Clean industry in the Netherlands?

Identifying constraining and enabling factors on the adoption of green ammonia as an energy carrier for Dutch industry, Tata steel in particular.

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Abstract

The Netherlands is currently situated at a critical point in the energy transition. Although the energy supply is quickly turning away from fossil fuels, the infrastructure for this electricity is suffering from growing pains. This thesis examines the potential of green ammonia as a sustainable energy carrier to support Dutch industry, with a specific focus on Tata Steel. Green ammonia, produced using renewable energy, offers a promising solution to the challenges of energy storage and intermittency that hinder the adoption of renewable energy sources. The research identifies both enabling and constraining factors for the adoption of green ammonia through a comprehensive TES-analysis, which is an adaptation on the PESTEL-analysis model. Key advantages of ammonia include its high energy density and ease of storage and transport compared to hydrogen. However, challenges such as production costs, safety concerns, and environmental impacts must be addressed. The methodology includes policy examination, literature review, and participant observations, combined with a detailed case study of Tata Steel. Various scenarios are explored, including the use of 100% ammonia, a combination of ammonia and electricity, and hydrogen-based alternatives. Technical opportunities such as advancements in ammonia production technologies and improvements in safety standards are analyzed alongside economic factors like cost implications and market readiness. Spatial factors, including the infrastructure required for ammonia generation and integration into existing industrial processes, are also considered. This thesis concludes that ammonia is best used for specific uses such as long-distance hydrogen transport and stockpiling. Ammonia is deemed economically uncompetitive with hydrogen as it has higher production costs, meaning its largescale adoption in industry is unlikely.

Keywords: *Green ammonia, renewable energy, energy storage, TES-analysis, industry, The Netherlands, direct reduction*

Contents

List of abbreviations

Abbreviation	**Definition**
ADR	Agreement of 30 September 1957 concerning the International Carriage of Dangerous Goods by Road
CRI	Commercial Readiness Index
EU-ETS	European emission trading scheme
GHG	Greenhouse gas
H-B	Haber-Bosch
HyDR	Hydrogen direct reduction
ICE	Internal combustion engine
LH2	Liquid hydrogen
LOHC	Liquid organic hydrogen carrier
LPG	Liquified petroleum gas
N2O	Nitrous oxide
NFPA	National Fire Protection Association
NH3	Ammonia
NOX	Nitrogen oxides
PM2,5	Particulate matter with a diameter <2,5 um
SOFC	Solid oxide fuel cell
TRL	Technological Readiness Level

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1 Introduction

1.1 Background and problem statement

At COP28, at the time of drafting this thesis the latest United Nations Climate Change Conference, one of the main takeaways is the movement away from fossil fuels soon (Erbach and Roniger, 2023). Energy systems around the world will rapidly transition towards renewable energy sources. These ambitions combined with the natural gas supply problems due to the closure of the Groningen gas field and imposed sanctions on Russia following its invasion of Ukraine make this transition even more urgent (Cheng, 2023). The national government of the Netherlands has additionally committed itself to climate neutrality by 2050 and a 55% reduction of CO_2 relative to 1990 by 2030 according to Art. 2 of the Climate act (Klimaatwet, 2023). This follows on the 2019 Urgenda case which stipulated that the Netherlands should omit 25% less CO_2 compared to 1990 by 2020, a goal the Netherlands achieved in 2020 and 2022 but not in 2021 (Centraal Bureau voor de Statistiek, 2024; Hoge Raad der Nederlanden, 2019).

The Dutch energy system is as of 2022 still dependent on fossil fuels, with 47,5% of the energy mix for electricity and warmth production consisting of natural gas and around 9,2% being produced by coal (Centraal Bureau voor de Statistiek, 2023a). Nevertheless, renewables are on the rise, with solar energy taking up a share of 10,4% while wind energy takes up 13% (Centraal Bureau voor de Statistiek, 2023a). As the Dutch electricity demand is projected to increase due to rising population and increased electricity usage for transport, heating, and industry (Tennet, 2024a). Because of this rise in electricity usage, the current infrastructure is at its limit in many places around the Netherlands, prohibiting companies and soon housing from receiving electricity (NOS Nieuws, 2023). These infrastructural problems concerning storage and congestion can prove detrimental to the ambitions to increase adoption of renewable energy sources. For the near future for instance, it is projected to become difficult to connect large scale energy suppliers such as a nuclear power plant to the electricity grid by 2035 (Tennet, 2024b).

The government aims that the backbone of the future Dutch electricity grid will be formed by offshore wind energy (Ministerie van Economische Zaken en Klimaat and Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2024). A major problem associated with renewable energy sources is their intermittent nature. This intermittency prohibits renewables on their own to provide energy on demand, negatively affecting the stability and reliability of these energy sources (Aneke and Wang, 2016). To ensure the ability of the energy network to match energy supply and demand, it is critical to develop storage solutions that can store surplus energy when it is available and provide it when it is necessary (Olabi and Abdelkareem, 2021).

1.1.1 Molecular storage: why ammonia matters

The energy transition is currently hampered by a two-pronged problem: it is firstly challenged by the lack of electricity infrastructure, and it secondly suffers a problem with intermittency and storage. These problems, especially the storage issue, stem from the fundamental nature of electricity. Electricity is non-tangible, it cannot be touched, it does not have volume nor mass and it cannot be stored in itself. To store electricity, we need to make it tangible again by converting it to other forms of energy. A way to make electricity tangible is to use it to power chemical reactions to produce molecules that can be used for energy later on. As it is not reliant on the grid for transport and can be stored as it is tangible, chemical energy storage can be the two-pronged solution to boost the energy transition.

Although they were not fabricated by humankind to store electrical energy, the fossil fuels we use today can also be considered as molecular energy. Fossil fuels in essence store the kinetic (pressure) and thermal (geothermic heat) energy summoned upon them for millions of years in the earth's crust. Since the industrial revolution, civilization has relied on this molecular energy and its exploitation. In the last 2 centuries, molecular fuels have entrenched themselves into our infrastructure, institutions, and culture. As such, the transition towards renewables cannot be seen as *just* a transition from fossil fuels to renewables, but also as a transition from molecules to electrons. It can be argued that the transition to the generation of renewable energy is further along than the transition towards electrons, with the progress in the first being hampered by the lack thereof in the second. Ultimately, to solve this roadblock, green chemical energy carriers are needed as these can be seen as the bridge between the electrical future and the molecular present.

The most well-known chemical energy carrier is hydrogen (H_2), which is an abundant and carbon-free molecule which can simply be produced by the electrolysis of water. Hydrogen does however have some problems regarding its extreme storage conditions, which makes its carriers promising alternatives as well. One of these hydrogen carriers is ammonia (NH_3), which has more permissive storage conditions than hydrogen while retaining the carbon-free nature.

1.1.2 Ammonia for Tata steel

Like the rest of civilization, industry has since the industrial revolution relied on the use of fossil fuels to power their processes. As the era of fossil fuels is closing, we need to adapt our industries to an electron-based system. An example of this is for instance the largest Dutch industrial CO_2 emitter Tata steel (Nederlandse Emissieautoriteit, 2022). This steel plant is at this point in time still reliant on fossil fuels such as natural gas and especially coal. With it being a steel plant, thereby needing some form of reductors that turn iron ore into iron, it cannot just switch to electricity, especially combined with the pressure that already exists on the electricity grid. This is where the bridging role of ammonia comes in, as it could allow fossil fuel-based infrastructure to function in a renewable energy-based world. Because of this promising and important role for ammonia, this research aims to examine and understand the role that ammonia can take in the energy transition for Dutch industry, using the case of Tata steel in particular.

1.2 Relevance for spatial planning science and practice

Studying ammonia's role and potential in the energy transition through the lens of spatial planning fills an important knowledge gap. This is because there is currently little published research about the feasibility of ammonia for industry or energy through a spatial perspective, instead focusing on the techno-economical aspects instead as is revealed by Google Scholar searches[1]. Nevertheless, the conclusions of a literature review by Salmon et al. (2021) underline the need for a more holistic research approach on ammonia as an energy carrier and to both focus on the spatial and institutional factors. With the impacts that the energy transition can have on the spatial fabric of the Netherlands, combined with the institutional groundwork needed for the new energy system, research from the planning perspective is justified and essential.

Although energy carriers might seem unrelated or at least far away from the field of planning, choices we make here can have grave consequences on how the environment, landscape, and institutional fabric will take shape. The spatial implications of ammonia as a green energy carrier can be explained quite clearly. As an example, the technology to produce it needs to be situated somewhere, the power that powers the reaction needs to come from somewhere and it needs to be shipped to us and stored in infrastructure that is placed somewhere. Understanding the institutional side of ammonia as an energy carrier might be a bit more difficult, however. A well-known definition of institutions is that they "are the rules of the game in society" (North, 1990, p. 3). With this definition, laws and regulations can for instance be quite clearly interpreted as institutions. These impact energy carriers as because it is subject to external safety regulations, either for toxic or explosive risk for ammonia and hydrogen respectively, meaning that a lot of land-uses are prohibited in the vicinity of it. A lot of existing institutions are not necessarily devised with ammonia as an energy carrier in mind, which might lead to difficulties. This impact on our surroundings and institutions are key to understand the relevance of this thesis as it can help with reducing fossil fuel reliance.

With this in mind, it is key to identify what spatial planning entails. Spatial planning can be defined as the intervention in the spatial order, both via physical (constructing a pipeline) or institutional avenues (making a zoning plan) (Voogd, 2004). It also includes the systematic preparatory process for the creation and execution of spatial policy (Voogd, 2004). The ultimate objective of spatial planning is the preservation and, if possible, enhancement of the daily environment and societal well-being (de Roo and

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[1] Search terms that were used: 'ammonia', 'energy storage', 'ammonia economy', 'ammonia infrastructure', 'ammonia power', 'hydrogen carrier' & 'ammonia fuel'

Voogd, 2024; Voogd, 2004). In this light, a systematic preparatory study into ammonia can provide valuable planning insights, both for scientific discourse and planning practice. Although switching to ammonia might not be directly visible in the environment, it serves to (1) preserve the stability of the energy grid, which benefits well-being and (2) reduce fossil fuel usage, enhancing environmental quality on both a local and a global scale. Based on these benefits, a systematic preparatory study into the implementation of ammonia for Dutch industry is warranted. The results of this study can provide various valuable lessons for planning as a science and policy advice for planning as a practice.

Up until recently, the role of green ammonia in the energy transition was considered to fill a niche mostly specific to its role in industrial processes. Currently, the role of ammonia as an energy storage medium is also being considered, attracting more scientific attention (Heijnen and Jetten, 2023). This study aims to expand on the technical feasibility studies by viewing ammonia through a spatial planning perspective. By employing such a perspective, the knowledge on the spatial dimension of ammonia in the energy transition will be expanded. The context of the Netherlands is relevant as it is a densely populated and advanced country meaning that strict standards must be reached on the field of external safety, which is particularly important due to the toxic nature of ammonia. The Netherlands is also an interesting area of research as it is an important trading nation with good access to major industrial areas in Europe and Europe's largest port in Rotterdam. Lastly, The Netherlands is due to its density and flatness uniquely ill-equipped to use other more established modes of energy storage such as pumped hydroelectric storage. Researching the feasibility of ammonia in the Netherlands can internationally also be applicable for other flat and densely populated nations.

1.3 Research aims and questions.

With it being a thesis for the MSc Environmental & Infrastructure planning, this study will use a spatial planning perspective, focusing also on the spatial and institutional aspects rather than being a pure techno-economic feasibility analysis. The aim of this research is to find out how ammonia can be understood within the energy transition in the Netherlands, especially for industry. Therefore, the main question is:

“How can the role of ammonia be understood in the energy transition for Dutch industry and the energy system as a whole?”

To support this main question, the following sub-questions are proposed:

- Is the use of ammonia for industry technically feasible?
- Is the use of ammonia for industry economically feasible?
- Does ammonia fit within the Dutch spatial fabric?
- Can the regime accommodate a transition to ammonia?
- In what time frame can ammonia be a solution?
- Does ammonia have advantages over hydrogen?

