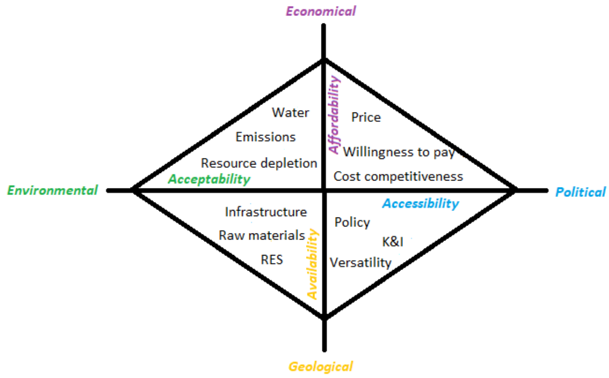

Figure 3: Renewable Energy-Focused Four A's Framework

Affordability

The affordability pillar addresses economic factors related to energy security. It considers the costs involved in the production, transport and utilisation of the energy source (Kruyt et al., 2009; APERC, 2007; Al Mufachi & Shah, 2022). The indicators price, willingness to pay and cost competitiveness are mentioned in the literature as relevant for analysing the affordability of the renewable energy system.

First of all, the **price** plays a role in the affordability of an energy source. The price affects the supply and demand of an energy type (Kruyt et al., 2009). The lower the production and consumption costs, the higher the affordability to produce and consume the energy (Bodgadov et al., 2021). Therefore, the contribution of price as an indicator of affordability can be examined by means of two indicators (1) the price of an energy source on the market, (2) and specific for hydrogen, the production cost for 1 kg of hydrogen, also known as the Levelized Costs of Hydrogen (LCOH), which includes the costs of water, energy input, stack replacement, investment and operation (Al Mufachi & Shah, 2022;

Steinberger-Wilckens et al., 2017; Perey, 2022). For renewable energy sources, such as green hydrogen, to play a part in a country's energy security, consumption and production prices must be attractive to households and industries (Ren & Sovacool, 2014; Al Mufachi & Shah, 2022).

An energy price is regarded as attractive when it is cheaper than other energy sources. This brings us to the second indicator, **cost-competitiveness**. An energy source is considered cost-competitive when it is less expensive than comparable sources (e.g., oil, gas). Higher cost-competitiveness will contribute to affordability and, thereby, to energy security (Hydrogen Council, 2020).

To make renewables cost-competitive and reduce the price, governmental investments are necessary (Al Mufachi & Shah, 2020). The **willingness to pay** indicators is of interest here. This indicator is intended to measure the proportion of GDP that a country is ready to pay to decrease energy security risks (Bollen, 2007). Increased government support can thus enhance energy affordability (Al Mufachi & Shah, 2020).

These three points together form the analysis of the affordability dimension of the Renewable Energy-Focused Four A's Framework. The literature review above shows an evident interdependence between the three indicators. All three have an influence on each other. It is important to keep this interdependence in mind.

Availability

The physical/geological availability of an energy source is discussed in the second dimension of the energy security framework (Kruyt et al., 2009). The availability of production feedstocks and infrastructures are important factors within this pillar (Steinberger-Wilckens et al., 2017; Al Mufachi & Shah, 2022). The corresponding indicators are, therefore, Renewable Energy Sources, Raw Materials and infrastructure.

Firstly, the availability of **Renewable Energy Sources (RES)** is an important indicator for the Renewable-Energy Focused Four A's Framework. Renewable energy is defined as energy produced from natural resources that are replenished at a faster rate than it is consumed (United Nations, n.d.). The availability of RES (e.g., solar and wind) is important not only on its own but also as a feedstock for hydrogen generation. An analysis of the availability of RES includes examining the climate conditions prevailing in the area to feed these Renewable Energy Sources (Ren et al., 2014; Al Mufachi & Shah, 2022). High number of RES and good climate conditions (e.g., lots of wind and sun) increase energy availability (Al Mufachi & Shah, 2022).

For the production of Renewable Energy Sources, **raw materials** are needed. These materials are used in photovoltaics (solar PV), hydrogen electrolysers and wind turbine technologies. A disruption of raw material supply could impact energy security (Stuchtey & Below, 2015; Rybak et al., 2022).

The disturbance may occur due to price fluctuation or (political) instability in the supplier country, causing failure to deliver raw materials on time. Therefore, it is important to assess (1) the availability of the materials in the producing country itself (2) and the dependence on other countries to receive the raw materials. Energy security is higher when materials are available domestically, and reliance on foreign countries is low (Rybak et al., 2022).

Finally, **infrastructure** is an important indicator of the availability of an energy source. Infrastructure refers to the pipeline network and storage facilities. The pipelines ensure the transportation of the generated energy to the end users, where surplus energy can be stored in the storage facilities and consumed at a later time. Both ensure a stable flow of energy and prevent energy supply interruption, resulting in an increase in energy availability (Al Mufachi & Shah, 2022; Narula & Reddy, 2016).

Together, the three indicators form the analysis model for energy availability. Again, there is interdependence between the indicators, which is essential to consider when analysing a case study.

Accessibility

The third element of the energy security framework, accessibility, focuses on the extent to which the energy source is accessible to consumers. (Geo)Political factors play a major role in this, mainly focused on government policy, stability and support (Kruyt et al., 2009; Ren et al., 2014). Indicators identified by academia as affecting energy accessibility are policy, knowledge & information and the versatility of an energy source.

The **policy** of a country or region has a great impact on energy accessibility due to their ability to obstruct or support energy developments. A change in political stability or energy regulation can alter access to an energy source. For example, a higher carbon tax could increase demand for renewable energies. A policy indicator that is, therefore, important for the energy security of a particular region or country is the decisions made regarding energy subsidies, taxes and strategies/goals (Azzuni & Breyer, 2018; Kruyt et al., 2009; Ren & Sovacool, 2014). Clear policies strengthen people's access to energy (Azzuni & Breyer, 2018).

Part of public policy is providing access to **knowledge & information (K&I).** K&I is a crucial aspect of energy security. It is important that people have knowledge of how an energy system works and how it could be improved. To achieve this, there should be (1) research and development (R&D) on the topic and (2) facilities (e.g., training courses) to create a qualified workforce. Energy system research and access to a qualified workforce ensure that an energy system runs safely and without interruptions (Azzuni & Breyer, 2018).

Finally, the demand side is key for energy access. Demand for an energy resource ensures that energy is produced continuingly (Azzuni & Breyer, 2018). The high **versatility of an energy source** can thus contribute to energy security. In which versatility considers the access to the volume of energy end-users (industry, households etc.) (Al Mufachi & Shah, 2022).

Policy, knowledge & information and the versatility of an energy source together form the basis for analysing the accessibility dimension of the Renewable Energy-Focused Four A's Framework.

Acceptability

The final pillar of the framework is acceptability. Acceptability focuses on environmental sustainability, which means that energy sources should be developed and used sustainably to make sure that future generations can also still enjoy nature and meet their needs. Besides environmental aspects, this element also entails the social acceptance of the energy source resulting in the following indicators: natural resource depletion, water and emissions (Kruyt et al., 2009; APERC, 2007).

The **depletion of natural resources**, first of all, influences energy security because it can disrupt the energy supply (Jansen, 2004). A depletion of a resource means that the source is being consumed faster than it can regenerate itself. Natural resource depletion can consist of mining activities, deforestation, and resource contamination (Azzuni & Breyer, 2018; Ali et al., 2021).

As discussed under the availability dimension, raw materials are needed for the production of renewable energies (Stuchtey & Below, 2015; Rybak et al., 2022). The exploitation and depletion of these raw materials cause many environmental impacts, reducing the acceptance of the energy source (Azzuni & Breyer, 2018).

Besides the using raw materials, a large amount of **water** is needed to generate renewable energy, especially hydrogen. The amount of water used to generate energy is an important factor in the acceptability of the energy source, according to Narula & Reddy (2016). The less water used, the higher the acknowledgement of the energy source and thus an increase in energy security (Narula & Reddy, 2016; Azzuni & Breyer, 2018).

The last indicator of the acceptability dimension is **emissions**. The amount of Co2 emitted during the energy production process is an often-mentioned indicator for the acceptability of an energy source. The lower the emissions, the more the energy source is accepted (Narula & Reddy, 2016).

Considering the perspectives of the three indicators listed above, the social acceptance of a renewable energy system can be examined.

Relationships between dimensions

Besides the fact that the four A's dimensions separately impact energy security, they also affect each other. The availability of RES, for example, reduces emissions and thereby increases acceptability. In addition, the affordability dimension affects the accessibility of an energy source due to the increase in demand (versatility) as a response to price reductions (Ren & Sovacool, 2014). These interrelationships are reflected in the analysis chapters of this thesis and are essential to keep in mind.

Application of theory

The thesis applies the Renewable Energy-Focused Four A's Framework to the HEAVENN and HyBalance Hydrogen Valley projects. However, due to time reasons and to provide a comprehensive description, it is decided to apply 4 of the 12 indicators to the projects. One indicator is selected from each of the dimensions to maintain a balanced framework in which each dimension is equally important.

The indicator cost-competitiveness, first of all, will be used from the availability dimension. Besides the fact that this indicator immediately includes the price of the energy source (LCOH), the cost competitiveness of hydrogen is seen as the way to deploy the real value of hydrogen for energy security. An increase in cost-competitiveness creates more investments and non-economic support for hydrogen generation and Hydrogen Valley development making it an important indicator (Hydrogen Council, 2020).

Additionally, the raw material indicator is utilised to examine the availability of hydrogen. This indicator is selected since raw materials are needed to manufacture electrolysers, develop wind turbines and solar farms and install hydrogen infrastructure in the Hydrogen Valley projects (Stuchtey & Below, 2015; Rybak et al., 2022). Therefore, this indicator has to be analysed before the infrastructure and RES indicator can be researched. Without raw materials no Hydrogen Valleys.

The third indicator applied is policy. According to Azzuni & Breyer (2018), policy is one of the indicators that affects energy security the most. Policy decisions do not only have a positive or negative effect on the accessibility dimension but also on choices made in the other three dimensions. Therefore, the decision was made in this thesis to discuss policy rather than the indicators of Knowledge & Information and the versatility of an energy source.

The final indicator selected is the depletion of natural resources. This indicator expands on the availability indicator (raw materials) while incorporating the environmental dimension (Azzuni & Breyer, 2018). As hydrogen is an emerging energy market (IEA, 2019) and thus much remains to be built, it is seen as important to address the depletion of natural resources already at this stage.

Selecting these four indicators does not imply that the other indicators are considered less important. However, for this thesis, these four are regarded most relevant.

By applying the indicators, it is examined in what way the two Hydrogen Valley projects correspond with the four elements of the energy security theory: affordability *(cost competitiveness),* availability *(raw materials)*, accessibility *(policy),* and acceptability *(natural resource depletion).* From this analysis, a conclusion is drawn on the contribution of Hydrogen Valleys to EU energy security and the challenges attached to it.

Conclusion

To conclude, security is a broad concept. From the 1990s onwards, global events caused the securitisation of new issues rather than just security aimed at military purposes. One of these emerging security concerns is energy security. Although the concept originated during the First World War, it gained renewed interest after 1990. This led to several energy security frameworks, including the one of APERC and Kruyt et al., known as the Four A's Framework. This broad framework focusing on the four dimensions of Affordability, Availability, Accessibility and Acceptability is used in this study. To do this properly, new indicators have been added so that the existing criticism about the outdated indicators and unclear description of the theory is considered. Moreover, by modifying indicators, the framework is now applicable to renewable energy systems such as hydrogen.

The four pillars of the Renewable Energy-Focused Four A's Framework, including one corresponding indicator of each dimension, are discussed separately for the HEAVENN and HyBalance projects.

Methodology

This chapter outlines the qualitative methodology of the thesis, content analysis in combination with a case study analysis. The reasons for selecting these methods and associated deficiencies are also discussed and evaluated.