1.4 Structure

This concludes the introductory first section in which the background and relevance have been outlines. In the following second section, a literature review aims to investigate and examine the theory surrounding energy carriers, ammonia, and transitions, concluding with a conceptual framework for the following sections. In the third section, the approach and methods of this study will be presented and defended. This is followed by the fourth section, which aims to identify generic or context-independent findings about the actual feasibility of ammonia and its potential usage. This knowledge is then built upon by employing a specific case study for the context-dependent factors that could not be answered in the generic empirical analysis. This case study will focus on Tata steel and aims to identify the challenges and opportunities for ammonia from the specific view of this case. In the fifth section, the research questions will be answered using the findings and policy advice will be proposed. The thesis concludes with the sixth section in which the findings will be discussed, and I will reflect on the thesis process.

2 Literature review & theoretical framework

Ammonia is potentially able to play a crucial bridging role in the energy transition and the changing nature of energy in itself. To further define this role, an understanding of ammonia and its alternatives, particularly chemical-based ones such as hydrogen, is vital. Besides this, transition theory is used in this study as a framework to examine the role and potential of ammonia in the energy transition, as well as serving as a base for the empirical analysis. This literature review aims to develop a perspective on where in the transition the ammonia niche is located and what that entails for its prospects. The combination of the research on ammonia and transition theory can yield some rudimentary insights into the answers to the research questions. Additionally, at the conclusion of this section, a conceptual framework that will shape the empirical portion of this thesis is presented which aims to guide the empirical evidence towards answering the research question.

2.1 Ammonia & Hydrogen

To understand the ammonia economy, an insight on hydrogen (H_2) is crucial. Hydrogen is widely researched as a carbon-free energy carrier for the energy transition to cope with the storage and transport problem (Arsad et al., 2023). Compared to ammonia, it is a more mature technology for energy storage, with hydrogen trains already existing for instance (Alstom, 2021). The technology to produce hydrogen from fossil fuels is already mature and water splitting technology is rapidly advancing. Although it has great potential to help ease and speed up the energy transition, particularly for industry, hydrogen has a few key issues. It needs to be stored under extreme conditions, making storage over large periods of time and transport quite difficult. This is ultimately where ammonia enters the discussion as it has less extreme storage and transport conditions while retaining a few key benefits of hydrogen.

2.1.1 The advantages of ammonia

Ammonia (NH_3) is a widely manufactured chemical compound with an established market ever since the invention of the Haber-Bosch process in 1909 (MacFarlane et al., 2020). Today, ammonia knows many uses, it for instance serves as a feedstock for nitrogen in industrial processes, primarily in the manufacture of fertilizers (MacFarlane et al., 2020). Ammonia consists of 1 nitrogen atom bound to 3 hydrogen atoms. Because of this, ammonia is widely considered as a suitable hydrogen carrier or as a fuel (MacFarlane, 2023; Machaj et al., 2022). Like hydrogen, it is a carbon-free storage medium, and it is a mature and well-established technology as well, arguably even more so than hydrogen. Because ammonia is a carbon-free compound, it has the benefit of not emitting CO_2 when combusted or decomposed into hydrogen. Ammonia is one of the most manufactured chemicals in the world and boasts a mature industry, infrastructure, and supply chain already, with shipping and storage technology and knowledge already widespread. In the United States, NuStar runs a 3200-kilometrelong pipeline network transporting 1,5 million tons of ammonia per year (NuStar, 2021). Over water, ammonia can already be shipped by LPG tankers which is well-established technology at this point. Besides this, it can use existing propane infrastructure as well (Shiozawa, 2015)

Compared to liquified hydrogen (LH_2), ammonia has less extreme storage conditions as it stays liquid at much higher temperatures than hydrogen, with boiling points of 33˚C and -253˚C respectively. Besides this, ammonia can be liquidized at a much lower pressure than LH_2 (Ishimoto et al., 2020; Meng et al., 2024). In particular, the higher boiling point makes ammonia less costly to store and makes it suffer from less boiloff than LH_2, which makes it particularly suitable for long-term storage across seasons as shown in Figure 1 (Wijayanta et al., 2019).

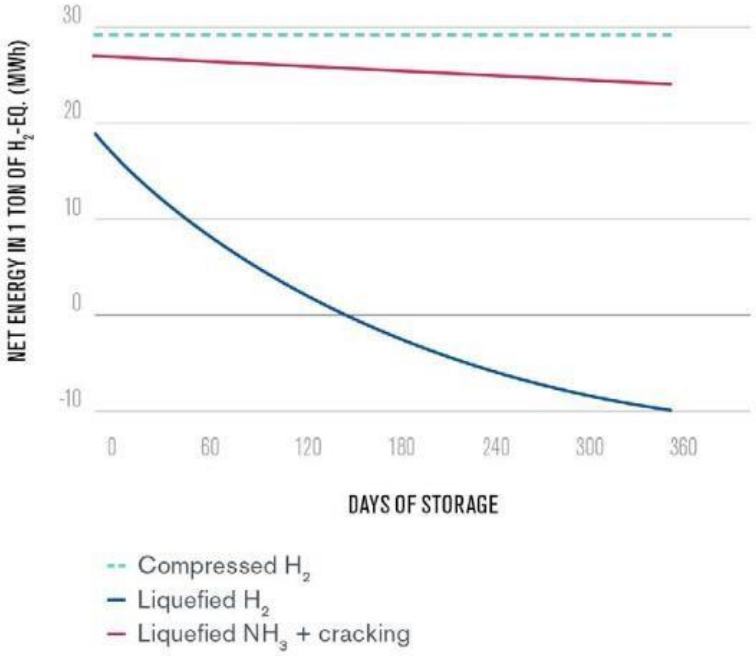

Figure 1: Net remaining energy of hydrogen and ammonia storage over time (Serpell et al., 2023, p. 4)

Another option for the storage of hydrogen is to compress it instead of liquifying it. Compressed hydrogen solves the boil-off problem as it does not need cooling (Serpell et al., 2023). Compressed hydrogen does however need storage vessels that can withstand high pressure, making it relatively heavy and difficult to scale (Otto et al., 2022; Serpell et al., 2023). Additionally, compressed hydrogen has lower energy densities compared to ammonia and LH_2, particularly when the weight of the storage vessels is considered as well (Otto et al., 2022).

Liquid organic hydrogen carriers (LOHC's) have also been researched to carry hydrogen. The first problem with LOHC's is that they are ultimately still carbon-based (Oner and Khalilpour, 2022). Secondly, ammonia boasts a higher efficiency than LOHC's, especially if cracking can be bypassed (Wijayanta et al., 2019). Ammonia also boasts a higher volumetric and gravimetric hydrogen, and therefore energy density than most LOHC's, with only methanol being comparable in this regard, as is shown in Figure 2, which explains the carrying capacity of hydrogen carriers in volumetric density (how much hydrogen this carrier can fit within a liter) and gravimetric density (how much of a kilo of the carrier consists of hydrogen) (Oner and Khalilpour, 2022).

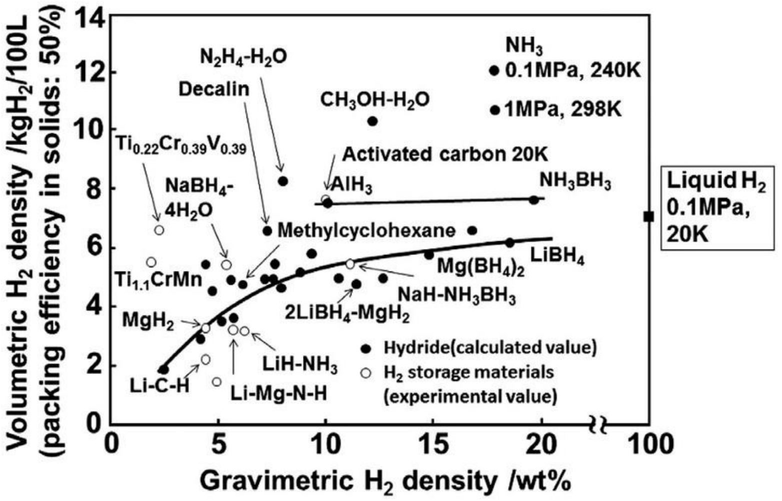

Figure 2: Hydrogen carriers by density (Kojima, 2017; Valera-Medina et al., 2018)

Hydrogen, ammonia and LOHC's all fall under the category of chemical energy storage, which entails that these are "technologies where the electrical energy is used to produce chemical compounds which can be stored and used when needed for energy generation." (Aneke and Wang, 2016, p. 17). According to Figure 3, chemical energy storage is an appropriate solution for large scale and long-term energy storage, which is applicable to industry. Nevertheless, there are some alternatives that are comparable in storage time and scale. First of these are the mechanical solutions, of which pumped hydro and compressed air are most relevant for large scale and long term storage (Aneke and Wang, 2016). The chemical energy media can both be converted back to electricity in gas turbines or fuel cells as well as used directly (Valera-Medina et al., 2015; Zamfirescu and Dincer, 2009). These technologies use electric energy to either pump water into a reservoir or to compress air into a vessel, which can be used for energy generation at release using a hydroelectric dam and a dynamo respectively (Aneke and Wang, 2016). Although mechanical storage, particularly pumped hydro, are well proven, there are some problems associated with them. Firstly, pumped hydro has many spatial constraints, with it needing sufficiently hilly terrain and a lot of space, although underground construction is promising (Gono et al., 2015). On the other hand, compressed air energy storage is more practical in a flat country like the Netherlands. Nevertheless, it boasts a low efficiency and a lack of energy density, which makes it still quite space-intensive (Wang et al., 2017). The other main avenue for longer-term storage is batteries, which rely on electrochemical processes. An advantage of batteries is that they are relatively efficient (around 60 to 80% energy retention) with shorter storage durations such as a day-night cycle (Aneke and Wang, 2016). A disadvantage of batteries is their reliance on rare earth materials such as lithium and nickel (Aneke and Wang, 2016). Because of this, batteries are mainly interesting for smaller scale applications such as individual homes or other small energy users.

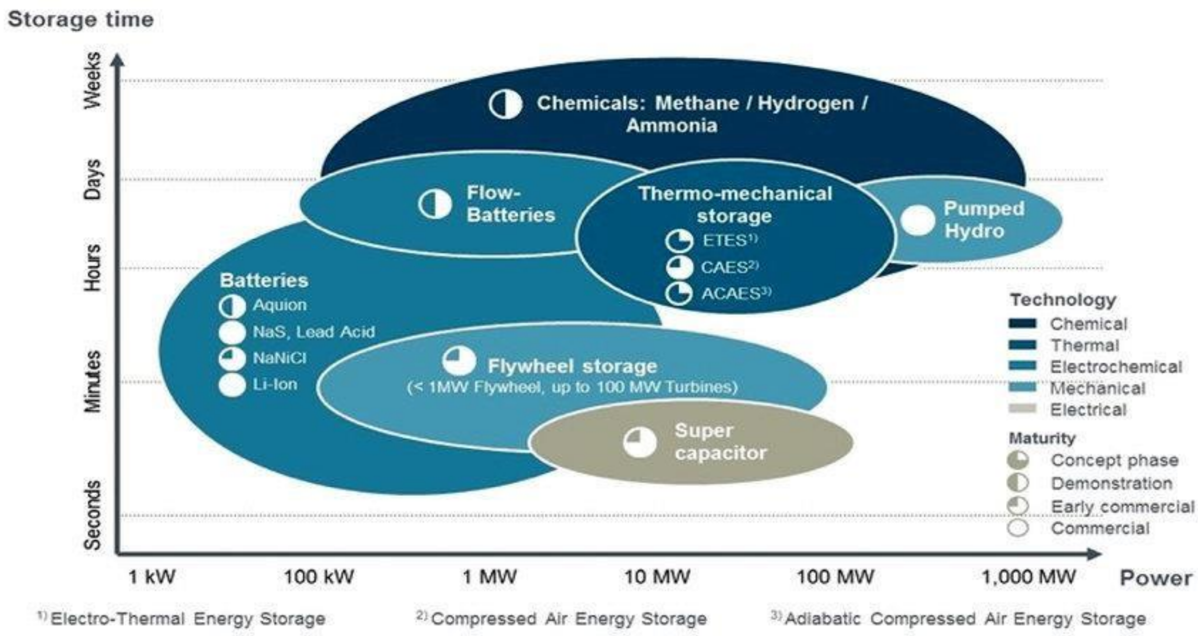

Figure 3: Comparison between different storage technologies (Valera-Medina et al., 2018, p. 68; Wilkinson, 2017)

2.1.2 The path to green ammonia

To reduce fossil fuels, green ammonia can be a good alternative molecular fuel. Because ammonia itself is currently produced using fossil fuels, it is key to understand the insights surrounding green, carbon-free ammonia as ammonia produced by fossil fuels will not be beneficial for the energy transition. Ammonia is currently still produced by the Haber-Bosch process which is conducted under high heat ranging from 300˚C to 500˚C and pressure 200 bar to 350 bar (Hasan et al., 2021). The Haber-Bosch process is shown below:

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad (1)$$

This process is currently based on fossil fuels, with the hydrogen being sourced from natural gas using steam methane reforming (Hasan et al., 2021). The three-step process of steam methane reforming is shown below:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad (2)$$

$$4CH_4 + O_2 + 2H_2O \rightarrow 10H_2 + 4CO \quad (3)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad (4)$$

Although the fossil fuel based H-B process is proven and reliable, the CO_2 emissions are high, with this process being responsible for around 1,2% of global CO2 emissions in itself (Hasan et al., 2021; Morlanés et al., 2021). Because of this, there is a lot to be gained from a carbon-neutral ammonia synthesis process. Thanks to its reliance on fossil fuels, Ishaq and Crawford (2024) have coined this as the ‘grey’ method of producing ammonia.

Due to the large amount of emitted CO_2, there is interest in developing ammonia synthesis processes that are more sustainable. MacFarlane et al. (2020) proposes three overlapping generations of green ammonia production which is shown in Figure 4.

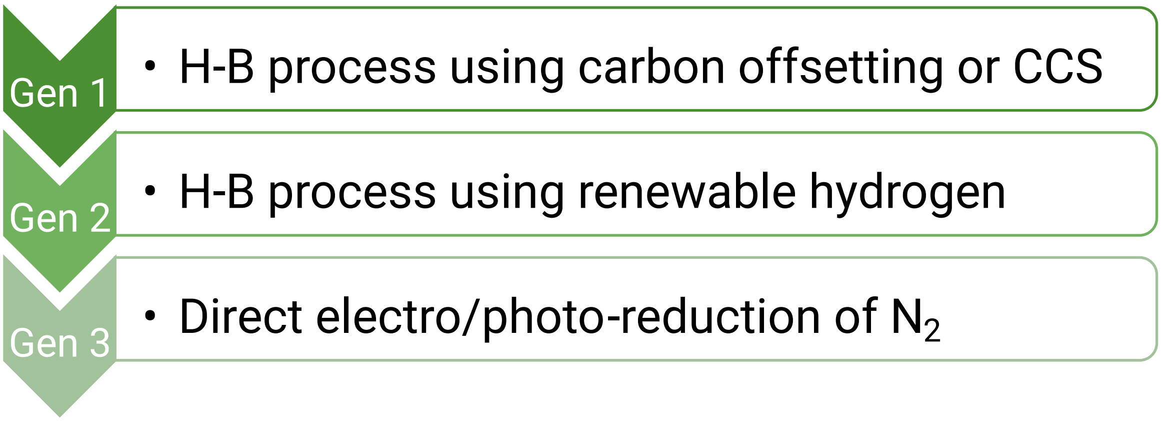

Figure 4: 3 generations of ammonia synthesis (Based on MacFarlane et al., 2020)

The first generation of carbon neutral ammonia is still produced using the 'grey' Haber-Bosch process, emitting loads of CO_2 in the process (Ishaq and Crawford, 2024). The difference is that this generation of ammonia production aims to limit the net CO_2 output by using offsetting or carbon capture and storage on the CO_2 emitted during the process (MacFarlane et al., 2020). Although blue ammonia has less emissions than grey ammonia, it cannot be considered truly green as it would be far from carbon-free (Howarth and Jacobson, 2021). Due to this, combined with the rapid advancements in electrolysis technology, the first generation of cleaner ammonia can already be considered as obsolete. Howarth and Jacobson (2021, p. 1685) even went as far as to state that they "see no advantage in using blue hydrogen powered by natural gas compared with simply using the natural gas directly for heat" as well as suggesting that "blue hydrogen is best viewed as a distraction, something than may delay needed action to truly decarbonize the global energy economy".

The second generation of ammonia omits the steam methane reforming, instead sourcing its hydrogen from renewable-driven water splitting which makes this process entirely carbon-free (El-Adawy et al., 2024; Ishaq and Crawford, 2024; MacFarlane et al., 2020). Because it is carbon-free, it is labelled as green ammonia, requiring no fossil fuels (Dawood et al., 2020; Ishaq and Crawford, 2024). Water splitting relies on energy to split water into hydrogen and oxygen, shown in the reaction below (Zainal et al., 2024):

$$2H_2O \rightarrow 2H_2 + O_2 \qquad (5)$$

According to Zainal et al. (2024) the energy for this water splitting process can be sourced by either electricity (electrolysis), heat (thermolysis) or light (photolysis). Electrolysis is the most widely known water splitting process which relies on a negatively charged electrode (cathode) and a positively charged electrode (anode), this process can be done on conventional electrolysers as well as on fuel cells functioning reversely (Zainal et al., 2024). The main drawback of electrolysis is its high production cost due to low efficiency (Mazloomi and Gomes, 2012). This can be mitigated however by lower energy prices associated with renewable energy (Zhang et al., 2020). Additionally, due to advancements in technology, the electrolysis process is becoming increasingly more efficient (Arsad et al., 2023). Thermolysis can be a possible alternative to electrolysis to split water. Thermolysis uses heat energy instead of electricity which could allow it to use residual heat, nuclear power, or solar thermal energy (Safari and Dincer, 2020). Nevertheless, thermolysis suffers from a few problems such as the high required heat, with 2500˚C being necessary without reductors and still necessitating 500˚C using the least heat-intensive reductor (Safari and Dincer, 2020; Zainal et al., 2024). This far, thermolysis is some way short of being competitive, although it could prove somewhat useful for utilizing residual heat, even though it could be utilized as well by fuel cell electrolysis (MacFarlane et al., 2020; Safari and Dincer, 2020; Zainal et al., 2024). Lastly, photolysis is a water splitting technology relying on solar light energy and a photocatalyst (Singla et al., 2024; Sun et al., 2019). Photolysis is particularly promising as it would enable the direct manufacturing of hydrogen from the sun, bypassing the need for solar electricity electrolysis and thereby increasing efficiency (Singla et al., 2024). Like thermolysis however, this water splitting technology is still some way from being technologically mature which means it will only start to play a role on a later term (Dawood et al., 2020).

The third generation of ammonia manufacturing uses direct reduction rather than the Haber-Bosch process. Directly reduced ammonia is instead manufactured from water and air, bypassing the need for separate hydrogen and therefore skipping the SMR or water splitting processes (MacFarlane et al., 2020). As the Haber-Bosch process necessitates extreme conditions, switching to direct reduction is also beneficial for ease of production (Zhao et al., 2021) Like for water splitting, there are multiple possible sources of energy for this direct reduction process (MacFarlane et al., 2020). First among these is the electrocatalysis process, which relies on a catalyst and electricity as an energy source to create ammonia from hydrogen and nitrogen (Sahoo et al., 2020). Alternative energy sources have also been studied for direct ammonia reduction such as light in the case of photocatalysis (Hasan et al., 2021; MacFarlane et al., 2020).

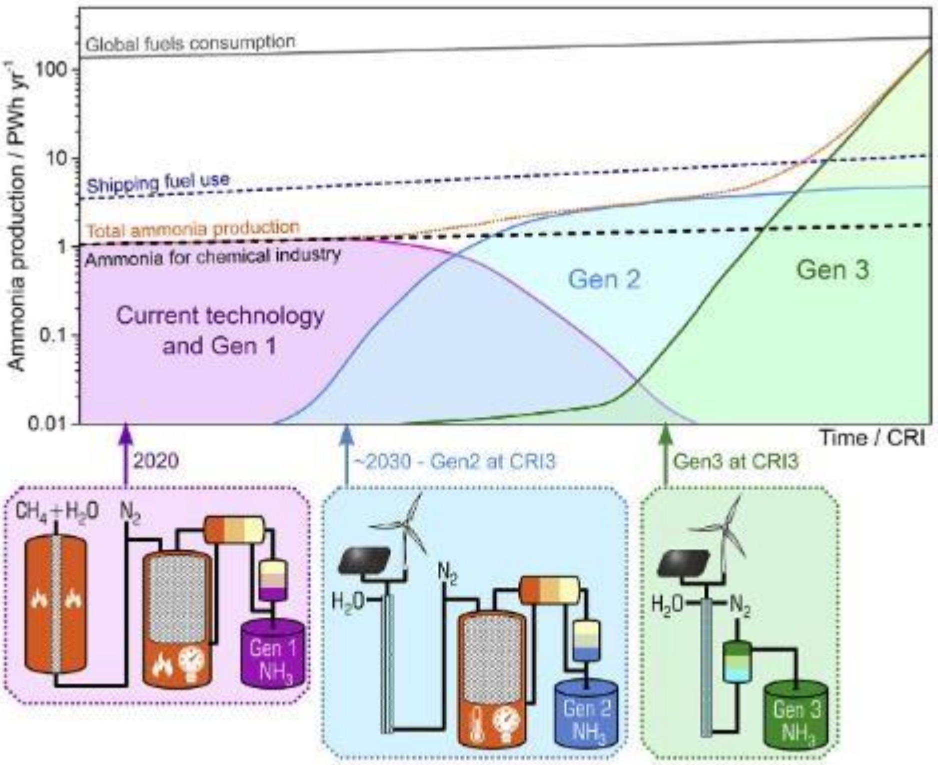

Figure 5: Ammonia Economy Roadmap Showing Current and Projected Contributions of the Current and Gen 1 (purple), Gen 2 (light blue), and Gen 3 (green) Ammonia Production Technologies (MacFarlane et al., 2020, p. 1201)

According to MacFarlane et al. (2020), we are currently in a first generation system, with second generation ammonia reaching a commercial readiness index (CRI) of 3 around 2030 and third generation being further in the future, as show in Figure 5. The CRI is an index that examines the readiness of a renewable technology to compete on the market (ARENA, 2014). A CRI of 3 means that a technology is ready to be deployed competitively on a commercial scale, as shown in Figure 6 (ARENA, 2014). The CRI serves as a commercial advancement on the Technological Readiness Level (TRL), that focuses solely on the technological side (ARENA, 2014).