Content analysis

This thesis aimed to examine the value of Hydrogen Valleys for European energy security. While research has been conducted on the contribution of hydrogen to energy security, this still needs to be explicitly done for Hydrogen Valleys. Therefore, the study contributes to the research gap in the literature on the contribution of Hydrogen Valleys to energy security. To gain a better understanding of this topic, qualitative research is conducted. Methods used within this research methodology are content analysis and case study analysis. The decision was made to apply these methods and no other qualitative methods, such as interviews, because of the limited time available for this research and the existence of numerous articles consistent with this topic. The content used for the analysis comprises secondary and primary sources in both English and Dutch.

The databases of Google Scholar and the RUG library, SmartCat, were consulted to collect the academic literature (secondary sources). Articles were selected based on the presence of the search term in the title, abstract or keywords. Furthermore, attention was paid to the articles' publication date in the sampling process to minimise the literature list and increase the research's relevance to current challenges. Only literature written between 2016 and 2023 was included in the analysis and introduction sections. It was chosen to run the time frame from 2016 because pre-research showed that the most relevant articles regarding hydrogen and Hydrogen Valleys were written from this point onwards. Additionally, setting a time frame increases the reliability of the study because it specifies the method allowing other researchers to follow the same procedure and find the same results in the process (Halperin & Heath, 2020).

The research terms that led to the finding of the appropriate analysis and introduction literature are: *''Green hydrogen energy'', ''Fossil fuel prices'', ''Hydrogen policy Europe'', ''Hydrogen strategy Europe'', ''Hydrogen Valleys'', ''Hydrogen Valley Denmark'', ''Denmark & Hydrogen'', ''Hydrogen policy Denmark'', ''Hydrogen Valley Netherlands'', ''Hydrogen & Netherlands'', ''Dutch Hydrogen Strategy'', ''HyBalance project'', ''LCOH'', ''Environmental effects & Raw materials'', ''Wind farms Denmark'', ''Wind energy & Raw materials'', ''Hydrogen & Iridium''*, *''Raw materials & Green hydrogen''* and *''Emissions & Hydrogen''.*

In addition to academic sources for the introduction and analysis section, policy papers and newspapers were consulted. The used policy papers and newspapers were collected via Google Search. The time frame of 2016 – 2023 was also maintained for the policy letters and news articles to ensure the inclusion of up-to-date information in the thesis.

Contrary to the introduction and analysis literature, no time frame was applied to the theoretical articles. Security in general and energy security specifically are topics which have been appearing in academic literature for many years and are subject to change, as highlighted in the theoretical chapter. Choosing one specific time frame could have resulted in important terms and concepts not being included. The following keywords were applied for the search of appropriate articles for the theoretical framework: *''Characteristics of security'', ''Security'', ''Securitisation'', ''Concept of Security'', ''Energy security'', ''Indicators & energy security'', ''Energy security & Renewable energies'', ''Energy security & Hydrogen'', ''Affordability & energy security'', ''Critique on Energy security''* and *''Resource depletion & energy security''.*

Besides secondary sources, primary sources were also used to support the study. These comprise reports and websites. These sources were found using Google Search. Using both primary and secondary sources, the aim was to write an inclusive study reflecting all perspectives on the subject. The combination of various sources facilitates the data triangulation of the research leading to an increase in the validity of the study, according to Wilson (2014).

Case study analysis

As mentioned, the research was conducted using two case studies, the HEAVENN and HyBalance Hydrogen Valley projects. As explained in the introduction, these two Hydrogen Valleys were chosen because they both receive funding from the EU, are at different stages of project implementation, and contain differing production methods, storage facilities and end-users[2] (Weichenhain, 2022). Together the two projects encompass the most possible production, storage and consumption opportunities. Because of this, an analysis of these two case studies together gave a comprehensive picture of Hydrogen Valleys in Europe in general. This increases the likelihood that the results obtained from the analysis of these case studies are consistent with any analysis of other EU-funded Hydrogen Valleys in the field of energy security research, also enhancing the validity of this study (Halperin & Heath, 2020).

The shortcoming of using two case studies is that it is more challenging to generalise the results to similar projects. However, a more detailed analysis can be made for these cases than if time, words and attention had to be divided among several case studies. Furthermore, Denzin & Lincoln (2017) discussed in their book about qualitative research, that a small selection of case studies can already lead to new insights into a phenomenon, theory or concept because it helps to understand their

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[2] The HyBalance project was finalised in 2020 and is therefore labelled fully implemented. The HEAVENN project, on the other hand, is in the implementation phase. It is expected that the project will be completed in 2025. The HyBalance project, furthermore, uses a PEM electrolyser for the production of hydrogen, stores the produced hydrogen in cylinders and transports it via pipelines and trucks to the end-users, the mobility and industry sector. On the contrary, in the Dutch Hydrogen Valley, PEM and Alkaline electrolysers are used for production, storage takes place in caverns, and hydrogen is transported to the end – users (mobility, industry and energy sector) via pipelines, trucks and ships (Weichenhain, 2022).

advantages and limits, providing room for adjustments. The selection of the two case studies is, therefore, seen as legitimate.

The information retrieved through content analysis and the two case studies presented were analysed using the Renewable Energy Focused-Four A's Framework. The theory and the steps taken in applying the framework to the literature are outlined in the previous chapter. Before the analysis starts, the specifications of both case studies are described in the next section.

CHAPTER 1: HEAVENN & HYBALANCE HYDROGEN VALLEY PROJECTS

The HEAVENN and HyBalance Hydrogen Valley projects are described in this chapter, answering sub-question 2, *how can the HEAVENN and HyBalance projects be described?* As the introduction outlines, a Hydrogen Valley consists of a defined area (city, industrial area, region) with a locally integrated hydrogen ecosystem for regional economic growth and climate change mitigation. Key features of a Hydrogen Valley are a double-digit multi-million-euro investment, the demand for hydrogen from various end-users and the presence of the complete hydrogen value chain (Weichenhain et al., 2022; Petrollese et al., 2022). The descriptions of HEAVENN and HyBalance outline the characteristics of a Hydrogen Valley.

1.1 HEAVENN

The H2 Energy Applications in Valley Environment for Northern Netherlands project (HEAVENN) started in January 2020. This Hydrogen Valley connects projects spread across the hydrogen chain to develop an integrated hydrogen economy in the Northern Netherlands with a completion date of December 2025 (HEAVENN, n.d.; European Commission, 2022a). The project aims to produce 36,500 tons of hydrogen each year (Weichenhain et al., 2022) to utilise hydrogen as a storage method to manage constrained and intermittent renewable supplies in the electrical grid and as a way to decarbonize mobility, industry and the built environment (HEAVENN, n.d.; Weichenhain et al., 2022; Sahoo et al., 2022).

The project was the first Hydrogen Valley to receive European funding (EU Horizon 2020 subsidy) from the Clean Hydrogen Partnership (HEAVENN, n.d.; European Commission, 2022a). The European grand of 20 million euros covers only a small part of the 96 191 883, 93 costs calculated for the project. The remaining investments cost are covered by public and private partners[3] within the HEAVENN project. The project partners range from knowledge institutions and companies to government agencies (see footnote 3) (European Commission, 2022a).

The HEAVENN project entails the integration of existing or yet-to-be-developed hydrogen project clusters in Eemshaven, Delfzijl, Emmen, Groningen, Hoogeveen and Zuidwending.

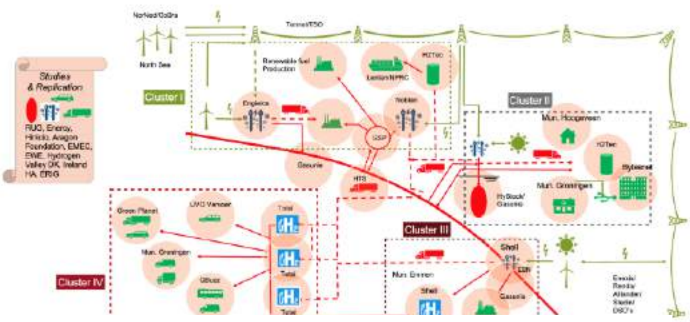

Figure 4: HEAVENN project design (HEAVENN, n.d.)

[3] **Companies:** New Energy Coalition (coordinator), Gasunie, Nobian, Engie, GETEC, Groningen Seaports, NAM, Qbuzz, EBN, Green Planet, HyEnergy, Enercy, Bytesnet, H2tec BV, UVO, NPRC, Hinicio, EMEC, Lenten Scheepsvaart BV, EWE, Hydrogen Valley, Hydrogen Ireland, TotalEnergies & Shell
Knowledge institutions: University of Groningen, Ha, ERIG
Government institutions: Gemeente (municipality) Groningen, Gemeente Hoogeveen, Gemeente Emmen (HEAVENN, n.d.).

The clusters contain separate projects coordinated and integrated within the cluster (HEAVENN, n.d.). The linked clusters I, II, III and IV (see Figure 4) span the complete hydrogen chain, including hydrogen production, storage, transportation and end-use (New Energy Coalition & Impact Hydrogen, 2022).

Within the project clusters, large-scale hydrogen production is being deployed and developed. The production of hydrogen is done with both Polymer Electrolyte Membrane (PEM) and Alkaline (ALK) electrolysers powered by solar farms and on- and offshore wind parks located in the Wadden Sea and North Sea. Additionally, surplus renewable energy from Norway, Denmark and Germany is transported to the Groningen area (Clean Hydrogen Partnership, n.d.; Pronvincie Groningen, 2020). The DJEWELS 1 (20 Megawatts (MW) ALK electrolyser) and 4 MW electrolyser on industry park Emmen are two major hydrogen production plants being developed as part of the HEAVENN project. In 2019, the first large-scale electrolyser (1 MW PEM electrolyser) for the generation of green hydrogen has already opened in Veendam (HEAVENN, n.d.; Djewels, n.d.; ITM power, 2021).

To transport the generated hydrogen through the Hydrogen Valley, new infrastructure is built, and existing gas pipelines are adapted to facilitate hydrogen transport (see red line in Figure 4). The gas pipeline infrastructure is well developed in the Northern Netherlands due to the long period of gas extraction that has taken place in this region (Thomann, 2023). In addition to pipeline infrastructure, storage facilities are established. In Northern Netherlands, there is access to salt caverns where surplus hydrogen can be stored (Provincie Groningen, 2020).

The hydrogen generated is transported to multiple project partners. The chemical industry is the largest off-taker of the hydrogen produced within the Northern Netherlands (Thomann, 2023). This so-called hard-to-abate sector is mainly located in Chemie Park Delfzijl and Industry Park Emmen. Besides the chemical industries, hydrogen is used in mobility as fuel for buses, taxis and municipal vehicles. For this purpose, four gas stations are being developed for the refuelling of both trucks and passenger cars. Furthermore, power and heating are produced by hydrogen for 100 new houses in Hoogeveen and the Bytesnet data centre in Groningen. The end-users thus consist of the industry sector, mobility sector, and power and heating of the built environment (HEAVENN, n.d.)

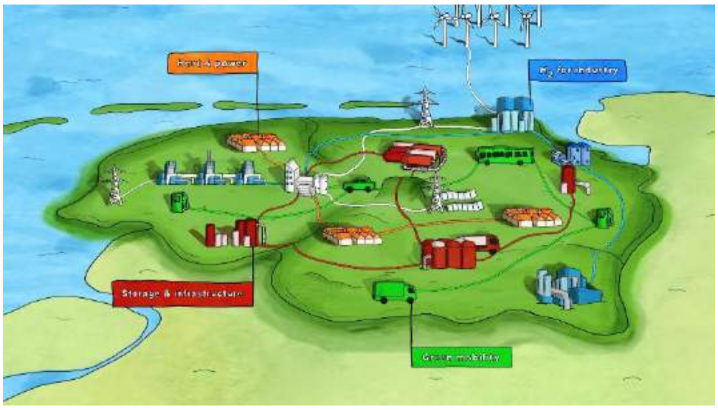

Figure 5: HEAVENN Hydrogen Valley (NOM, 2023)

Alongside the focus on the generation, transport, storage and utilisation of hydrogen, the HEAVENN project also includes research and development to promote innovation and improvement. Studies conducted as part of HEAVENN are focused on the replication of HEAVENN, the analysis of impact and business models, the certification of hydrogen, the application of heavy-duty mobility in the Northern Netherlands and the scaling up of production. The studies are done in collaboration with the University of Groningen, a partner of the HEAVENN project located in the Northern Netherlands Hydrogen Valley (HEAVENN, n.d.; Thomann, 2023).