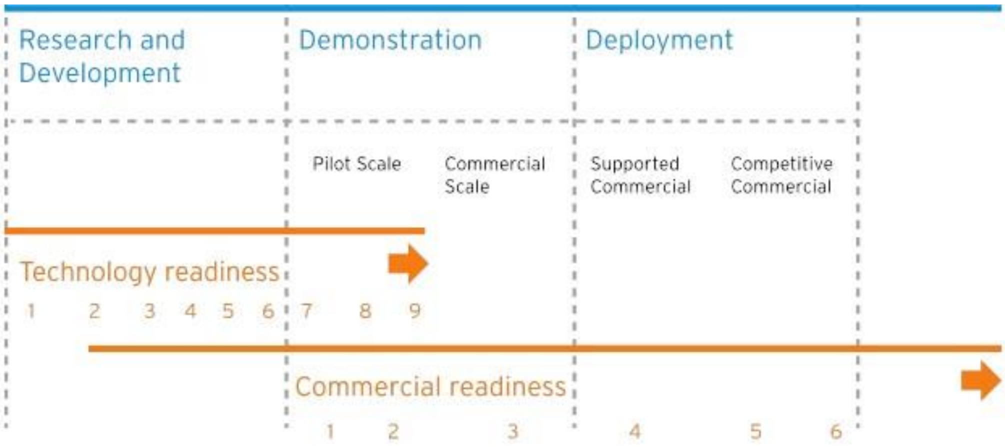

Figure 6: TRL and CRI mapped on the technology development chain (ARENA, 2014, p. 3)

2.2 Transition(s)

A grasp of transition theory is essential for understanding the inner workings of the energy transition. This knowledge is crucial because it aids the planning process by examining the role of ammonia within the transition, thereby informing policy decisions. By understanding the relationship between the ammonia niche and the broader regime, planners can better develop policy to manage the adoption of ammonia, which is in line with the definition of spatial planning laid out by Voogd, (2004).

A transition can be described as the movement from an existing equilibrium to a new equilibrium within a system (Rotmans et al., 2001). Considering this, the switch from fossil fuels to renewables can also be seen as a transition. Transitions can roughly be split up into four phases, those being the pre-development phase, take-off phase, acceleration phase and a stabilization phase (Hebinck et al., 2022; Rotmans et al., 2001). These phases can best be explained by using the metaphor of dominoes:

1. **Pre-development:** Picking up dominoes from a pile and arranging them.
2. **Take-off:** Tipping over the first domino, setting the transition in movement.
3. **Acceleration:** The dominoes are being tipped over by the previous one and tip over the next ones, setting a chain-reaction in motion.
4. **Stabilization:** All dominoes are tipped over and a new pile has formed.

Using this knowledge, it can be argued that the energy transition is, in the case of the Netherlands, currently in the acceleration phase, with changes happening quickly and renewables taking up a larger share of the energy supply (Lindberg and Kammermann, 2021). This can be backed up by the fact that renewables have increased their share in the total Dutch energy supply from 4,66% in 2012 to 14,97% in 2022 (Centraal Bureau voor de Statistiek, 2023b)

Although the energy transition has thus far been described as a single transition, it can be seen as a set of changes across four different energy regimes, with fossil fuels being switched out for renewables as energy source for electricity, transport, heating and industry (Bakhuis et al., 2023). Within these four sub-transitions, there is a difference in how far along they are within their respective transitional processes, as well as in which form these transitions take place.

Within the multi-level perspective on transition theory, a transition can be understood as a process that takes shape across three levels: the landscape, the regime, and the niche(Geels, 2002; Kanger, 2021). The landscape can be defined as the overarching context in which a transition takes place, these can both be slow and gradual changes as well as sudden shifts (Geels, 2002; Geels and Schot, 2007; Kanger, 2021). A shifting landscape changes the playing field which threatens the stability of the current regime and pressures it to change and innovate or to be replaced by a new regime altogether (Geels and Schot, 2007). Within the frame of this research, several landscape pressures can be identified, among which the most notable are the climate crisis, the war in Ukraine, and the stress on the energy grid. In the most simple terms, the regime can be seen as the current status quo, it consists of all the established rules and norms that shape the current system (Geels, 2004, 2002; Sorrell, 2018). Subsequently, niches can be described as novel and unproven technologies that can potentially cause important changes to the current system in the future (Geels, 2004, 2002; Schot and Geels, 2008).

In the context of the energy transition, ammonia can be seen as a niche which challenges the current fossil fuel regime, similar to hydrogen (Bakhuis et al., 2023). Although the entire energy transition is an exceptionally large and complex ‘transition of transitions’ that warrants extensive research, it is outside of the scope of this study. Using the dominoes metaphor again, we can see ammonia (or a comparable energy carrier) as a crucial domino that will decide if the further stones will fall over or not (Kovač et al., 2021). Without a proper way to store and transport renewable energy, the transition will stagnate, and the Netherlands will remain dependent on fossil fuels. Although hydrogen and ammonia can both play a crucial role in the different subtransitions they should not be seen as a singular solution to the roadblock in the energy transition. While this research focuses on ammonia, it should not be considered as a ‘silver bullet.’

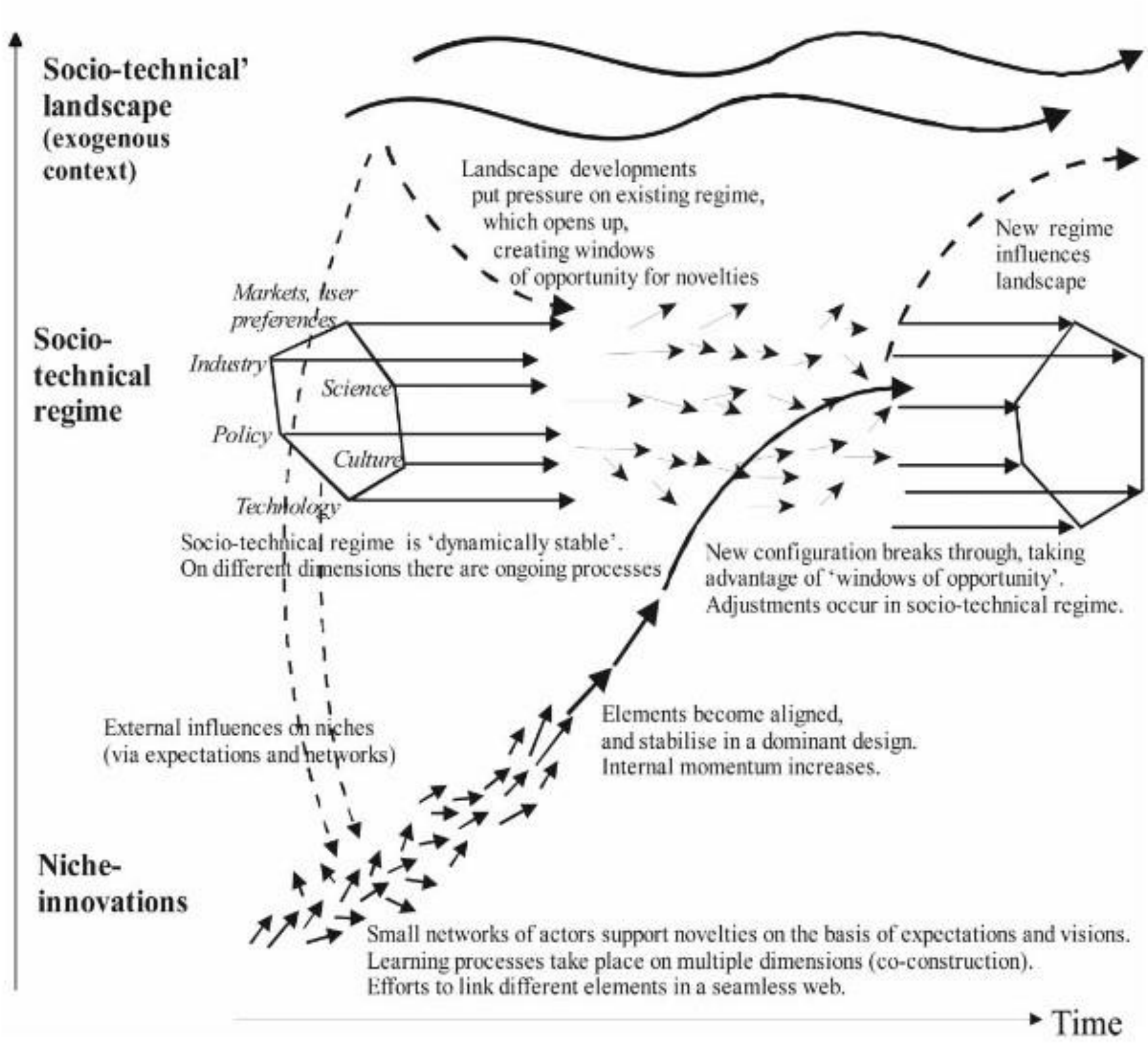

Figure 7 Multilevel perspective on transitions (Schot and Geels, 2008, p. 546)

Figure 7 is a visual representation of the multilevel perspective, in the case of this study, the existing regime is shaken up by landscape developments like climate change and the war in Ukraine. These landscape pressures open a window of opportunity for different niche innovations like ammonia to be adopted into an adjusted regime as the status quo is stirred up (Hebinck et al., 2022). In this perspective, a constraining factor can be seen as a hurdle to the adoption of a niche, in this case the ammonia niche (Polzin, 2017). In contrast, an enabling factor can be seen as a factor that encourages the adoption of a niche. In this case, something like an uncertain legal framework serves as a constraining factor while decreasing stability of the energy supply serves as an enabling factor for the adoption of ammonia.

2.3 The energy regime

The fossil-based energy regime is currently dominant in four main energy areas. These areas are industry, heating, transport and electricity specifically (Bakhuis et al., 2023). In the current situation, fossil fuels are used extensively across the industrial sector, mostly for heating or as a feedstock in chemical processes. In the Netherlands, there are a few large industries that are still heavily dependent on fossil fuels for this reason, notably the steel and petrochemical industries. A second use for fossil fuels is the heating sector, mainly using natural gas due to the historic abundance of it in the Netherlands. Additionally, fossil fuels in the form of petrol, diesel, kerosene, or marine fuels are used for transport. Lastly, coal and gas-powered electricity plants still form a large part of the Dutch electricity supply. Nevertheless, the increasing share of renewables in the electricity sector has spearheaded an increasing tide of electrification across the other three sectors. The energy transition will therefore alter our relationship with energy drastically.

One of the main changes will be the economics associated with the energy system. One of the main advantages of fossil fuels is the fact that these energy sources can be exploited on-demand, you can extract gas when demand is high and stop extracting it when it is not needed. The fact that fossil fuel is an energy source and carrier at the same time makes it possible to create a demand-led energy system in which the supply is adjusted according to the demand for energy. Transitioning to renewables will also mean that the energy system becomes more supply-led, in which demand must adjust to the available supply of energy. This can already be seen in practice as flexible energy usage is increasingly rewarded (Veeger, 2024). Another consequence of the energy transition is more spatial in nature. Due to their small footprint and small yield, the energy system will be more dispersed and decentralized than it is currently. Instead of having a few enormous power plants distributing electricity to consumers across the country, we are moving towards a system wherein people have their own solar panels or small windmills, meaning that the consumer becomes a producer as well.

The combination of a supply-led energy system, the dispersed and decentralized nature of renewables and the increased drive towards electrification means that electricity infrastructure is under great stress as it now must cope with both sharply increasing electricity demand and the shift from a centralized one-way energy system to a decentralized two-way system. The manager of the Dutch national energy grid is Tennet, which is a state-owned company. On the other hand, the move away from fossil fuels means that natural gas usage for the electricity, industrial, and heating sector will decrease. This means that the gas infrastructure might become unused and obsolete when fossil fuels are phased out. The management of the gas grid is the responsibility of Gasunie, which is like Tennet, a state-owned company. By law, both Tennet and Gasunie are prohibited to deviate from their core task of managing their respective grids to protect fair competition (*Elektriciteitswet*, 2024; *Gaswet*, 2024). This means that neither party is allowed to store and sell electricity.

In its core, the regime aims to remain stable and dominant (Hebinck et al., 2022). The stability of regimes (for example the fossil fuel regime) can be pressured from both the landscape level (climate change) as well as from the niche level (more efficient renewable energy sources), which is also reflected in Figure 7 (Dzebo and Nykvist, 2017; Schot and Geels, 2008). Because it is inherently retentionist in nature, the regime will hinder the ascension of niche innovations. To assess the feasibility of ammonia, it is crucial to understand how pressures from the regime and landscape either enable or constrain the adoption of the ammonia niche. This involves analyzing the broader socio-technical environment and its impact on ammonia integration. Identifying the constraining and enabling factors in the regime-niche relation is key in managing the energy transition and can help with developing valuable policy.