HEAVENN is thus a large-scale Hydrogen Valley project comprising 30 project partners, two hydrogen production methods, storage and transport facilities and multiple end-users, covering the complete hydrogen value chain within the Northern Netherlands.

1.2 HyBalance

HyBalance is a Hydrogen Valley project located in Hobro, northern Denmark. The project aims to implement a hydrogen ecosystem within the Hobro area, meaning that all parts of the hydrogen value chain (production, transport, storage and end-use) are taking place in this defined region. The project started in 2016 and was fully implemented in October 2020 (Clean Hydrogen Partnership, n.d.). After the finalisation of the project, Air Liquide (the project coordinator) proceeded with the production, storage and transportation of the developed hydrogen plant (HyBalance, n.d.).

HyBalance was one of the first megawatt (MW)-scale electrolysis projects funded by the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU) (now Clean Hydrogen Partnership). The total investment of the project was 15 million, with 8 million granted by the European FCH JU and 2.6 by the Danish Energy Technology Development and Demonstration Programme (EUDP). The remaining of the funding was covered by project partners[4] (HyBalance, n.d.; European Commission, n.d.).

For the production of hydrogen, a 1.25 MW (PEM) electrolyser was developed. This PEM electrolyser is powered entirely by the surplus of wind energy generated by on and offshore wind farms in the Hobro region (HyBalance, n.d.). Using wind energy to generate hydrogen made HyBalance one of the first projects to implement the so-called Power to Hydrogen concept (Wulf, 2018). By transforming the excess wind energy into hydrogen, the project aims to *''balance the grid''* (IRENA, 2019, p.20). which means that the generation of too much energy by wind turbines and the fluctuations that can occur in electricity generation by wind can be addressed by conversion to hydrogen. The generated hydrogen is stored in a 2 MW compressed cylinder at the Hobro facility (Clean Hydrogen Partnership, n.d.; Baumgarte, 2020).

[4] **Partners:** Air liquide (coordinator), Hydrogenics, Centrica, Copenhagen Hydrogen Network (CHN), Ludwig-Bölkow-Systemtechnik, Hydrogen Valley / **Associated partners:** Energinet.dk, Sintex, Akzo Nobel (HyBalance, 2021)

To transport the hydrogen, pipelines and trucks are employed by the HyBalance project. Here the constructed pipelines are used for transport to nearby industries. The trucks, on the other hand, are utilised for transport to more distant consumers (HyBalance, n.d.; HyBalance, 2021). Between 2018 and 2020, 120 tons of hydrogen have already been transported to end-users (FuelsCellsWorks, 2020).

The end users to which the hydrogen is transported are the mobility and industry sectors (IRENA, 2019). Hydrogen refuelling stations have been built to refuel hydrogen buses, Fuel Cell Electric cars and forklift trucks. Not only in the Hobro region are vehicles running on hydrogen generated by the HyBalance plant, but also in the capital, Copenhagen, where hydrogen taxis operate (FuelsCellsWorks, 2020). Additionally, the excess hydrogen produced is utilised by industries around Hobro, primarily by Sintex, an industrial manufacturer (HyBalance, 2018a). The use of hydrogen by these consumers contributes to the aim of the project to decrease Co2 emissions from the mobility and industry sectors (HyBalance, n.d.).

Within the Hybalance project, the entire hydrogen chain (production, transport, storage and consumption) is thus represented within the defined region of Hobro (see Figure 6). Making it a Hydrogen Valley (Weichenhain et al., 2022).

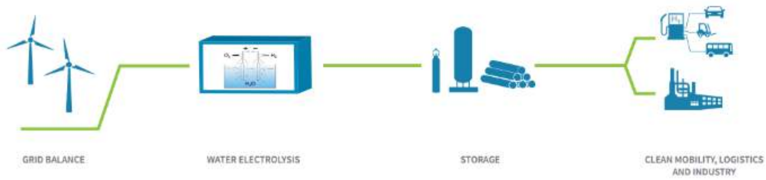

Figure 6: HyBalance Value Chain (HyBalance, 2018)

1.3 Conclusion

To conclude, the HEAVENN and HyBalance projects are developing a hydrogen ecosystem involving all parts of the value chain (generation, storage, transport and consumption). This is done within a defined region, the Northern Netherlands (HEAVENN) and Hobro (HyBalance). Where the larger-scaled HEAVENN project is scheduled for completion in 2025, the HyBalance project is already in operation since 2020.

In the following chapters, the contribution of these projects to EU energy security is examined by applying the Renewable Energy-Focused Four A’s Framework. Starting with the affordability dimension.

CHAPTER 2: AFFORDABILITY

Chapter 2 discusses the affordability dimension of the Renewable Energy-Focused Four A's Framework based on the indicator of cost-competitiveness. As described in the theoretical section, cost-competitiveness means that the cost of the energy source, in this regard green hydrogen, is cheaper than comparable sources. The higher the cost-competitiveness, the more the energy sources contribute to energy security (Hydrogen Council, 2020).

The cost of hydrogen in this section is based on the Levelized Cost of Hydrogen (LCOH) as calculated by the Fuel Cells and Hydrogen Observatory (EU body). The calculation of the LCOH includes investment costs, the lifetime of the system, electricity consumption (kWh/kg), maintenance costs and annual production of hydrogen (FCHO, 2022). The LCOH consist of the production price (€) of hydrogen per kg (Mufachi & Shah, 2022). By comparing the LCOH in the HEAVENN and HyBalance project to the production costs of comparable energy sources, sub-question three can be answered: *how do HEAVENN and HyBalance contribute to energy security looking from an affordability perspective?*

2.1 HEAVENN

The calculated Levelized Cost of Hydrogen (LCOH) is dependent on the type of energy source used for green hydrogen production (Tromp et al., 2022). In the HEAVENN project the electrolysers are fuelled by local on- and offshore wind parks and solar PV to generate green hydrogen (Clean Hydrogen Partnership, n.d). A comparison between the Dutch LCOH and fossil fuel-based electricity production shows that green hydrogen is not yet cost-competitive, affecting the contribution to energy security (Hydrogen Council, 2020).

The lowest average LCOH in the Netherlands is calculated when the electrolysis process is powered by onshore wind farms (3,28 €/kg) followed by offshore wind parks (4,95€/kg) and solar PV (7,23 €/kg) (see Table 1). The calculation shows that utilising onshore wind energy for green hydrogen generation is the most beneficial (FCHO, 2022).

	LCOH
Onshore wind	3,28 €/kg
Offshore wind	4,95 €/kg
Solar	7,23 €/kg

Table 1: Dutch average LCOH per energy source (FCHO, 2022)

There are, however, additional costs for producing green hydrogen in the Netherlands. Hydrogen generated from renewable energy sources must be certified with a Guarantee of Origin (GO) to prove it is green hydrogen. Purchasing these GOs increases the LOCH by 0,1 €/kg. For using the renewable energy of Dutch origin, as the HEAVENN project does, another 0,25 €/kg is added due to the more expensive certification scheme in the Netherlands (Hulshof et al., 2019; Mulder et al., 2019). This increases the cost of green hydrogen.

The LCOH, including the price of the GO, has to compete most with the fossil fuel natural gas, the main source of energy production in the Netherlands. In 2018, 52% of the electricity in the Netherlands was generated by gas (IEA, 2020). It has been calculated that over an eight-year period (2010 – 2018), the average price of gas in the Netherlands was 20 €/MWh with a price of 25 €/MWh if worldwide gas market conditions are tight. Currently, gas market circumstances are tight due to a shortage in supply and growing demand as a result of a disruption in the global natural gas supply chain, resulting in an average gas price of 25 €/MWh (Perey, 2022). To be cost-competitive with an average natural gas price of 25 €/MWh, the LCOH of green hydrogen produced by electrolysis should be 1,92 €/kg, according to Tromp (2022). As Table 1 shows, hydrogen costs in the Netherlands are still far above 1,92 €/kg. Green hydrogen comes closest to being cost-competitive with natural gas when onshore wind (3,28 €/kg) is employed to produce green hydrogen within the HEAVENN project (Tromp, 2022; Mulder et al., 2019).

Additionally, green hydrogen is not yet cost-competitive with natural gas fuelled grey and blue hydrogen generation (Khatiwada et al., 2022). In the Netherlands and Europe, producing hydrogen based on renewable energies (green hydrogen) is still 2-3 times more costly than the hydrogen generated by natural gas (Patonia & Poudineh, 2022). While high gas prices in Europe are causing grey and blue hydrogen production to become more expensive and create an opportunity for green hydrogen (Binni, 2021; Van der Graaf, 2022), high electricity prices of renewable energy are keeping the cost of green hydrogen high as more than 50% of the LCOH is determined by electricity prices (Perey, 2020).

The HEAVENN LCOH is thus not yet cost-competitive with the primary source of energy production in the Netherlands, natural gas, and natural gas-based hydrogen production methods. The LCOH should be below 1,92 €/kg to compete with natural gas but is currently 3,28 €/kg or higher (Tromp, 2022). The expensive renewable energy certification scheme, in combination with electricity prices, plays a significant role in the high LOHC and non-competitive of the generated green hydrogen in the Northern Netherlands Hydrogen Valley project (Mulder et al., 2019).

The non-competitive nature of green hydrogen calls for new rules to counter this issue. Therefore, innovations, carbon tax policies and subsidies by the Dutch Government and the EU are needed to incentivize investments in green hydrogen and reduce energy prices (Perey, 2022; Mulder et al., 2019; Khatiwada et al., 2022). Green hydrogen-promoting policies can lower the LCOH increasing cost-competition with natural gas and blue and green hydrogen. This is where the accessibility dimension of the energy security framework comes into play which is further explained in Chapter 4.

The low cost-competitiveness means that the HEAVENN Hydrogen Valley's contribution to energy security is currently limited when looking through the lens of the Renewable Energy-Focused Four As Framework. The low-cost competitiveness makes it unattractive for households and industries to use or invest in green hydrogen instead of fossil fuel-based energy sources, according to Al Mufachi & Shah (2022). Reduced investment in green hydrogen may lead to insufficient production (IEA, 2019), which means that a continuous supply of green hydrogen cannot be guaranteed. According to APERC's definition, a steady supply of an energy source is required to ensure energy security (APERC, 2007). From this finding, it can be assumed that a full focus on green hydrogen produced in the HEAVENN project as a replacement for electricity generation by gas will, at this point, reduce energy security in the Netherlands.

2.2 HyBalance

In the HyBalance project, the Levelised Cost of Hydrogen (LCOH) also depends on the energy source used. The 1.25 MW PEM electrolyser, within the Danish project, is powered by surplus energy from on- and offshore wind parks in the region of Hobro (HyBalance, n.d.). Therefore, the average Danish LCOH of onshore wind or offshore wind as feedstock for green hydrogen production are relevant for the cost-competitive analysis of the HyBalance project, which shows that green hydrogen is not yet cost-competitive in Denmark.

The highest average LCOH of hydrogen has been calculated for green hydrogen production by offshore wind (4,96 €/kg). More than 1 €/kg lower in costs, in comparison to offshore wind, is the powering of the PEM electrolyser by onshore wind farms with an average LCOH of 3,36 €/kg (see Table 2). Using onshore wind, thus, involves the lowest green hydrogen production cost in Denmark (FCHO, 2022).

	LCOH
Onshore Wind	3,36 €/kg
Offshore Wind	4,95 €/kg

Table 2: Danish average LCOH per energy source (FCHO, 2022)

However, one factor keeping the LCOH high in Denmark is the fact that there is not enough surplus wind produced yet to keep the electrolyser running continuously. During 1238 hours, Danish wind farms generated surplus energy in 2018. Due to this, electrolysers could only generate hydrogen for 14% of the total yearly hours available. Also, within the HyBalance project, the PEM electrolyser is powered by available surplus wind. The underproduction may result in lower revenue and higher costs (Berg et al., 2021).

The low capacity combined with the already high LCOH ensures that green hydrogen is not yet cost-competitive with fossil fuels (gas & oil) in Denmark. On top of that, also in the HyBalance project, around 50% of the cost of hydrogen comprises electricity costs. The high electricity costs also contribute to the non-competitive nature of hydrogen in

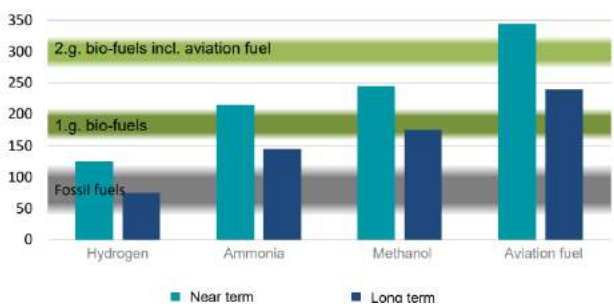

Figure 7: *''Forecasted production costs for PtX fuels in the longer term (DKK/GJ)''* (Danish Ministry of Climate, Energy and Utilisation, 2021, p.31)

Denmark (Skov et al., 2021; HyBalance, 2021). While no specific numbers are known at which LCOH rate HyBalance green hydrogen will be cost-competitive, several articles and reports indicate (Singlitico, 2022; Berg et al., 2021; Danish Ministry of Climate, Energy and Utilisation, 2021; Panah et al., 2022) that cost-competitiveness with fossil fuels is not feasible before 2030. In the longer term (after 2030), however, hydrogen production costs are expected to fall below those of fossil fuels in Denmark, resulting in cost-competitiveness of hydrogen (see Figure 7) (Danish Ministry of Climate, Energy and Utilisation, 2021; Megavind, 2020). According to Panah et al. (2022), the LCOH will have to move towards 1 €/kg to make green hydrogen cost-competitive in Denmark.

To make this happen, policies need to be drafted on Co2 taxes to raise the cost of fossil fuel use, and subsidies on renewable energy have to be established to lower the price of wind energy and scale up electricity generation (Panah et al., 2022). The existing and required policy will be discussed in more detail in Chapter 4 about accessibility.

From this analysis, it can be concluded that the HyBalance project is not yet cost-competitive with fossil fuels. The underproduction of electrolysers, in combination with electricity prices, contributes to the high LCOHs. The cost of hydrogen generation at this point is higher than fossil fuel production and will have to drop towards 1,0 €/kg to be cost-competitive with gas and oil in Denmark. Cost-competitiveness of hydrogen is expected to increase after 2030. However, this requires policy adjustments supporting green hydrogen production.

As a result, the HyBalance project does not add to energy security yet due to the non-cost competitive nature of the green hydrogen produced. The non-cost competitiveness creates a situation where the price of green hydrogen is not attractive for industries and households to invest in. As with HEAVENN, the low attractiveness may cause less generation of green hydrogen (IEA, 2019), which ultimately reduces supply in Denmark but also towards other European countries via the planned European Hydrogen Backbone (EHB). Therefore, looking from the affordability perspective (Ren & Sovacool, 2014; Al Mufachi & Shah, 2022), a single focus on green hydrogen for energy production as a substitute for fossil fuels is, therefore, not feasible at this stage and would diminish the region's energy security and that of Europe.

2.3 Conclusion

To conclude, from an affordability perspective, both the HEAVENN and HyBalance projects do not contribute to energy security yet. The LCOH in both projects is still too high to be cost-competitive with fossil fuels and natural gas-based hydrogen production (blue and grey hydrogen). In both Hydrogen Valleys, renewable electricity prices (the price of onshore wind, offshore wind and solar PV) significantly influence the high level of LCOH. Additionally, whereas within the HEAVENN project, the certification of green electricity drives the LCOH up, the underproduction of electrolysers does so within HyBalance. Denmark and the Netherlands have comparable LCOH, indicating that neither country is closer to attaining a cost-competitive position than the other.

The low-cost competitiveness of the green hydrogen generated in HEAVENN and HyBalance causes an insufficient contribution of green hydrogen to the energy security of the regions and countries where these projects are located. This is mainly due to the low attractiveness of investing in green hydrogen due to the high costs, which could hamper the energy supply not only in Denmark and the Netherlands but also throughout Europe when the EHB is established. Therefore, from the analysis of the two European case studies, it can be assumed that viewed from the affordability dimension, HEAVENN and HyBalance cannot yet fulfil the EU's energy strategy goal of contributing to European green hydrogen production to enhance energy security.

Chapter 3: Availability

The availability of an energy source is the second dimension of the Energy-Focused Four A's Framework. The analysis of the availability pillar is done by using the indicator of raw materials. Raw materials (e.g., iridium, copper, aluminium) are important materials for manufacturing wind turbines, electrolysers and solar panels. Failure to deliver raw materials for the production of these RES may impact green hydrogen production and, as a result, energy security. Therefore, energy security is higher when raw material dependence on foreign countries is low, and materials are available domestically (Stuchtey & Below, 2015; Rybak et al., 2022).

For both the HEAVENN and HyBalance Hydrogen Valley projects, Chapter 3 describes whether raw materials needed for hydrogen production are available in-country or if there are dependencies towards other nations for obtaining these materials. In this manner, sub-question four can be answered *how do HEAVENN and HyBalance contribute to energy security looking from an availability perspective?* The analysis also takes into account the question of the material availability in the European Union in order to answer the main question about the contribution of Hydrogen Valleys to European energy security in the conclusion of the thesis.

3.1 HEAVENN

In the HEAVENN Hydrogen Valley, wind and solar energy are the primary feedstock for the PEM and Alkaline electrolysers to generate green hydrogen (HEAVENN, n.d.). For the manufacturing of wind turbines, solar panels and the two types of electrolysers, raw materials are of great importance (Wieclawska & Gavrilova, 2021; Gavrilova & Wieclawska, 2021; Mathieux, 2017). However, importing these raw materials is required (International Energy Agency, 2022a), which creates a high dependency on non-European countries and impacts the availability of the resources necessary for HEAVENN.

Solar photovoltaics (PV) are produced with the raw materials copper and aluminium. European mines (in Portugal, Poland, Finland, and Sweden) contribute only 1% to the global production of this mineral, making the Netherlands and the rest of the EU import-dependent on copper-extracting countries outside the EU (International Energy Agency, 2022a; Carrara et al., 2022). The main copper export countries are China, Chile and Peru, with China taking an increasing role in the copper trade. Also, for the import of aluminium, the Netherlands is highly dependent on China and, to a lesser extent, on Russia (International Energy Agency, 2022). The materials needed for the production of solar panels employed in the HEAVENN project are thus not available domestically considering the Netherlands and the EU as a whole, creating a raw material dependency on mainly China. The dependency negatively influences the availability of the energy source green hydrogen, as outlined by Rybak et al. (2022).

Although using solar energy to produce green hydrogen in the HEAVENN Hydrogen valley increases dependence on other countries, this is even more the case with wind energy (see Figure 8). For the manufacturing of wind turbines, copper, zinc and Rare Earth Elements (REE, mainly dysprosium and neodymium) are essential raw materials. Despite small REE mines in Estonia and France, these materials, in particular, also create a dependence on China, where 83% of global extraction and processing takes place (Carrara et al., 2020; Meng et al., 2020).

The dependency assures, according to Rybak et al. (2022), that supply disruption of REE due to, for example, political instability or new legislation can easily impact the availability of raw material in the Netherlands (International Energy Agency, 2022a; Wieclawska & Gavrilova, 2021).

Figure 8: Raw material producing countries for wind turbines (Carrara et al., 2020, p.7)

Green hydrogen production in the Dutch Hydrogen Valley thus requires a significant number of imported raw materials for the production of wind turbines and solar PV. However, the materials mentioned above are not assigned to the group of critical materials. Critical materials are raw materials that are key to an economy and have a high probability of supply disruption (Wieclawska & Gavrilova, 2021). Iridium and Platinum are categorized as critical materials and are essential for the manufacturing of PEM electrolysers that have yet to be installed within the HEAVENN project.

Iridium and platinum are part of the Platinum Metal Group (PGM) and are one of the rarest metals on earth (Wieclawska & Gavrilova, 2021; Minke et al., 2021; Riedmayer et al., 2023; IRENA, 2020). More than 90% of global iridium reserves are located in South Africa, while much smaller reserves can be found in Russia, Canada, the United States and Zimbabwe (See Figure 9) (Davis, 2022; Minke et al., 2021; Clapp et al., 2023). Figure 9 shows that iridium is not available in the Netherlands or the rest of the European Union (Ansari et al., 2022).

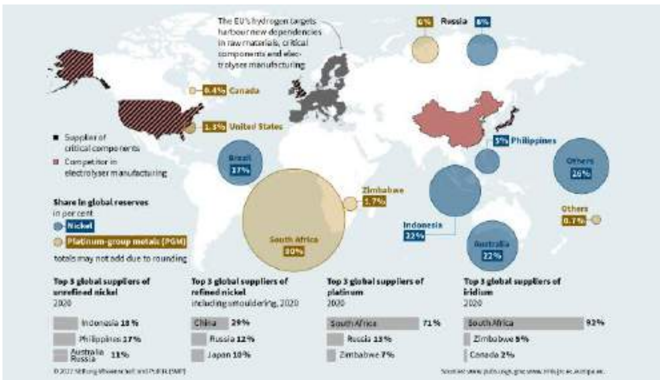

Figure 9: Raw materials for electrolyser production (Ansari, 2022, p.3)

This makes PEM manufacturing and use in the HEAVENN project entirely dependent on raw material export from other countries, especially South Africa, which again may influence the availability of the energy source green hydrogen due to the dependency relationship (Stuchtey & Below, 2015).

Alkaline electrolysers, on the other hand, do not require so-called critical materials like iridium or platinum. The key raw material of the alkaline electrolyser is nickel. Nickel is not extracted in the Netherlands or other EU countries but is neither concentrated in one place like iridium and platinum are. Importing nickel is possible from Indonesia, Brazil, Russia, the Philippines and Australia (See figure 8). The multiple import options, in combination with the spread of nickel reserves, make the supply of this raw material less vulnerable to availability disturbance (Ansari et al., 2022).

None of the raw materials required for the production of solar panels, wind turbines and electrolysers are thus available in the Netherlands. Few of the materials are extracted in the EU but only consist of a small percentage of the total worldwide extraction. For the production of green hydrogen, the HEAVENN project is, therefore, highly dependent on foreign countries outside the EU. This dependence, in particular, focuses on China and South Africa (Carrara et al., 2022; International Energy Agency, 2022a; Davis, 2022). This reliance on (two) foreign countries for the entire Hydrogen Valley value chains allows for faster disruption of green hydrogen production, lowering of energy security, as discussed in the theoretical framework (Stuchtey & Below, 2015; Rybak et al., 2022).

The tumultuous political situation in South Africa, for example, may cause a disruption of green hydrogen production as it already caused a disruption of the raw materials value chain in 2021. The civil uprisings in 2021 against the established government, corruption and inequality caused mining activities to stagnate and made roads and ports unusable for exporting products. In 2024, elections will take place in South Africa, which could again lead to insurrections (ACCORD, 2021; Harding, 2022). The fragile situation may not only disrupt the supply of critical materials but also increase the price of iridium and platinum due to the shortage of materials. The increased prices, in turn, create an affordability security issue as it increases the cost of hydrogen production and therefore reduces the cost-competitiveness of green hydrogen, as outlined in Chapter 2 (Hydrogen Council, 2020). The dependence on South Africa thus may create a reduced contribution to energy security by green hydrogen in terms of both the energy security dimensions availability and affordability.