2.4 Ammonia in the transition

As stated before, ammonia should not be considered as a 'silver bullet' that will solve the energy transition outright, it can however play a valuable role in solving some of the problems associated with this transition. This research focuses on industry, with a case study on the Dutch Tata steel plant in Ijmuiden. This specific focus is because niches need to be developed before they can be adopted by the regime (Schot and Geels, 2008). To develop the ammonia niche, experimentation within the industry sector can provide important lessons that can be used to develop the ammonia niche and help it to achieve wider adoption for the other energy areas such as transportation and heating.

Industry is especially promising as it from less constraining factors than the other energy areas, while still providing a large impact in CO_2 reduction relative to the amount of infrastructure that is needed. The first enabling factor is that major industrial emitters in the Netherlands are relatively concentrated in a few areas like Moerdijk, Chemelot and the port of Rotterdam. Secondly, these locations have good access to potential ammonia infrastructure as they are either situated near ports such as Rotterdam, Moerdijk and Ijmuiden or along existing pipeline corridors towards the Ruhr area like Chemelot (PPS Pipelines, 2018). The locations for industry are also relatively far away from large population clusters which minimizes the impact of an ammonia release. Lastly, ammonia is especially promising for industrial use as it is an important feedstock for other processes and requires less adaptation for natural gas-based systems compared to electricity.

2.5 Conceptual model

Figure 8 summarizes the findings of the theoretical framework into a conceptual model. It proposes that the role of ammonia for industry in the Netherlands depends on the three main factors of feasibility, competitiveness among alternatives and the timeframe. In turn, the feasibility can roughly be split between technological, economic and spatial factors impacting it.

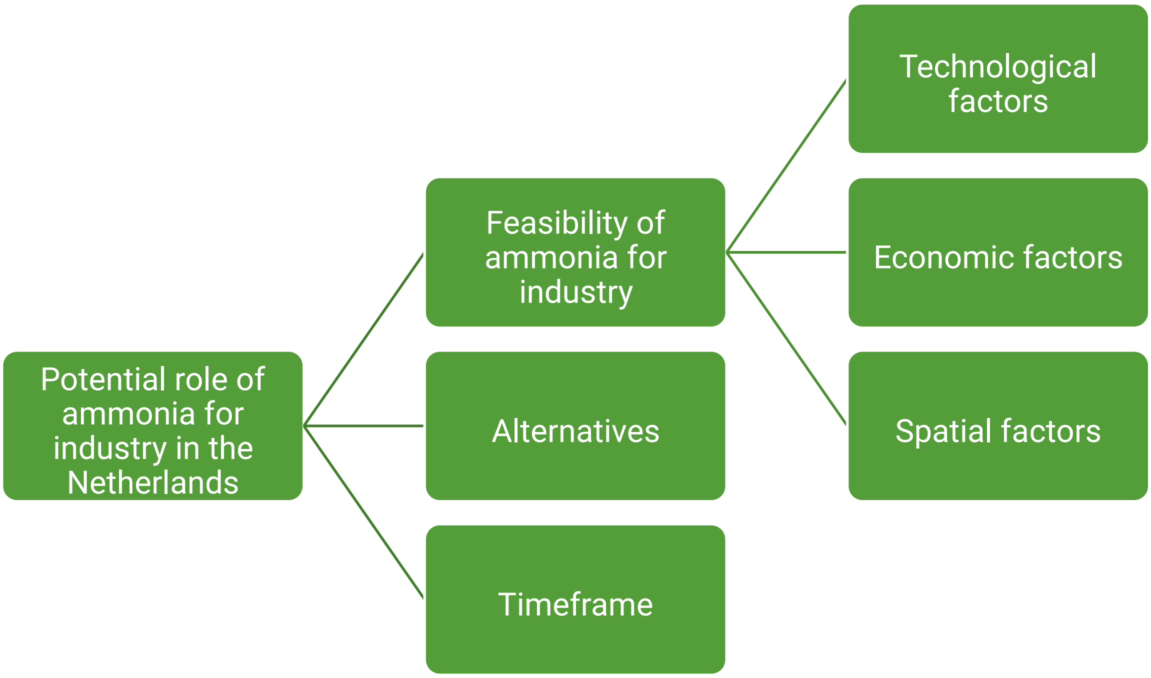

Figure 8 Conceptual model (Author, 2024)

3 Methodology

This section of the study is dedicated to discussing the research methods utilized for this thesis. It begins by presenting and justifying the chosen research approach. Furthermore, it explores the rationale behind integrating an empirical analysis with a specific case study centered on the Tata Steel plant in IJmuiden. Lastly, the section concludes with an examination of the limitations associated with the selected research methodology.

3.1 Research approach

This study is structured around an initial examination of the technological feasibility of ammonia, followed by a detailed exploration of its economic and spatial viability within the Dutch industry. This sequential approach prioritizes the investigation into whether ammonia can be practically implemented before delving into its broader economic and spatial impacts. By establishing this order of research, the study aims to effectively allocate resources, ensuring that efforts are concentrated on viable options and alternatives if ammonia proves technologically impossible or prohibitively expensive compared to other options available within the foreseeable future.

To answer the research question "How can we understand the role of ammonia in the energy transition for Dutch industry?" a qualitative research approach is utilized. Qualitative research can most easily be described as what it is not, being the antithesis of quantitative research. Quantitative research aims to reach conclusions by using standardization, generalization and the use of objective measurement, with a focus on statistics, numbers and experiments (Hammersley, 2013). Hammersley (2013, p. 12) then goes on to define qualitative research as: "a form of social inquiry that tends to adopt a flexible and data-driven research design, to use relatively unstructured data, to emphasize the essential role of subjectivity in the research process, to study a small number of naturally occurring cases in detail, and to use verbal rather than statistical forms of analysis." Although some numerical data is used in this thesis, it still classifies as a qualitative study using this definition because it focuses on the study of a hypothetical but nevertheless real-world implementation of a general concept in which context is a deciding factor (Hammersley, 2013). Additionally, the nature of the research question itself, which can be framed as a niche-regime interaction within a transition, is downright impossible to quantify.

To answer the research question, an empirical analysis has been conducted, which is split between a generic empirical analysis and a more specific case study on Tata steel. Combining these two approaches can help with drawing lessons and conclusions for the general application for industry while combining it with a more detailed look at the barriers on a context-dependent level.

3.1.1 Empirical analysis

The generic part of this study is focused on the general technical barriers of ammonia and its potential uses. This is done by an analysis of empirical evidence. According to Costa (2024), empirical evidence can be defined as “information gathered directly or indirectly through observation or experimentation that may be used to confirm or disconfirm a scientific theory or to help justify, or establish as reasonable, a person’s belief in a given proposition.” Since the collection of first-hand experimental data was unfeasible for this study, the empirical analysis relied on the examination of existing literature. This approach ensured that the study was grounded in established research and findings, enabling a comprehensive understanding of the subject despite the lack of new experimental data.

The method of conducting a general empirical analysis of ammonia's feasibility for industry was chosen because it aligns better with the research question's broader framework. Focusing solely on a case study, such as Tata Steel, might result in conclusions applicable only to steel plants, of which there are none else in the Netherlands. To ensure the findings are relevant to various industrial applications, in accordance with the original research question, the technical feasibility of ammonia was studied independently of the Tata Steel case. This approach allows for broader applicability and more comprehensive insights into ammonia's potential industrial uses.

3.1.2 Case study

The specific part of this study focuses on the economic and spatial aspects and the feasibility of ammonia. This will be conducted using a case study approach, as context is crucial in understanding these dimensions. Crowe et al. (2011, p. 1) define the case study as “a research approach that is used to generate an in-depth, multi-faceted understanding of a complex issue in its real-life context.” The real-life context advantages of a case study offer significant benefits over the more general empirical analysis proposed for the industrial aspects. By focusing on a specific case, a clear and direct understanding of the economic and spatial factors is achieved, allowing for the examination of a single supply chain and specific spatial issues unique to a particular context. In contrast, a general study would yield broader conclusions that may offer limited insights for practical planning. This targeted approach enhances the ability to draw meaningful lessons and apply them effectively in planning practice.

For this study, a single case study is chosen on the case of Tata steel. Tata steel is a steel manufacturer in the Dutch port town of IJmuiden and is the most prominent CO_2 emitter in the Netherlands (Nederlandse Emissieautoriteit, 2022). With plans already established to switch to hydrogen, an alternative future scenario for a switch to ammonia has been laid out and studied to compare with hydrogen (Roland Berger, 2021). The case of Tata steel will be described further in section 5.

3.2 Case description

To examine the viability for ammonia in Dutch industry, the case of Tata steel has been chosen. Situated in the Dutch province of Noord-Holland, about 23 km northwest of Amsterdam, the plant is located to the west of the town of Velsen and to the north of the port town of IJmuiden, separated by the Noordzeekanaal (North sea canal) as is shown by Figure 10. In recent years, outrage has been mounting over the negative climate, health, and environmental impacts of the steel plant (Jak, 2024; Kraan, 2024). With the climate crisis becoming more acute by the year, a solution is necessary for the most polluting plant in the Netherlands (Nederlandse Emissieautoriteit, 2022). A report on the future of Tata steel outlined 5 scenarios, which paint a picture that Tata steel needs to adapt or to be left behind, as the authors suggest that a transition to green energy is necessary for the plant to remain operational on the long term thanks to the EU-ETS (Wijers and Blom, 2024). Although it might be easier to just close the facility, there are merits to keeping it open for the sake of jobs, strategic autonomy, or the fear that Tata steel will just produce more environmentally harmful steel elsewhere. Therefore, this study assumes that there is the will to keep Tata steel in the Netherlands. Tata itself has plans to switch to 50% HyDR by 2030 and 80% around 2040 (Roland Berger, 2021; Wijers and Blom, 2024). Although Tata steel is aiming to decarbonize by using hydrogen, there is a window of opportunity opening for ammonia. Ma et al. (2023) established that ammonia is suitable for the reduction of steel within the established HyDR process, which makes it an excellent energy carrier to reduce the climate impact of Tata steel.

Figure 10: Location of Tata steel in the Netherlands (Author, 2024)

In this case study, three economical scenarios are laid out for the steel plant, with these being a 100% ammonia scenario, a 100% liquid hydrogen scenario, and the fossil-fuel scenario. In their respective scenarios, ammonia and hydrogen are utilized as energy carriers by carrying renewable energy from Morocco to the port of IJmuiden. Using the Global Wind Atlas, developed by the Technical University of Denmark, an area in front of the Moroccan coast between Essaouira and Agadir with high wind speed potential has been identified, which is shown in Figure 11.