Additionally, dependency on China may create raw material supply problems due to events impacting the Netherlands-China relationship. This is mainly related to the changed EU policy towards China since 2019, which is more vocal towards political and ideological decisions made by the Chinese government. Underlying the EU's change in policy is the alliance between most European countries, including the Netherlands and the United States (US), through the North Atlantic Treaty Organisation (NATO) (Feng, 2022). The stringent foreign policy of the US towards China has a major influence on Dutch and European policy, which puts pressure on the Netherlands-China relationship. Added to this is China's ambiguous stance on the Russia-Ukraine conflict, which further increases the tensions (Feng, 2022). The distorted relationship between the Netherlands and China could lead to sanctions on raw material imports, decreasing the availability of raw materials for green hydrogen production in the Netherlands and eventually reducing the contribution of green hydrogen to energy security (Stuchtey & Below, 2015; Rybak et al., 2022).

The unavailability of raw materials domestically and the dependence on non-European countries thus create a situation in which the availability and affordability of raw materials cannot be guaranteed, which can hamper the supply of green hydrogen. As a result, the dependency on foreign countries for raw material imports reduces the contribution of green hydrogen to Dutch energy security.

3.2 HyBalance

In the HyBalance Hydrogen Valley, the PEM electrolyser is powered by wind energy from wind farms in the Hobro region. The electrolyser has already been installed in 2020, however raw materials are still needed to install and replace wind turbines to ensure the supply of wind energy for green hydrogen production in the HyBalance project (HyBalance, n.d.) because, as indicated in Chapter 2, not enough surplus wind is yet produced in Denmark to keep green hydrogen production running (Berg et al., 2021). However, for the import of necessary raw materials, Denmark is dependent on non-European countries, which affects the availability of the raw materials and green hydrogen generation.

In-country raw material extraction is possible in Denmark. Extraction of raw materials also takes place in the Nordjylland region, where the Danish Hydrogen Valley is located (Statistics Denmark, 2021). The locally extracted sand, limestone and gravel are usable for buildings and infrastructure and also for the concrete base of the wind turbines (Farina & Anctil, 2022; GEUS, n.d.). However, as described in the section above on HEAVENN, the raw materials copper, zinc, and REE are essential for manufacturing the 25,000 components that together form a wind turbine (Razdan & Garrett, 2018). These materials are not available in Denmark and are hardly within the European Union (see Figure 8) (Carrara et al., 2020).

Denmark depends on imports from foreign countries to obtain zinc, copper and REE for wind turbine manufacturing. The dependence mainly focuses on China, the primary supplier of these three raw materials. While zinc and copper are still available in multiple countries, this is hardly the case for REE, in which China has an 83% market share. Zinc, for example, can be imported from India, Australia and to a smaller extent from neighbouring Sweden, and copper from Chile and Peru, but REE is mainly concentrated in one place, China. As in the case of the Netherlands, this makes REE a rare material that is difficult to obtain and sensitive to disruption (International Energy Agency, 2022a; Carrara et al., 2020). For the development of wind turbines, Denmark is thus highly dependent on countries outside the European Union, which could affect the availability of raw materials for wind turbine production, as discussed in the theoretical part of this thesis (Rybak et al., 2022).

The risk of supply disruption is increased by the changed policy Denmark has been pursuing towards China in recent years. As in the Netherlands, this stems from the changed EU policy towards China and the alliance between Denmark and the US through NATO (Shi & Lanteigne, 2019). However, especially from the re-evaluation of the relationship with China by the alliance of Scandinavian countries, which includes Denmark, in response to the Uyghur detention camps and the protests in Hong Kong (Forsby, 2022). Criticising Chinese policy and supporting the foreign policy of the United States is causing the relations between China and Denmark to deteriorate. The weakened relationship could lead to sanctions against Denmark which could reduce the supply of raw materials for wind power production, which in the end, affects HyBalance's green hydrogen generation.

Therefore, the contribution of the HyBalance project to energy security is low looking from an availability perspective. Because as the theoretical part outlines, when dependency on foreign countries is high, energy security diminishes (Stuchtey & Below, 2015; Rybak et al., 2022). In Denmark, the government and researchers are committed to decreasing the dependence on other countries for raw materials. They explore the option of recycling wind turbine materials to reduce dependency and decrease environmental impact (MegaVind, 2022). This topic is discussed further in Chapter 5 (acceptability).

3.3 Conclusion

From a raw material availability perspective, the contribution of HEAVENN and HyBalance to energy security is low due to the high dependence on foreign countries for raw material imports. One advantage of HyBalance over HEAVENN is that their PEM electrolyser is already constructed, reducing their reliance on PGM metals. However, the essential raw materials for manufacturing solar PV and wind turbines are not available in the Netherlands or Denmark. The domestic unavailability of the materials creates a dependence on raw material producing countries, focusing mainly on China and South Africa.

The deteriorating relationship with China for Denmark, the Netherlands and the EU, in addition to the unstable situation in South Africa, increases the likelihood of disruption in the availability of these materials, which may hamper green hydrogen generation. As a result, the dependence on China and South Africa thus can creates a reduction of energy security due to possible supply disruption in Denmark, the Netherlands and the European Union when relying entirely on green hydrogen generation.

CHAPTER 4: ACCESSIBILITY

The third dimension, accessibility, is discussed in this chapter based on the indicator policy. A country or region's policy significantly impacts energy accessibility due to its ability to obstruct or support energy developments. A policy indicator that is, therefore, important for the energy security of a particular region or country is the decisions made regarding energy subsidies, taxes and strategies/goals (Azzuni & Breyer, 2018; Kruyt et al., 2009; Ren & Sovacool, 2014). Clear policies strengthen energy accessibility to a population (Azzuni & Breyer, 2018). The policies of the Netherlands and Denmark on green hydrogen are therefore analysed. This includes a focus on national policies and policies in the region where the Hydrogen Valley is located. Since both countries are part of the European Union, European policies and strategies on green hydrogen are important and are therefore discussed in a separate section.

The analysis of the policies of Denmark (HyBalance), the Netherlands (HEAVENN) and the EU provide an answer to sub-question five in the conclusion of this chapter: *How do HEAVENN and HyBalance contribute to energy security looking from an accessibility perspective?*

4.1 HEAVENN

As indicated before, the HEAVENN Hydrogen Valley is located in the Northern part of the Netherlands (HEAVENN, n.d.). This makes Dutch national and regional policies regarding green hydrogen relevant to hydrogen development within HEAVENN. Contributing to energy security through the HEAVENN Hydrogen Valley requires clear policies that give access to hydrogen development that ensures green hydrogen consumption. However, in the Netherlands and Northern Netherlands specifically, clear policies promoting hydrogen development do not appear to be completely in place yet.

At the national level, hydrogen policy stems mainly from the Dutch Climate Agreement, which describes an important role of hydrogen in reducing Co2 emissions and countering climate change. The role of hydrogen is reflected in the hydrogen policy the Dutch Government is currently pursuing, which consists of two key pillars (Government of the Netherlands, 2019).

First, carbon pricing is used to stimulate the development of a hydrogen economy. Since January 2021, the carbon pricing law has entered into force, which means that industries have to pay a levy per tonne of Co2 emission (European Commission, 2021; Government of the Netherlands, 2019). The levy started at €30 per ton of Co2 and increases each year with 10,56€ (See blue bars Figure 10).

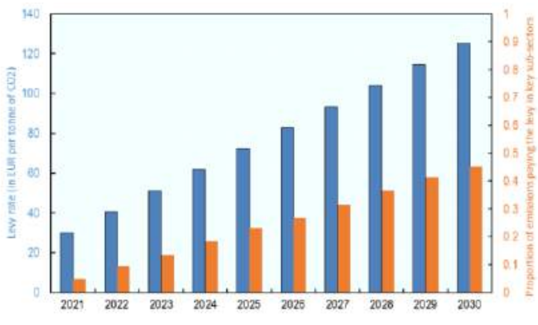

Figure 10: Dutch Carbon pricing (OECD, 2021, P.21)

The second pillar of the Dutch hydrogen strategy focuses on subsidies to promote the scaling up of the blue and green hydrogen economy by ensuring cost reduction. The *''Energy Innovation Demonstration Scheme''* (Government of the Netherlands, 2020, p.7) (DEI+) and the SDE++, the expanded version of the SDE+ (a subsidy to stimulate sustainable energy production) scheme, are the two most important subsidies (Government of the Netherlands, 2020; Ministry of Economic Affairs and Climate, 2022).

The hydrogen focus of the Climate Agreement and the two pillars of the national hydrogen strategy benefit the accessibility of green hydrogen on the one hand. Both carbon pricing and subsidies promote the scaling up of production, lowering costs and, as a result, making investment in green hydrogen more accessible (OECD, 2021; Government of the Netherlands, 2020). Cost reduction is, in particular, important since Chapter 2 on affordability has shown that cost reduction is key for HEAVENN to be cost-competitive with fossil fuel-based energy generation and, as a result, contribute to national and European energy security (Perey, 2022; Mulder et al., 2019). One of the projects within HEAVENN, the Djewels project, is already receiving DEI+ funding to install the 20 MW green hydrogen plant (Gasunie, 2021). From the supportive Dutch policy, it could be concluded that it promotes greater access to green hydrogen generation. The decrease in access leads to a more dependable energy supply and improved accessibility of green hydrogen for Dutch citizens, ultimately contributing to energy security. However, the regulations are not clearly formulated yet, and this may cause the accessibility to an energy source to decrease, as stated in the theoretical framework (Azzuni & Breyer, 2018; APERC, 2007).

First, carbon pricing exceptions are made for large energy companies, for example, by charging a lower rate or excluding them from taxation. This ensures the creation of inequalities between energy companies and the failure to increase the cost of fossil fuel-based energy production (OECD, 2021). Consequently, the cost of green hydrogen production within HEAVENN remains high, decreasing the cost-competitiveness of the energy source and reducing the attractiveness and accessibility to investment in green hydrogen. Low cost-competitiveness decreases the affordability of an energy source and diminishes energy security (Hydrogen Council, 2020). The contribution of green hydrogen from HEAVENN remains low due to unclear policy.

On top of that, SDE++ focuses mainly on high-readiness and low-cost technologies. Therefore, newer green hydrogen technologies often do not qualify for the subsidy. This is also reflected in the HEAVENN project, where so far, no projects received SDE++ (Rijksdienst voor Ondernemend Nederland, 2023), while many technologies focus on sustainable production to reduce CO2 emissions (OECD, 2021). The incomplete SDE++ policy may also reduce accessibility for HEAVENN partners to supply and demand green hydrogen and thereby lower green hydrogen contribution to energy security due to moderate support of the Dutch hydrogen policy (Azzuni & Breyer, 2018).

To establish a green hydrogen economy in the Northern Netherlands, clear policy and coordination on the regional level are in addition essential (OECD, 2021). The policy of the North Netherlands region focuses mainly on supporting these national but also European subsidy applications, sometimes involving co-financing from the Provinces of Drenthe and Groningen (Nationaal Programma Groningen, 2020). The regional authorities consider the North Netherlands as the place where the hydrogen-based energy transition should also emerge as an alternative to the discontinued gas extraction in the Province of Groningen. Although a *''Northern Netherlands Roadmap''* (Provincie Groningen, 2020, p.25) has been developed, it is unclear from this roadmap what policy steps the regional government will take to achieve these goals and ensure that subsidies reach the regional hydrogen projects. The lack of clarity potentially reduces accessibility to hydrogen investments, which negatively affects the contribution to energy security, according to the Renewable Energy Focused Four A's Framework (Azzuni & Breyer, 2018), as it reduces citizens' access to green hydrogen.

At both national and regional levels, the importance of hydrogen production for energy transition and climate adaptation is thus recognised. The policies promote the accessibility to the energy source hydrogen, which reduces the risk of hydrogen supply interruption, thereby contributing to energy security according to APERC's (2007, p.7) definition of energy security, which prioritises a stable supply of the energy resource.

However, the regional and national regulations have not yet been formulated clearly, which creates inequalities in the energy sector and prevents subsidies from reaching their destination, including within HEAVENN. The ambiguity of the policy, as a result, cause a decrease in accessibility to green hydrogen project development and consumption (Azzuni & Breyer, 2018) and, thereby, the contribution of HEAVENN to energy security by creating a security danger of insufficient supply and low cost-competitiveness. Thus, from the accessibility dimension, HEAVENN partially contributes to energy security, but there is room for improvement by adjusting hydrogen policies in a green hydrogen-promoting way.

4.2 HyBalance

Regarding the HyBalance project, Danish national policy and Northern Denmark's regional policy concerning hydrogen are essential (HyBalance, n.d.). The HyBalance project is already finalised, but policies in place are important for the continued existence of the Hydrogen Valley project. A clear Danish hydrogen policy is necessary to increase accessibility to green hydrogen generation and use and contribute to energy security. However, Danish policy is not yet complete and, in some cases, ambiguous.

As with the Netherlands, Denmark's hydrogen strategy is inspired by the national climate agreement (Skov et al., 2021; Danish Government, 2020). Policies pursued by the Danish government and the municipality (Mariagerfjord) and province (North Jutland) where the HyBalance project is located are focused on promoting hydrogen development to meet the 2030 climate and energy targets (Mariagerfjord Kommune, 2023; Region Nordjylland, n.d.). The province of North Jutland and the municipality of Mariagerfjord comply with the government guidelines. No further information can be found on national policy additions.

The Danish hydrogen strategy consists of allocating subsidies to facilitate upscaling to reduce the cost of hydrogen production and use. This involves subsidising (green) hydrogen technologies and purchasing green means of transport such as green trucks, taxis and buses. In addition to subsidies, the Danish government is pushing for geographically dependent electricity tariffs. By clustering electrolysers plants in designated areas where integration into the energy grid is still possible without making major adjustments (see production-dominated areas in Figure 11), energy tariffs can be brought down in these areas (Danish Ministry of Climate, energy and utilisation, 2021; Ministry of Climate, Energy and Utilisation, 2022). Moreover, the Danish government has committed to developing an additional 2 GW of offshore wind to increase the supply of renewable energy for green hydrogen production. The additional capacity can increase the volume of surplus wind that can be deployed for electrolysis (Danish Ministry of Climate, energy and utilisation, 2021).

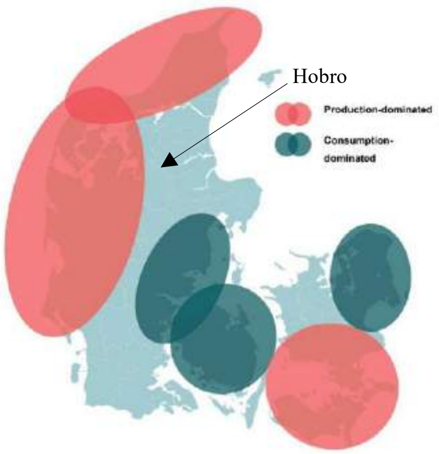

Figure 11: *''Capacity map the Danish electricity grid''* (Danish Ministry of Climate, energy and utilisation, 2021, p.46)

Denmark's comprehensive hydrogen policy on energy tariffs, subsidies, and wind energy development benefits accessibility to green hydrogen. All three policy focus points ensure lower hydrogen generation costs by facilitating production scale-up, which promotes investments in green hydrogen generation. Encouraging investment in green hydrogen can ensure a reliable supply and improve citizens' access to hydrogen consumption. Although in terms of green hydrogen technology subsidies, the HyBalance project is not gaining much since the PEM electrolyser plant is already completed, the scaling up of the entire Danish hydrogen economy in combination with the energy tariffs may ensure a lower average LCOH (HyBalance, 2021). Chapter 2 has shown that a reduction in LCOH is required for HyBalance to increase cost-competitiveness with comparable energy sources to contribute to energy security (Panah et al., 2022). Furthermore, developing additional wind areas can help prevent the underproduction of hydrogen (see Chapter 2), which can increase revenues and reduce costs, contributing to the affordability and accessibility of green hydrogen.

Danish market policy is, however, not yet fully accustomed to facilitating a hydrogen economy, which decreases accessibility to green hydrogen. Denmark currently has no green hydrogen certification scheme, and, in addition, subsidies are still granted to competing energy sources, mostly biofuels and blue hydrogen (Skov & Mathiesen, 2017; Skov et al., 2021). Green hydrogen already has to compete with these more economically attractive energy technologies, and continued subsidies for blue hydrogen and biofuels are not helpful (Skov et al., 2021). The ambiguity in the Danish policy regarding green hydrogen reduces accessibility to the energy source, as viewed from the energy security theory (Azzuni & Breyer, 2018).

Denmark is thus keen to be at the forefront of the energy transition, and hydrogen generation plays a vital role in this. The hydrogen policies make green hydrogen production and use within the HyBalance Hydrogen Valley more accessible by reducing costs and increasing wind energy capacity. These policies ensure an increased supply guarantee of this energy source, enhancing public access to green hydrogen use and thereby increasing energy security, according to the energy security definition of APERC (2007).

However, on the other hand, accessibility is reduced by the non-existence of certification schemes and the continued support of competing energy sources. The lack of clarity and ambiguity in Danish policy may increase the likelihood of insufficient hydrogen supply due to reduces attractiveness to invest in green hydrogen, lowering access to green hydrogen consumption, which negatively affects energy security according to energy security theory (APERC, 2007; Kruyt et al., 2009; Ren & Sovacool, 2014). Thus, from an accessibility perspective, the HyBalance Hydrogen Valley contributes to energy security on the one hand, but policy choices hold it back on the other.

4.3 Europe

HEAVENN and HyBalance are located in two of the 27 European member states, Denmark and the Netherlands (European Union, n.d.). Because both countries are members of the European Union, they are also bound by policies made at the EU level. As described in the theory section, a policy can encourage access to energy development but also obstruct them (Ren & Sovacool, 2014). This is the case with EU policies that, on the one hand, boost green hydrogen development and use but, on the other hand, delay green hydrogen processes.

The European Commission set up a range of policy frameworks over the years to combat climate change and promote hydrogen generation within the European Union. The European Green Deal was one of the first frameworks fully committed to banning fossil fuels and creating a competitive market for renewables (Khatiwada et al., 2022; European Commission, 2019). The main instruments for reducing Co2 emissions and achieving Green Deal targets are the revised Renewable Energy Directives (RED II) and the European Energy Trading System (ETS). RED II includes the development of a framework to control guarantee of origin (GO) of hydrogen (Khatiwada et al., 2022; European Commission, 2023; European Commission, 2023b).

Additionally, a European hydrogen strategy was presented in 2020 to promote the development of a hydrogen economy by introducing legislation and support schemes (European Commission, 2020). The fit for 55 packages (2021) and the more ambitious REPowerEU (2022) programme, launched in response to the Russian invasion of Ukraine (Proedrou, 2023), expanded the EU's hydrogen ambitions and strategies (Barnes, 2023). Part of this expansion has taken shape in the provision of IPCEI (Important Projects of Common European Interest) grants to hydrogen projects, the establishment of the Clean Hydrogen Partnership (Horizon Europe funded) to promote innovation and research in the hydrogen supply chain such as in the HEAVENN and HyBalance Hydrogen Valleys, and plans to establish the European Hydrogen Backbone (EHB) to ensure hydrogen access for all members states of the EU (Chatzimarkakis, 2022; European Commission, n.d.; HEAVENN, n.d.; HyBalance, n.d.).

EU policy thus shows that hydrogen developments are considered a key strategy to reduce Co2 emissions. The hydrogen support policy that results from the EU hydrogen strategy ensures that accessibility to hydrogen production and use increases in Denmark, the Netherlands and other EU countries (Azzuni & Breyer, 2018). This is reflected in the Horizon 2020 grant both HEAVENN and HyBalance received from the Clean Hydrogen Partnership (European Commission, 2022; European Commission, n.d), which contributed to the generation of green hydrogen and, therefore, to the accessibility of green hydrogen to the citizens of Denmark and the Netherlands. Similarly, the European grand scheme, IPCEI, is providing an extension national grant schemes in Denmark and the Netherlands to increase green hydrogen accessibility by getting large hydrogen projects off the ground (Danish Ministry of Climate, energy and utilisation, 2021; Government of the Netherlands, 2020).

Finally, the ETS scheme also makes hydrogen accessible by reducing the cost differential between fossil fuels and hydrogen, making hydrogen use and production a sound market option (Liakopoulou, 2020). The EU policy thus provides both HEAVENN and HyBalance not only with greater consumer accessibility to green hydrogen due to the promotion of hydrogen generation but also contributes to the affordability of the source, which increases the cost-competitiveness of green hydrogen. An increase in cost-competitiveness and hydrogen-supportive policy may enhance energy security, looking from the theoretical framework (Azzuni & Breyer, 2018; Hydrogen Council, 2020).

However, EU policy should be clear to fully contribute to the energy security of green hydrogen (Azzuni & Breyer, 2018). The ambiguous ETS policy does not contribute to this. Despite efforts to reduce Co2 emissions within ETS, companies remain exempted from the requirements. The exemption is based on concerns that these large emitters may relocate to other countries and increase their emissions there, also known as *''carbon leakage''* (Dorsch et al., 2019).

Initially, the exoneration of companies was planned to end in 2027, but it has been postponed due to major industrial countries in Europe (e.g., Germany) advocating for the carbon leakage argument (Markard & Rosenbloom, 2020). By continuing to support these industries, there is no economic motivation to transition to environmentally-friendly alternatives (Dorsch et al., 2019) like green hydrogen. Consequently, the production of hydrogen remains limited, leading to low accessibility of green hydrogen in EU member states.

Moreover, the not yet determined definition of green hydrogen by the European Union is reducing accessibility and, as a result, energy security. The lack of definition clarity makes it unclear to businesses when an investment meets European green hydrogen requirements (Barnes, 2023). This, in turn, is holding back green hydrogen regulations in European countries. In the Netherlands, it is, for example, holding up hydrogen mobility policies and, in Denmark, it is an obstacle to the development of GO schemes (Government of the Netherlands, 2020; Danish Ministry of Climate, Energy and Utilisation, 2021; Ministry of Economic Affairs and Climate, 2022). Obstructing green hydrogen policies may lead to reduced investment in green hydrogen, which eventually leads to diminished production of hydrogen, resulting in an insufficient generation to meet demand. The energy source then no longer matches the energy security definition (APERC, 2007), in which the guarantee of supply is key.

To conclude, the European Union promotes hydrogen development through subsidies and regulations. This ensures that access to hydrogen in EU countries such as Denmark and the Netherlands increases and, with it the contribution of hydrogen to energy security. However, the European definition of green hydrogen is still unclear, making regulation development in this green source less accessible. The unclear policy reduces energy security due to the creation of a risk of insufficient supply of green hydrogen as a result of less investment due to unclear regulations. A reduced supply of hydrogen could lead to insufficient availability of hydrogen to meet the demand of the population in the EU, Denmark or the Netherlands, resulting in reduced accessibility to green hydrogen. In European policy, there are thus also two sides to consider from an accessibility perspective.

4.4 Conclusion

To conclude, it can be stated that from a Dutch and Danish green hydrogen accessibility perspective, there is a contribution to energy security by HEAVENN and HyBalance promoted by subsidies and tax regulatory policy in the countries and the EU, but clarification and extension of policy are needed to guarantee sufficient green hydrogen supply from the Hydrogen Valleys so that energy security increases.