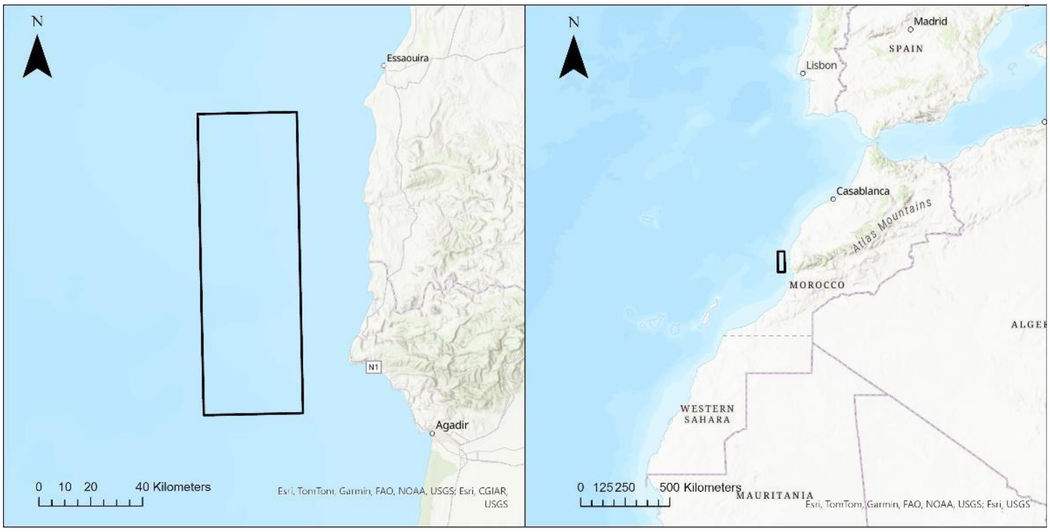

Figure 11: Proposed wind area in Morocco (Author, 2024)

The ammonia or hydrogen will be produced at sea and shipped to IJmuiden, which is a route that is around 1630 nautical miles or 3020 kilometers when using the port of Agadir as reference (VesselFinder, 2024). Assuming the ship travels at an average speed of 12 knots, the journey will take 5 days and 16 hours (VesselFinder, 2024). In their study on transport costs of hydrogen carriers from Africa to Europe, Agyekum et al. (2023) found that transporting 1 kilogram of hydrogen in ammonia form costs €0,18 while 1 kilogram of hydrogen in liquid form costs €0,44. These costs are based on a shipping route from Agadir in Morocco, which is the same origin port as the case study, to Blexen, which is located in the Niedersachsen region of Germany. Although Blexen is somewhat further than IJmuiden, the difference in distance is small enough that no modifications on this data were deemed necessary as it might cause overcorrection and reduce accuracy. Another important note is that they assume ship sizes of 160.000 m^3 for both ammonia and liquid hydrogen, LPG carriers for ammonia usually have half the size and large hydrogen tankers have not been into production yet (Agyekum et al., 2023; Kawasaki Heavy Industries, 2022; Riviera News, 2024). Once ashore, the ammonia will be stored in a 80.000 m^3 storage tank, which is similar to a tank that OCI plans to construct in the port of Rotterdam (Antea Group, 2022). As this case assumes 100% reliability on the energy carriers, the carriers will be consumed within a matter of 12 days. In this case study, a boil-off rate of 0,3% per day is considered, which is in line with Yang and Ogden (2007). If we consider this 0,3% boiloff rate for 12 days, the cumulative boil-off of hydrogen will be roughly 4% of the total supply during this time span, which will add to its cost. For both ammonia and hydrogen, the current energy cost for manufacturing is used to avoid discrepancies in the projections (one study projecting a cost for 2030 while another study projecting it for 2040). This is justified as the energy cost of green ammonia is tied strongly to that of electrolysis, meaning that the comparison will stay roughly equal if the efficiency of electrolysis increases (Giddey et al., 2017).

3.3 Data collection

There are three main sources of data being used to answer the research question: scientific literature; models, calculations and projections; and legal and policy documents. This variety of sources has been used as it allows for a complete view across the technical, economical, and spatial factors.

In this study, the general findings are mostly represented by the scientific literature. The existing scientific literature on ammonia as an energy carrier is mostly exploratory in nature, with technical and economical options and outlooks of this subject being widely researched. This scientific literature is mostly used in this study to examine and define the opportunities for ammonia in a technical sense. Additionally, the scientific literature can provide valuable economical metrics for the case study. Besides this, it is also expected that the scientific literature can help establish a time frame in which the expected technical and economic advancements for ammonia will take place. To summarize, the scientific literature will be used to (partially) answer the research questions on technical and economic feasibility as well as those on the timeframe and its comparability to hydrogen.

The second category of sources concerns the more quantitative data obtained from models, calculations, and projections. These sources pertain to the more case-focused part in the economical analysis as the scientific literature is too general to provide case-specific findings on the economical feasibility and competitiveness of ammonia. This ultimately helps to answer the research questions on economic feasibility and the comparison to hydrogen.

The last group of sources consists of policy documents, legal documents, business strategies, and news sources. This group of sources can be designated as “grey literature”. Grey literature can be defined as “publicly available, foreign or domestic, open source information that is usually available only through special channels and may not enter normal channels or systems of publication, distribution, bibliographic control, or acquisition by book sellers or subscription agents.” (Benzies et al., 2006, p. 56; U.S. Interagency Grey Literature Working Group, 1995). This grey literature is important as it allows for the study of context-specific factors, such as the legal regulations or the existing business strategy. The grey literature will be used to answer the research questions on the spatial feasibility of ammonia as well as the ability of ammonia to fit in the current regime.

3.3.1 Limitations and ethical considerations

Yin (2018) mentions that case studies should ideally use at least two different information sources, as it can help with backing up the validity of findings. Nevertheless, this case study is heavily reliant on documentation sources, under which both the scientific and grey literature fall, with some archival records in the form of models and geographical data being used (Yin, 2018). This reliance on documentation stems from the preparatory nature of this study, with the study being conducted before actual changes start to be made. Therefore, there is no real possibility to use interview or participation sources as there are currently no projects being conducted or finished in this niche.

As this study will not primarily rely on interviews or participatory observations, there are no concerns surrounding the protection, consent, and use of sensitive personal data. Another important consideration is personal bias from the researcher which can lead to (sub)conscious misinterpretation and misrepresentation of findings based on personal preconceptions or ideals (Yin, 2018). For this study it is therefore important to report the full scope of the truth and to not just selectively use evidence that fits with a certain narrative. Similar to this, a conflict of interest can also lead to a biased and distorted view of the truth to align with personal interests. Ultimately, no conflict of interest can be identified as neither the author nor people close to the author are major stakeholders within the ammonia economy. Additionally, this study subject was selected based on genuine interest and curiosity and not to support or undermine a specific narrative.

3.4 Data analysis

The study method is based on a PESTEL analysis framework which serves as a systematic approach to analyze enabling and constraining factors for ammonia in Dutch industry. The PESTEL analysis method originally stems from management and researches the political, economic, social, technological, environmental, and legal factors surrounding a project (Kokkinos and Nathanail, 2023). Kokkinos and Nathanail (2023, p. 8) state that the goal of a PESTEL-analysis is to: "[identify] and [analyze] important external elements to develop a strategic plan". This fits well within the frame of spatial planning as defined by Voogd (2004), which aims to conduct a systematic preparatory process for the creation and execution of spatial policy. Linking back to transition theory, the PESTEL analysis can be seen as a systematic way to identify the factors within the current regime that either hinder the wider adoption of the ammonia niche or that provide a benefit to its adoption, also explained as the constraining and enabling factors respectively. As this is a thesis written from an infrastructure planning perspective, the political, social, environmental, and legal factors of the original PESTEL will be grouped in a single 'spatial' category. When rearranging the factors based on the sequence of this thesis, the TES analysis framework forms. Grouping the factors together in the spatial category has two main benefits. It firstly limits the scope of this research, meaning that more detailed insight can be gained into the spatial feasibility of ammonia, fitting with the infrastructure planning background of this thesis. Secondly, grouping those factors together leads to a more integrated and holistic view compared to studying these factors individually. This integration is important as this is a project in which a lot of factors are intertwined. An example of this could for instance be appeals from worried citizens against a permit, which can both be interpreted as a legal and as a social factor. The factors of the TES-analysis will be explained below:

- **Technological:** Green ammonia is a rapidly developing field with significant innovation. However, it is crucial to assess whether it can be effectively utilized in (the steel) industry, identify the specific roles it could play, and determine the timeline for its potential implementation. If green ammonia is found to be unfeasible for industrial use in the foreseeable future, further research on the subject would lack merit. Early assessment of its feasibility ensures efficient resource allocation and directs attention to more promising alternatives, preventing unnecessary expenses on impractical solutions.

- **Economic:** The economic considerations for Tata Steel are crucial, as high costs could render its operations unviable. This analysis focuses on comparing green ammonia and green hydrogen to the current fossil fuelbased system. Key factors in this comparison include production costs, electricity expenses, and transportation costs. By evaluating these elements, the study aims to identify the most cost-effective and sustainable energy option for Tata Steel. Understanding these economic aspects will help determine whether transitioning to green energy sources is feasible and advantageous for Tata Steel's future operations and which green energy carrier to use ensuring both environmental sustainability and economic viability.

- **Spatial:** The spatial factor aims to determine whether ammonia production for Tata Steel can be integrated into the Netherlands, considering both physical and institutional aspects. This involves investigating barriers imposed by the current regulatory framework, including the new environmental act. Additionally, the study will examine specific spatial requirements, such as the land needed for wind farms and the impact of electrolysis on water supply. The goal is to assess if ammonia can be accommodated within existing institutions and physical spaces to ensure feasibility and compliance with regulatory standards.

The TES-analysis methodology can be seen as a way to examine the constraining and enabling factors provided by the current regime. In Figure 7, the regime is displayed as the combination of the industrial, economic, cultural, political, and scientific status quo (Schot and Geels, 2008). These regime factors are clearly linked to the PESTEL-factors and thereby also the TES-factors. Therefore, the TES-analysis serves as a systematic method to analyze the regime-niche relation for ammonia.

4 Results

In this section, the findings from the research will be laid out according to the three TES-factors.

4.1 Technical factors

The chemical formula for ammonia is NH_3 which classifies it as a carbon-free fuel. The lack of carbon makes ammonia stand out from other chemical hydrogen carriers such as toluene (C_7H_8), naphthalene ($C_{10}H_8$), or methane (CH_4) (Oner and Khalilpour, 2022). Carbon-based fuels emit CO_2, an important greenhouse gas, as well as soot, which is on a local level detrimental to air quality in the form of $PM_{2,5}$ (Awad et al., 2023). Another benefit of the carbon-free nature of ammonia is that it is theoretically possible to manufacture without using fossil fuels and relying on electricity and hydrogen instead (Hasan et al., 2021). The fact that ammonia is a carbon-free hydrogen carrier gives it a unique advantage in terms of emissions.

Another benefit of ammonia is its high carrying capacity of both hydrogen and therefore energy among hydrogen carriers. Ammonia (121kg/m^3) contains 1,7 times as much hydrogen than an equivalent amount of liquid hydrogen (70,8kg/m^3) and 2,6 times as much as liquid organic hydrogen carriers (47,3kg/m^3) (Kojima, 2024). This higher hydrogen carrying capacity naturally gives it an advantage in volumetric energy density as well, with ammonia outscoring methane, liquid hydrogen and compressed hydrogen in this regard, as well as electrical and kinetic energy storage media (Otto et al., 2022). This higher volumetric density ensures that ammonia requires less space to store and transport large amounts of energy compared to other modes.

A drawback of liquid hydrogen is that it needs to be stored at extreme temperatures and pressures that make it difficult to work with. Hydrogen must be cooled below 250˚C to liquify under atmospheric pressure which is energy-intensive and difficult to maintain in transport (Ishimoto et al., 2020; Meng et al., 2024). Ammonia on the other hand is able to liquify when pressurized to at least 1,1 MPa at room temperature or when cooled to -33˚C at atmospheric pressure (Lhuillier et al., 2019; Meng et al., 2024; Saraçoğlu, 2022). Compared to liquid hydrogen, liquid ammonia can be stored under less extreme conditions which eases transport and storage.

Although chemical energy storage media, among which ammonia, suffer from boil-off, they provide relatively long storage time compared to other energy storage media (Otto et al., 2022; Serpell et al., 2023; Valera-Medina et al., 2018). Although batteries and thermal solutions can prove useful in mitigating intermittency across a few hours or days, such as the day-night cycle, they discharge too fast to store energy reliably across longer periods of time, making them impractical for mitigating intermittency across seasons (Otto et al., 2022; Valera-Medina et al., 2018). On the other hand, ammonia can be stored across longer periods of time with comparably small losses due to boil-off (Otto et al., 2022; Serpell et al., 2023; Valera-Medina et al., 2018). Due to its low energy discharge, ammonia is well-suited to store energy for longer periods of time, allowing the stockpiling of energy for periods of energy scarcity.

Ammonia consists of hydrogen and nitrogen which are both resources that can be found virtually anywhere and are among the most abundant elements on earth. Due to this abundance of resources ammonia can be produced around the world, especially when using a green manufacturing process. This contrasts with batteries which rely on rare metals such as nickel and lithium, which are both finite resources.

	SCENARIO 1	SCENARIO 2	SCENARIO 3	SCENARIO 4	SCENARIO 5
PRODUCTION 1	Electrolysis	Electrolysis	Electrolysis	Electrolysis	Electrolysis
PRODUCTION 2		Haber-Bosch	Haber-Bosch		
STORAGE AND TRANSPORT	Compression	Liquefaction (7 days)	Liquefaction (182 days)	Liquefaction (7 days)	Liquefaction (182 days)
CONVERSION		Cracking	Cracking		
MWH REQUIRED PER T-H_2	39.7–52.7	63.7–78.3	65.1–79.75	50.5–63.5	73.5–86.5
OVERALL RETURN ON ENERGY INVESTMENT	63–84%	42.5– 52.3%	41.8–51%	52.5–66%	38.5%–45%

Table 2: Return on energy investment for five storage pathways (Serpell et al., 2023, p.6)

4.1.1 Ammonia production

An important problem with ammonia is its low efficiency, which can be attributed to the electrolysis and the subsequent Haber-Bosch process on the production side and the cracking on the consumption side (Serpell et al., 2023). In Table 2 the energy usage and efficiency of ammonia is compared with compressed and liquified hydrogen, which clearly illustrates the relative inefficiency compared to hydrogen, especially on the shorter term. An important remark concerning these numbers is that ammonia does not necessitate cracking back to hydrogen for its usage in the direct reduction of steel and possibly industry in general, raising its efficiency somewhat higher than portrayed in Table 2 (Ma et al., 2023). According to MacFarlane et al. (2020), the HaberBosch process is expected to remain in place until novel third generation technologies are ready for commercial exploitation. The implication of this is that increasing efficiency of ammonia is reliant on advancements in the electrolysis of hydrogen. Currently, hydrogen electrolysis is comparatively expensive, although the price could fall due to increasing competition, advancements in technology and support from governments (Zainal et al., 2024). Terlouw et al. (2022) state that electrolysis costs are mainly dependent on the cost of electricity as well as the electrolysers themselves. Nevertheless, the price of green hydrogen is expected to drop substantially with the US aiming to reduce the price of hydrogen to $1 per kg by 2030 according to Zainal et al. (2024) and with Terlouw et al. (2022) projecting the price to reach €2 per kg in 2040.

4.1.2 Safety of ammonia

A drawback of ammonia compared to its alternatives is its high toxicity, which can be a major barrier to its adoption. As can be seen in Table 3, ammonia is a substance with multiple safety hazards for health and environment. Even though it is seen as a flammable gas by the European Union, it is far less flammable than other fuels as shown in Table 4. The NFPA flammability score of 1 means that ammonia will only ignite when preheating has occurred which makes it a lot less flammable than the alternative fuels with a NFPA score of 3, meaning that it can be ignited at normal temperatures, or a score of 4, meaning that it is extremely flammable and volatile (Duijm et al., 2005; McKinnon and Tower, 1976). The main safety concern with ammonia therefore lies in its effects on health rather than its flammability, with ammonia scoring a much higher NFPA score on health hazard than other fuels (Duijm et al., 2005; McKinnon and Tower, 1976). Ammonia will in low concentrations (25 – 134 ppm) irritate the respiratory system, and can lead to pulmonary oedema and eventually death with high concentrations (500> ppm) (PGS, 2014). Besides the respiratory danger, ammonia is also dangerous in contact with the skin. Ammonia gas in high concentrations in the air can cause blistering and burns, liquid ammonia will also lead to ice burns due to its low temperature.

HAZARD CLASS	HAZARD CODES	TEXT
Flam. Gas 2	H221	Flammable gas
Press. Gas	-	-
Acute Tox. 3	H331	Toxic if inhaled
Skin Corr. 1B	H314	Causes severe skin burns and eye damage
Aquatic Acute 1	H400	Very toxic to aquatic life

Table 3: Safety concerns of ammonia (European Parliament and Council of the European Union, 2008, tbl. 1.1, 1.2, 1.3, 3.1)

SUBSTANCE	HEALTH	FLAMMABILITY	REACTIVITY
AMMONIA	3	1	0
NATURAL GAS	1	4	0
METHANE	1	4	0
HYDROGEN	0	4	0
LPG (PROPANE & BUTANE)	1	4	0
METHANOL	1	3	0
PETROL (92 OCTANE)	1	3	0

Table 4: Ratings according the NFPA no. 704 ranging from 0 (not hazardous) to 4 (extremely hazardous) (Duijm et al., 2005, app. A, p.4; McKinnon and Tower, 1976)

4.1.3 Ammonia and the environment

Ammonia is a carbon-free fuel and therefore it should not emit CO_2 when used. Nevertheless, ammonia can lead to other emissions, notably NO_x, N_2O, and unburned ammonia (Jayabal, 2024; Valera-Medina et al., 2024). NO_x is a group term for nitric oxide (NO) and nitrogen dioxide (NO_2) because NO turns to NO_2 when in the air (WHO, 2021, 2006). NO_x is harmful to human health as it affects the respiratory system, worsening conditions for people who suffer from illnesses such as asthma and COPD

(WHO, 2006). Additionally it is, according to the WHO (2006), an important component of smog and is integral to the formation of both particulate matter and ozone, which both have negative effects on overall health as well. Another important emission that can occur from ammonia is nitrous oxide (N_2O), which is a highly potent greenhouse gas (GHG). According to Jayabal (2024), N_2O can be up to 300 times more strong as a GHG than CO_2. Additionally, N_2O serves as a major ozone depleting substance, with it being classified as the principal threat to the ozone layer during this century (Ravishankara et al., 2009). Lastly, unburned ammonia can also be a health threat, as underlined in the previous paragraph on the safety of ammonia. Besides its irritating effect on the respiratory system, ammonia is also a threat to the environment. Ammonia is a main part of nitrogen deposition and eutrophication, which is an important threat to biodiversity, especially for the already vulnerable nature in the Netherlands (Verweij et al., 2023).

Another environmental challenge for ammonia is its heavy use of drinking water due to the electrolysis process which is especially concerning as many areas with high potential for renewable energy such as Morocco or Australia are very arid (Mohammed-Ibrahim and Moussab, 2020). To reduce freshwater usage and allow offshore operations, it is important that a viable technology to electrolyze seawater is found. Unfortunately, d'Amore-Domenech et al. (2020) state that no seawater electrolysis method has reached commercial viability yet. Nevertheless, there has been a demonstration that large-scale seawater electrolysis is possible, which is promising for offshore wind farms (Liu et al., 2024).

4.1.4 Uses of ammonia

Although it is mostly studied as a hydrogen carrier, ammonia is also usable on its own for various applications. Existing gas turbine plants can be converted to ammonia power with comparably minor modifications, making this a feasible option for decarbonizing energy production (Pashchenko, 2024). Ammonia combustion, however, is inherently slow and inefficient compared to traditional fossil fuels (Pashchenko, 2024; Valera-Medina et al., 2015). To mitigate these issues, ammonia can be blended with other fuels to aid combustion (Valera-Medina et al., 2015). Hydrogen could be a promising blend fuel for ammonia as it, in contrast to ammonia, ignites easily. Additionally, blending ammonia with hydrogen has the benefit of retaining the carbon-free nature of ammonia, which would not be the case with methane or other hydrocarbon blend fuels. Besides the carbon-free nature of this blend, it also helps to reduce the NO_x emissions normally associated with ammonia combustion (Pashchenko, 2024; Valera-Medina et al., 2015). The ease of usability of ammonia in gas turbines is a large benefit as gas turbines are currently widely operated using fossil fuels which can allow an emission reduction without necessitating completely new infrastructure.

Besides this, ammonia can prove effective to reduce CO_2 emissions in industrial furnaces, either purely or co-fired with coal. Valera-Medina et al. (2024, p. 1603) define a furnace as an “enclosed structure for intense heating by fire” and underline its importance by stating that furnaces are “the basic building block of industrialized societies, with the main objective of reaching higher processing temperatures than those obtainable in open fires.” Because of the importance and prevalence of furnaces, an easy solution to reduce CO_2 without drastically modifying existing installations is needed which is where ammonia comes in. The substitution of a part of coal in furnaces with ammonia, or co-firing, is found to decrease a significant amount of CO_2 emissions which provides a way to quickly reduce CO_2 emissions without radical infrastructure change (Valera-Medina et al., 2024). Additionally, pure ammonia-fired furnaces are also promising for various industries, with a Chinese tile manufacturer successfully fabricating tiles using an ammonia powered kiln, which was previously used for natural gas (Ecological China Network, 2022; Valera-Medina et al., 2024). A major challenge associated with using ammonia as a fuel for furnaces is the emission of NO_x, which are harmful pollutants contributing to air quality degradation and respiratory issues (The State of Queensland, 2023; Valera-Medina et al., 2024). To reduce these new emissions of NO_x, more research and technologies are required according to Valera-Medina et al. (2024). Despite these challenges, (partially) replacing coal with ammonia for the use of furnaces could be a valuable avenue for the reduction of CO_2 emissions by industrial actors.

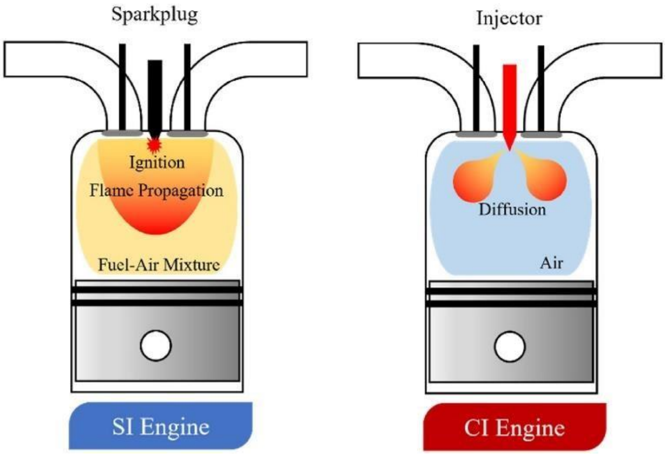

Figure 9: Comparison SI and CI engines (Adapted from Riyadi et al., 2023, p. 8)

Internal combustion engines are widely used across the world for transportation (cars) and power generation (generators), which makes the utilization of ammonia promising for this area. Ammonia to power internal combustion engines has been a field of research since the middle of the 20th century, with Koch (1945) and Starkman et al. (1967) already looking at it’s potential to power internal combustion engines. A benefit of ammonia over hydrogen and electricity for the use of internal combustion engines is that the infrastructure needed is comparable to that of propane and LPG (Kobayashi et al., 2019). This similarity to LPG enables it to be usable for LPG tanking stations quickly and for it to be transported using LPG ships (Kobayashi et al., 2019; Machaj et al., 2022). A drawback of using ammonia is again its difficulty combusting compared to more volatile fossil fuels or hydrogen, which is a similar problem to its adoption in gas turbines (El-Adawy et al., 2024; Pashchenko, 2024; Valera-Medina et al., 2015). The solution to this problem in ICE's is like the solution in this problem for gas turbines, with ammonia blends boasting more favorable combustion characteristics. For most main applications, there are two kinds of internal combustion engine shown in Figure 9. For spark ignition engines, which function by pulling in an air-fuel mixture, compressing it and igniting it with a spark to move the piston, El-Adawy et al. (2024) state that a blend of ammonia and hydrogen can alleviate the combustion issues of pure ammonia in spark ignition engines. For compression ignition engines, which compress air to high pressure and heat and subsequently injecting fuel which ignites from the heat of the compressed air to move the piston, ammonia is a potential green fuel as well, with a dual-fuel using ammonia and (bio)diesel being able to reduce CO_2 output considerably (El-Adawy et al., 2024; Jayabal, 2024). Ammonia, especially in blended form is a viable alternative fuel, both in technical and economic sense (ElAdawy et al., 2024; Zamfirescu and Dincer, 2009). Although ammonia is a CO_2 free fuel, it suffers from different emission problems, with the emissions of N_2O and unburned ammonia being the most problematic, as N_2O is a potent GHG with 300 times the impact of CO_2, while unburned ammonia can be detrimental for health and environment (Jayabal, 2024).