When comparing Dutch and Danish policies, it becomes evident that the Netherlands has implemented more policies than Denmark (e.g., DEI+, SDE++ and carbon pricing) to support green hydrogen development. While the Dutch policy is open to criticism, it is already in place. Conversely, the Danish government has mainly proposed plans and ideas yet to be implemented, such as energy tariffs and expanding wind capacity. Based on the information, one could infer that the Netherlands is taking more steps than Denmark to encourage investments in green hydrogen to increase access to green hydrogen use among the population.

However, both in the Netherlands, Denmark and the EU, unclear subsidy schemes, continued support for other energy sources and ambiguity about the definition of green hydrogen are now holding back accessibility to hydrogen development and use. Withholding green hydrogen developments could cause energy supply disruption to occur more quickly because not enough hydrogen can be produced to meet demand. The risk of energy supply disruption reduces energy security in the Netherlands, Denmark and Europe, where the planned European backbone cannot be supplied with enough hydrogen to meet the needs of the European citizens. Hydrogen policies currently in place thus need to be improved to overcome supply disruption risks due to the insufficient green hydrogen developments to guarantee energy security to citizens in Denmark, the Netherlands and other EU member states.

CHAPTER 5: ACCEPTABILITY

The last chapter of the analysis discusses the fourth dimension of the Renewable Energy-Focused Four A's framework, acceptability. The acceptability dimension is analysed based on the indicator depletion of natural resources. Deforestation, resource contamination and mining activities, including the exploitation of raw materials, can cause the depletion of resources (Ali et al., 2021). Environmental impacts related to the depletion of natural resources may disrupt the energy supply (Jansen, 2004) and reduce the public acceptance of the energy source, resulting in diminishing energy security (Azzuni & Breyer, 2018). Therefore, this chapter analyses the environmental effects of green hydrogen production in both the HEAVENN and HyBalance Hydrogen Valleys. In doing so, this chapter builds on Chapter 3 (availability) on raw materials but now from an environmental perspective.

The analysis will answer sub question six, *how do HEAVENN and HyBalance contribute to energy security looking from a social acceptability perspective?*

5.1 HEAVENN

Chapter 3 outlines that multiple raw materials are required to produce green hydrogen in the HEAENN project (International Energy Agency, 2022; Wieclawska & Gavrilova, 2021). Although the production of green hydrogen in the Netherlands reduces Co2 emissions and improves air quality, new environmental impacts emerge in mining countries by exploiting the necessary raw materials (Hermessmann & Muller, 2022; Mneimneh et al., 2023). The creation of new environmental impacts affects the social acceptance of green hydrogen.

Looking at the broader environmental perspective, the production of green hydrogen lowers Co2 emissions and reduces ozone depletion (Mneimneh et al., 2023; Hermessmann & Muller, 2022). In particular, using water electrolysers powered by renewable energy sources, such as the PEM electrolyser used in the HEAVENN project, reduces climate-related impacts in the Netherlands (Hermessmann & Muller, 2022). Reducing environmental impacts through green hydrogen production in the Netherlands could lead to greater social acceptance of green hydrogen, according to Azzuni & Breyer (2018) and Narula & Reddy (2016). Ensuring public acceptance is crucial to maintaining the demand (Mancheri et al., 2019) for green hydrogen and avoiding energy system disruption, contributing to energy security. However, a shift of environmental burden is taking place from the Netherlands and the European Union to the raw materials exploiting countries (Hermessmann & Muller, 2022).

In the Netherlands are no mines present that can provide the raw materials to produce electrolysers, wind turbines and solar panels required for green hydrogen generation within HEAVENN. Nor can other EU countries supply enough raw materials to keep up with the growing production of green hydrogen. These materials are therefore imported from non-European countries, mainly China and South Africa (Ansari et al., 2022; International Energy Agency, 2022; International Energy Agency, 2022a). Mining raw materials cause metal and mineral depletion and severe environmental impacts. These negative environmental impacts consist mainly of soil contamination by toxic materials, water pollution by the discharge of wastewater and Co2 emissions from the exploitation of both iridium and platinum in South Africa and the mining of REE, copper and aluminium in China (Díaz-Morales, 2021; Amnesty International, 2022; World Bank, 2022; Balaram, 2019). The contaminations indirectly impact the health of local people, the wildlife populations and the flora surrounding the raw material mines (Sepadi et al., 2020; Zapp et al., 2022). Additionally, the demand for iridium is excessive, which causes a depletion of this resource in South Africa (Davis, 2022).

Raw material extraction thus creates new environmentally related security concerns that threaten humans, biodiversity and resource reserves. The emergence of these new threats reduces the societal acceptance of raw materials exploitation and calls for measures to address safety issues. This aligns with the securitisation process described by Balzacq (2010). The Chinese government, for instance, has introduced new legislation to reduce the environmental impact of REE mines, partly in response to public concerns about environmental impacts. The new policy affects REE imports to the Netherlands and other European countries and drives up the price (Mancheri et al., 2019). The environmental effect of raw material exploitation ultimately thus causes less public acceptance leading to a higher probability of supply disruption of raw materials necessary for green hydrogen generation and contributes to a decrease in cost-competitiveness (Chapter 2) which affects Dutch and European energy security.

Although the environmental effects thus decrease in the Netherlands through green hydrogen production promoting the public acceptance of the energy source, the exploitation of raw materials causes depletion of natural resources and negative environmental impacts in the countries where the mines are located. The unacceptance of these negative effects triggers new environmental policies affecting the supply and price of raw materials to the HEAVENN project. As a result, the generation of green hydrogen may become less, reducing its contribution to energy security.

5.2 HyBalance

Green hydrogen production in the HyBalance project requires the raw materials copper, zinc and REE (Carrara et al., 2020). These materials are necessary for manufacturing wind turbines that supply energy to the established PEM electrolyser. Using wind energy to produce green hydrogen creates numerous positive effects in Denmark on one side, but on the other, the extraction of raw materials creates new environmental impacts, which may influence the social acceptance and supply of green hydrogen.

Wind energy is perceived as the energy source with the least environmental impact. Compared to fossil fuels and similar renewable energy sources, such as solar energy, wind energy emits the least Co2 emissions (Sayed et al., 2021). In addition, research shows that green hydrogen produced by wind power is the only form of hydrogen generation that remains within planetary limits. This means that by using wind energy, natural resources available on earth are handled sustainably (Weidner et al., 2023). Therefore, viewed from the Renewable Energy-Focused Four A's framework (Azzuni & Breyer, 2018), it could be argued that the HyBalance electrolyser powered by wind energy ensures greater societal acceptance of green hydrogen by reducing environmental impacts compared to other energy sources. However, looking beyond Co2 emissions, using wind energy creates several new environmental effects and resource depletion.

In Denmark, wind energy mainly affects the flora and fauna around wind farms (Sayed et al., 2021). Wind turbines create a changed environment in the air and underwater, in the case of offshore wind. The altered environment negatively affects bird populations and the submarine ecosystem (Sayed et a., 2021; Nazir et al., 2020). Additionally, building wind farms, constructing roads and installing power lines in Denmark cause resource depletion through deforestation and land erosion (Nazir et al., 2020). The effects of wind turbines on nature can reduce the acceptance of wind energy as a reduction of social acceptance occurs when environmental effects are created, as described in the theoretical framework (Azzuni & Breyer, 2018). Thereby it also influences the public acceptance of green hydrogen as wind energy serves as a feedstock for the generation of hydrogen. A decrease in social acceptance may result in a drop in demand for green hydrogen, disrupting the supply-demand system and exerting pressure on its production (Mancheri et al., 2019).

Moreover, as with the HEAVENN project, extracting raw materials to generate green hydrogen causes environmental impacts and resource depletion. Copper is a key component of wind turbine manufacturing and is one of the materials that has the largest impact on the environment (OECD, 2018). Copper mining releases toxic substances in water and soil, negatively impacting wildlife, biodiversity and human health (Rueda-Bayona et al., 2022). Because copper mines are not located in Denmark, or the European Union, the negative effects of green hydrogen production have shifted to the country of source, China (Hermessmann & Muller, 2022).

The needed scale-up of wind energy in Denmark for hydrogen production to reduce generation costs (See Chapter 2; Panah et al., 2022) will start increasing demand for copper from China, which will increase negative impacts and deplete the natural resource even further.

In 2015, the Chinese government already implemented emissions policies to address the adverse environmental impact of copper extraction (Li et al., 2017). The 14^{th} Five-Years plan (2021 – 2025) prioritizes further development of policies to protect resources such as copper and mitigate environmental impacts (UNDP, 2021). Thereby, it could be argued that the depletion of resources and the negative environmental impacts have reduced social acceptance in the supplying country, leading to the drafting of new regulations. The new regulations may cause reduced supplies of copper to the EU, including Denmark, halting the construction of wind turbines and, as a result reducing the contribution of HyBalance green hydrogen generation to energy security.

In Denmark, recycling raw materials from out-of-use wind turbines could be the solution to the creation of new environmental impacts and resource depletion (Cao et al., 2019; Rueda-Bayona et al.,2022; MegaVind, 2022). Recycling the raw materials could prevent supply disruption by reducing dependence on China and, on top of that, ensures that fewer raw materials, such as copper, need to be mined, diminishing environmental impacts. Recycling raw materials could thus contribute to energy security from both an availability and acceptance perspective. However, new policies are needed to encourage research into recycling raw materials and to enforce responsibilities on producers. In Denmark, such policies are not yet in place (Cao et al., 2019; MegaVind, 2022). The accessibility dimension (policy) thus holds back developments in the acceptance and availability of green hydrogen in Denmark, reducing the contribution of these areas to energy security.

From a social acceptance perspective, HyBalance, thus, partially contributes to energy security but improvement, mainly in the policy field is required. On the one hand, green hydrogen production based on wind energy reduces Co2 emissions, which could increase the public acceptance of green hydrogen from the perspective of the energy security framework. However, the manufacturing of wind turbines, on the other hand, creates many new environmental problems in Denmark and the raw material-supplying country, China. The environmental impacts in China may lead to more environmental policies, which affect the supply of raw materials and, as a result, energy security in Denmark. A solution proposed for both the dependence on China and the environmental impacts is recycling old wind turbines. However, sufficient policy is not yet in place.

5.3 Conclusion

From a social acceptability perspective, HEAVENN and HyBalance contribute partly to energy security. Based on the analysis, the factors impacting social acceptance, positively or negatively, are comparable between both projects. Green hydrogen is not more widely accepted in HEAVENN or HyBalance. Both projects reduce environmental impacts through Co2 emissions reduction, which increases the social acceptance of green hydrogen. However, the production of green hydrogen also created new environmental and depletion of resources that arise mainly in the raw materials supplying countries. The negative effects cause less public acceptance of green hydrogen in these countries, leading to new policies that can increase Danish and Dutch hydrogen costs and reduce raw materials supply negatively affecting green hydrogen production. In this manner, environmental and health impacts due to natural resource depletion lead to reduced energy security in Denmark, the Netherlands and the EU when green hydrogen is used.

CHAPTER 6: DISCUSSION

Chapter 6 provides a reflection on the results and the Renewable Energy-Focused Four A's energy security theory. Additionally, the limitations of the thesis are discussed, and recommendations for further research are given.

6.1 Reflection on Findings

The findings of the thesis illustrate that in terms of affordability, accessibility, acceptability and availability, there is potential for Hydrogen Valleys to contribute to European energy security, but many challenges still affect contribution at present. The potential of Hydrogen Valleys for energy security is particularly evident in their contribution to reducing Co2 emissions and in the high commitment of the Danish and Dutch governments and the European Commission to hydrogen, reflected in the development of a wide range of policy options (Hermessmann & Muller, 2022; Government of the Netherlands, 2019; Skov et al., 2021; Khatiwada et al., 2022). Green hydrogen produced in Hydrogen Valleys becomes more widely accepted by citizens and accessible to producers and consumers due to hydrogen-promoting policies (e.g., subsidies, carbon pricing, electricity tariffs, and upscaling of wind energy capacity) and environmental efforts (mainly domestic Co2 reduction), contributing to energy security.

The results, however, show that the low-cost competitiveness of green hydrogen with fossil fuels (oil & gas) and natural gas-based hydrogen generation (blue & grey hydrogen) due to the high LCOH, in combination with the still unclear and ambiguous policies (e.g., carbon pricing exceptions and lack of regional policies) create a challenge to Hydrogen Valley's contribution to energy security in Denmark and the Netherlands (FCHO, 2022; OECD, 2021; Skov et al., 2021). As is the heavy reliance of European countries on China and South Africa for the acquisition of raw materials, which in addition harms both the environment and public health in the extraction countries, causing new environmental regulations to be drafted (Mancheri et al., 2019). Therefore, the production of green hydrogen in European Hydrogen Valleys may face disruption due to the high costs, unclear policies, dependency on foreign countries, and environmental impact of raw material extraction, which negatively impacts energy security.

As a result, the findings suggest that the Hydrogen Valleys will not have the anticipated impact on the EU's energy strategy as initially planned by the European Commission. The European Commission considers Hydrogen Valleys a crucial approach to producing 10 million tonnes of European hydrogen by 2030 to enhance energy security (Weichenhain, 2022). In doing so, according to the European definition of energy security, *'a stable and abundant supply of energy'* (Russels, 2022, p.1) is required. Although Hydrogen Valleys have potential, the challenges mentioned above highlight that they are currently unable to ensure a consistent supply of green hydrogen, therefore, Hydrogen Valleys cannot yet meet EU's envisioned scale of contribution towards European energy security.

The lack of clear policies in Denmark, the Netherlands and the EU has the greatest impact on the inadequate contribution of Hydrogen Valleys to energy security. Upon analysing the case studies, it is clear that policy improvements consistently arise as the solution to energy security challenges. An effective policy can significantly reduce the LCOH of green hydrogen and promote cost competition by outlining more detailed hydrogen-promoting policies (Perey, 2022). Furthermore, implementing policies regarding the recycling of raw materials can decrease the reliance on China and South Africa by reducing the number of raw materials required (MegaVind, 2022; Wieclawska & Gavrilova, 2021). By reducing the demand for raw materials, the dependence on external factors is decreased, the impact of changing geopolitical relations between China and European Countries can be mitigated, as well as the effects of civil unrest in South Africa and new environmental policies in China on green hydrogen generation in the Netherlands, Denmark and EU. In order to enable the recycling of raw materials, policies should offer financial incentives to Research and Development (R&D) efforts that can lead to innovative solutions and cost reduction to make recycling technologies economically feasible. More explicit policies are key to Hydrogen Valley's contribution to energy security.

Considering the importance given to green hydrogen production by the Netherlands, Denmark and the EU, as well as the consistent publication of new policies (European Commission, n.d.a; Kavanagh, 2022), it is likely that policies will soon be formulated addressing the challenges outlined in this thesis. Moreover, the invasion of Russia into Ukraine has resulted in the advancement of renewable energy regulations (IEA, 2022a), and it is anticipated that the ongoing conflict will prompt additional policies to ensure the safety of the European energy supply, including policies to reduce the demand of raw materials. As a result, the role of Hydrogen Valleys in enhancing European Energy security is expected to grow.

6.2 Reflection on Theory

The thesis contributes to developing a Renewable Energy-Focused energy security framework and thereby to a better understanding of the contribution of Hydrogen Valleys to European energy security.

Developing a Renewable Energy-Focused energy security framework in this thesis is seen as an extension of existing theories rather than a challenge to them. As framework maintains the same four dimensions (availability, accessibility, acceptability and affordability) but with the addition, modification and removal of indicators.

Through the development of the Renewable Energy-Focused Four A's Framework, it has become possible to identify and recognise the risks, threats and entities affecting the supply security of renewable resources specifically. When analysing renewable energy security from the traditional fossil fuel-focused framework of APERC (2007) and Kruyt et al. (2009) instead of the Renewable Energy-Focused energy security theory, factors proved crucial in this thesis to analyse the contribution of renewable energy to energy security would not have been considered.

For example, cost competition and renewable energy policies may not be considered adequately, and environmental impacts may be given limited attention since these factors are not typically included in the traditional framework. Additionally, the reliance on renewable energy sources is bringing about a shift in dependency relationships (Cherp & Jewell, 2014), moving away from a dependence on imported oil and gas to a dependence on countries for the extraction and export of raw materials. Such a change would not be reflected in traditional energy security frameworks and their indicators.

Consequently, the extended theory allows for a more thorough analysis of the contribution of renewable energy to energy security and the remaining obstacles to its implementation. Once the obstacles have been analysed, policy measures can be implemented that effectively address the challenges. Therefore, the framework in this thesis is believed to be a valuable contribution to developing appropriate energy policies.

6.3 Limitations and Recommendations

Further research is recommended to address three main limitations identified in this thesis.

First, the generalizability of the results to all European countries is limited by the choice of two northwest European case studies. The results show that Denmark and the Netherlands share similarities in policies and climate. However, eastern and southern European countries may experience distinct conditions (Kakoulaki et al., 2021), particularly regarding the weather, which, for example, could impact the expense of green hydrogen generation. Therefore, examining Hydrogen Valleys' contribution to energy security in these countries may produce varying outcomes. The validity and generalizability of the two case studies are, however, ensured by including the European perspective through factors such as EU policies and availability of raw materials in the European Union, which are the same for all EU Hydrogen Valleys. Additionally, as explained in the methodology section, the HEAVENN and HyBalance case study covers most consumption, storage and production methods applicable to Hydrogen Valleys. The comprehensiveness also enhances the generalizability of the thesis' findings to other European Hydrogen Valleys.

Secondly, the analysis only utilised four of the 12 indicators outlined in the theoretical framework. Due to the limited selection of indicators, the results may give a partial view of Hydrogen Valleys' role in EU energy security and its associated challenges. To ensure a comprehensive consideration of the framework, however, the most relevant indicators were selected from each of the four dimensions based on academic underpinnings. As a result, it is believed that a detailed description was provided, enhancing the understanding of how Hydrogen Valleys contribute to energy security.

Lastly, sometimes it was challenging to find enough information due to the novelty of the topic. This was evident, for instance, in the search for data on regional hydrogen policy in Denmark (Chapter 4) and the cost of green hydrogen required for cost competitiveness in the country (Chapter 2).

Although the information was not found, it had little impact on the results as it only covered a small portion of the study and additional available information was regarded sufficient to answer the sub-questions.

Based on the results and limitations of the research, further research is needed on the other 22 European Hydrogen Valleys' contribution to energy security. In particular, research should focus on Hydrogen Valleys located in the southern and eastern regions of Europe, for example, on the Green Hysland Hydrogen Valley in Mallorca, to complement the findings of the two northwest European case studies. The results of additional studies, in combination with the findings of this thesis, will provide an even clearer understanding of how Hydrogen Valleys contribute to EU energy security and which challenges need to be overcome.

An additional opportunity for further research exists in analysing the HEAVENN and HyBalance case study with the indicators not utilised in this thesis. Analysis of the case studies using the other indicators described in the Renewable Energy-Focused framework *(water, emissions, willingness to pay, K&I, versatility, infrastructure, price and RES)* may reveal further potentials or challenges of Hydrogen Valleys related to European energy security. By gaining knowledge from this, policy steps could be taken to enhance the role of green hydrogen and Hydrogen Valleys in ensuring energy security in Europe.

A final recommendation for further research includes extensive research on recycling raw materials to decrease material demand. What exact policy steps are needed to encourage raw material recycling technologies? And which technologies are suitable? These two questions, among others, require future research to tackle one of the major obstacles Hydrogen Valleys face: reliance on foreign countries to supply raw materials.

Conclusion

The thesis aimed to examine the role of Hydrogen Valleys in enhancing European energy security while also identifying associated challenges. The purpose of the thesis guided the formulation of the leading research question: how do Hydrogen Valleys contribute to European energy security, and what are the challenges? A case study on the HEAVENN and HyBalance projects. To answer the research question, an analysis of two Hydrogen Valley case studies, HEAVENN and HyBalance, was performed using content analysis. A modified and expanded version of the Four A's Energy Security theory, named the Renewable Energy-Focused Four A's Framework, was utilised to analyse the case studies and to answer the research question. From the framework consisting of four dimensions (affordability, availability, accessibility and acceptability) and 12 indicators, one indicator per dimension was selected to analyse the case studies. The applied indicators are cost-competitiveness, resource depletion, policy and raw materials.

From the analysis, it appears that Hydrogen Valleys could be a valuable asset in bolstering Europe's energy security. The adoption of green hydrogen positively impacts the environment by reducing Co2 emissions, which contributes to greater public support for the energy source. Moreover, there are already several regulations in place (e.g., IPCEI, carbon pricing) or in development (e.g., electricity tariffs) in Denmark, the Netherlands and the EU to promote the use of green hydrogen, making it more easily accessible to consumers and reducing the cost of production, despite some ambiguity surrounding these policies. Public acceptance and policy development may ensure a stable supply and demand of Hydrogen Valley's green hydrogen, leading to an increase in domestic energy security in Denmark and the Netherlands and European energy security through the planned European Hydrogen Backbone.

However, upon analysis of the two case studies using the theoretical framework, it has been determined that there are several challenges to overcome in the field of affordability, availability, accessibility and acceptability. Green hydrogen's Levelized Cost of Hydrogen (LCOH) in the HEAVENN and HyBalance project is currently non-cost-competitive with fossil fuel-based energy generation, making investing in green hydrogen less appealing. Moreover, the policies regarding subsidies for green hydrogen remain unclear, other energy sources (e.g., bioenergy) still receive significant government support or are excluded from regulation, and there is no definitive European classification for green hydrogen at present which forms an obstacle for green hydrogen developments. Furthermore, the production of wind turbines, solar panels, and electrolysers required for HEAVENN and HyBalance green hydrogen generation heavily depends on importing raw materials from China and South Africa. The reliance on only two countries raises the risk of potential supply chain disruption. The unstable situation in South Africa and the strained relationship between China and European member states further exacerbate the risk of raw material supply disruption.

On top of that, the extraction of raw materials in supply countries has negative environmental impacts and depletes resources, leading to new legislations that affect the cost and security of raw material supply negatively. These four challenges make it difficult to guarantee a consistent and reliable supply of green hydrogen from Hydrogen Valleys, which is necessary to ensure energy security. Therefore, the current contribution of Hydrogen Valleys to European energy security is relatively low.

The results of the study provide a conclusive answer to the research question. Based on the thesis findings, it is evident that Hydrogen Valleys can potentially contribute to Danish, Dutch and European energy security. However, the current contribution to energy security is minimal due to expensive generation costs of green hydrogen, reliance on raw materials from other nations, negative environmental impacts in raw material extraction countries and unclear policies.

Upon reflecting on the findings, it has become clear that enhancing policy is key to addressing energy security challenges and unlocking the full potential of Hydrogen Valleys as a source of energy security. The reflection shows that implementing more explicit policies can overcome the obstacle of high LCOH and reduce material dependencies and environmental impacts in exploiting countries by focusing on recycling policies. Based on the implementation of multiple regulations in the EU, Denmark and the Netherlands in the context of the ongoing Russia-Ukraine dispute, improved policies are expected to be implemented to accelerate the promotion of green hydrogen as a strategy to secure energy supply.

By answering the main research question, the thesis has contributed to the research gap that exists in the literature on the contribution of Hydrogen Valleys to European energy security. To further expand knowledge on the contribution of Hydrogen Valleys to European energy security, it is recommended to conduct further research. The research could explore the unused indicators in this thesis, study alternative case studies, and thoroughly investigate the potential for recycling raw materials to decrease dependency. Further research to identify challenges and potentials enables governments to take appropriate steps to unlock the full potential of Hydrogen Valleys. As Ursula von der Leyen, president of the European Commission, states: *''Hydrogen can be a game changer for Europe''*.[5]

[5] Speech of President von der Leyen to the State of the Union on 14 September 2022.

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