An alternative way to use ammonia for transport is to utilize fuel cells, which have lower emissions of NO_x and unburned ammonia compared to ICE's (Micoli et al., 2024). The main point against fuel cell technology is that it is a technology that is still in development and will not play a role in the immediate future. There are many types of fuel cell that can potentially be used to convert ammonia to power, of which Jeerh et al. (2021) single out SOFC's as the most promising technology. According to Wojcik et al. (2003), ammonia can be used directly in SOFC's without any cracking beforehand. This is because SOFC's operate at high temperatures, which in turn cracks the ammonia to hydrogen within the SOFC itself (Wojcik et al., 2003). At lower operating temperatures, the efficiency and stability of ammonia fuel cells decrease, leading to performance issues, which is especially a problem for other types of fuel cells (Jeerh et al., 2021). Nevertheless, ammonia usage in fuel cells are a promising way to use ammonia without suffering from the combustion and emission issues that gas turbines, furnaces, and ICE's do (Micoli et al., 2024).

A study by Ma et al. (2023) shows that ammonia can be used to reduce iron ore, which can help with reducing CO_2 emissions as well. Currently, the steel industry is mainly reliant on coal to reduce iron oxides from the ore to actually usable iron, which makes it a major polluting industry that is in itself responsible for around 7% of global CO_2 emissions (Ma et al., 2023). Hydrogen-based direct reduction is currently the most promising alternative to the current coal-based process, with it already being demonstrated to work on an industrial scale (International Energy Agency, 2020; Ma et al., 2023). With the transport and storage issues of hydrogen, ammonia could be a valuable alternative, with Ma et al. (2023) proving that ammonia can be used instead of hydrogen without sacrificing on efficiency or necessitating new technologies as it can be cracked directly in the reduction reaction due to the high temperatures, similarly to SOFC's. These findings allow ammonia to make direct reduction a more economically feasible alternative to the current coal-based technologies due to its comparative ease of transport.

USE	REMARKS	REFERENCES
Gas turbines	• Existing gas turbine plants can be converted to ammonia power with small modifications. • Ammonia combustion is slow and inefficient. • Ammonia is best blended with other fuels to aid combustion. • An ammonia-hydrogen blend can lead to lower NO_x emissions and stable combustion	Pashchenko (2024); Valera-Medina et al. (2015)
Furnaces	• Co-firing coal with ammonia reduces CO_2 emissions. • Pure ammonia fired furnaces are applicable for ceramic production. • NO_x emissions are a large challenge	Ecological China Network (2022); Valera-Medina et al. (2024)
Internal combustion engines	• Ammonia infrastructure is like that of propane and LPG, which is already used as car fuel. • Researched for a long time. • Low performance and reliability with pure NH_3 • For spark ignition engines an NH_3 -H_2 blend is suitable • For compression ignition an NH_3(bio)diesel blend is promising • NH_3 is a viable fuel for ICE's. • NH_3 is an economical fuel. • NO_x emissions are a problem. • Unburned NH_3 is harmful	El-Adawy et al. (2024); Jayabal (2024); Kobayashi et al. (2019); Koch (1945); Starkman et al. (1967); Zamfirescu and Dincer (2009); Machaj et al. (2022)
Fuel cells	• Ammonia can be used directly for SOFC's. • Ammonia fuel cells are unstable at low temperatures. • SOFC's are the most promising. • Fuel cells have less emissions of NO_x	Jeerh et al. (2021); Micoli et al. (2024); Wojcik et al. (2003)
Steel making	• Ammonia can be used for direct reduction. • The technologies to use for this reduction are already existant. • Ammonia provides no real drawbacks to hydrogen	Ma et al. (2023)

Table 5: Literature overview of ammonia end uses (Author, 2024)

4.2 Economic factors

The economic analysis will be conducted by studying four future scenarios for Tata steel. The first scenario is based on a system in which Tata steel will rely on ammonia for both the direct reduction and its power need. The second scenario relies on ammonia for the direct reduction but uses grid electricity for its power need. The third scenario is based on hydrogen for both direct reduction and power while the fourth uses hydrogen for direct reduction and grid electricity for power.

There has been chosen for these scenarios as it enables a comparison between ammonia and hydrogen as well as examining less drastic solutions that rely partially on grid electricity. As the choice of energy carrier is highly dependent on future innovations, these scenarios do not serve as clear-cut choices, instead focusing more on broad uncertain paths that can be taken. Nevertheless, making a choice and investing in it can lead to path-dependency which can eliminate the other possible scenarios over time.

NUMBER	**SOURCE**
Green ammonia takes 10 MWh/t to produce Green hydrogen takes 45 MWh/t to produce	(Giddey et al., 2017)
Tata steel needs 380 kt H_2/y for HyDR	(Roland Berger, 2021)
Tata steel needs 5,6 TWh/y alongside it for HyDR	
Refitting the plant for hydrogen/ammonia will take at least 8 years in the most optimistic timeframe	
An area between Essaouira and Agadir provides 70 GWh/y on average for the 15 MW IEA reference turbine	(Davis et al., 2023)
The optimal wind farm power density for a 15 MW turbine is around 5 MW/km^2	(Bulder et al., 2018)
Volumetric H_2 density in ammonia is 107,7 kg/m^3	(Agyekum et al., 2023)
Volumetric H_2 density of liquid hydrogen is 71,1 kg/m^3	
Per kg hydrogen stored, ammonia costs €0,18 if shipped from Morocco	
Per kg hydrogen stored, LH_2 costs €0,44 if shipped from Morocco	
These costs are based on a 160.000 m^3 ship which will be used here as well	
Ammonia has an energy density of 4,33 MWh/m^3	(Valera-Medina et al., 2018)
Liquid hydrogen has an energy density of 2,53 MWh/m^3	
Liquid ammonia has a density of 0,677 g/ml	(Patnaik, 2003)
Green ammonia will cost around €700/t with an electricity price of €60/MWh	(Laval et al., 2020)
Hydrogen boils off at 0,3% per day so for 12 days this would be a cumulative 4%	(Yang and Ogden, 2007)
Power costs around €60/MWh in The Netherlands	(ICE Endex, 2024a)
Electrolyser prices are around €1400/kW	(Lichner, 2024)
Electrolyser lifetime is 20 years	(Knop, 2022)

Table 6: Literature overview for the economic analysis (Author, 2024)

4.2.1 Scenario 1: 100% Ammonia

The consultancy firm Roland Berger (2021) projects that Tata steel will, for a 100% DR based system, need at least 380 kilotons of hydrogen a year. Ammonia has a volumetric hydrogen density of 107,7 kg/m^3, meaning that 3.530.000 m^3 of liquid ammonia is needed to fill the annual hydrogen need of the plant (Agyekum et al., 2023; Roland Berger, 2021). Additionally, the report also states that the plant will use more than 5,6 TWh of electricity per year, which in this scenario will also be produced using ammonia (Roland Berger, 2021). At an energy density of 4,33 MWh/m^3, this provides an additional need for 1.290.000 m^3 of liquid ammonia (Valera-Medina et al., 2018). This means that a total of 4.820.000 m^3 of liquid ammonia is needed for this scenario. When using a 160.000 m^3 ship, there need to be 31 shipments of ammonia a year in this scenario. Ammonia has a density of 677 kg/m^3, which means that the ammonia needed for a year in this scenario has a mass of 3250 kilotons (Patnaik, 2003). With green ammonia currently taking 10 MWh per ton to produce, the annual electricity need to manufacture the energy carriers is 32,5 TWh (Giddey et al., 2017). Agyekum et al. (2023) estimated the shipping cost of ammonia from Agadir to Western Europe at €180 per ton of hydrogen, which would be around €96 million in total as in this scenario, ammonia is used to transport 533.000 tons of hydrogen. Electricity costs around

€60/MWh as of May 2024 (ICE Endex, 2024a). At this price point, ammonia would cost around €700 per ton (Laval et al., 2020). With the yearly need of 3250 kilotons for this scenario, the production price would amount to €2,3 billion yearly. Considering that the entire need for electricity is filled by hydrogen, the total cost of this scenario is €2,37 billion.

4.2.2 Scenario 2: Ammonia + Electricity

For this scenario, the ammonia needed for the hydrogen need from scenario 1 is used (Roland Berger, 2021). The additional 1.3 million m^3 to fill the electricity need is omitted as the plant will use power from the Dutch energy grid in this scenario (Roland Berger, 2021). This makes the total need of 3.530.000 m^3 of liquid ammonia. When using a 160.000 m^3 ship, there need to be 23 shipments of ammonia a year in this scenario. Ammonia has a density of 677 kg/m^3, which means that the total need per year in this scenario has a mass of 2390 kilotons (Patnaik, 2003). The annual electricity requirement to produce energy carriers using green ammonia, which according to Giddey et al. (2017) currently consumes 10 MWh per ton, amounts to 23,9 TWh. Agyekum et al. (2023) estimated the shipping cost of ammonia from Agadir to Western Europe at €180 per ton of hydrogen. Given that 380.000 tons of hydrogen are transported in this scenario, the total cost would be around €68 million. At a current electricity cost of around €60/MWh as of May 2024, ammonia production would amount to approximately €700 per ton (ICE Endex, 2024a; Laval et al., 2020). Given the annual requirement of 2390 kilotons in this scenario, the total production cost would be around €1.7 billion per year. Besides these costs, 5,6 TWh will need to be bought to fill the electricity need at a price of €336 million, with electricity costing €60/MWh (ICE Endex, 2024a). This brings the total cost of this scenario at €2,08 billion.

4.2.3 Scenario 3: 100% Hydrogen

Roland Berger (2021) project that Tata steel will, for a 100% DR based system, need at least 380 kilotons of hydrogen a year. LH_2 boasts a volumetric hydrogen density of 71.1 kg/m^3, meaning that 5.564.000 m^3 of LH_2 is needed to fill the annual hydrogen need of the plant (Agyekum et al., 2023; Roland Berger, 2021). Additionally, the report also states that the plant will use more than 5,6 TWh of electricity per year, which in this scenario will be made by using the liquid hydrogen (Roland Berger, 2021). At an energy density of 2,53 MWh/m^3, this provides an additional need for 2.298.000 m^3 of LH_2 (Valera-Medina et al., 2018). This means that a total of 7.862.000 m^3 of liquid hydrogen is needed for this scenario. If using a 160.000 m^3 ship to transport liquid hydrogen, 49 shipments a year of liquid hydrogen are needed to fill Tata's supplies. With a density of 71,1 kg/m^3 Tata steel would need 559 kilotons of LH_2 on an annual basis (Agyekum et al., 2023). With Giddey et al. (2017) assuming that green hydrogen costs 45 MWh per ton to produce, the annual electricity need for this scenario is 25,2 TWh. This amount of electricity means that there is an electrolysis need of 2877 MW, which at a cost of €1400/kW would be an investment of just more than €4 billion, which spread out across the 20 year lifespan would be €201.370.000 a year in capital investment costs

(Knop, 2022; Lichner, 2024). With the transportation costs per ton of hydrogen using LH_2 being estimated at €440, the yearly needed hydrogen would cost €246 million to transport the 533.000 tons necessary in this scenario (Agyekum et al., 2023). The energy needed to produce hydrogen is like ammonia set at a price of €60 per MWh, with the yearly production power requirement of 25,2 TWh, this amounts to a cost of €1,5 billion annually for the production of LH_2 (ICE Endex, 2024a). Considering that the entire need for electricity is filled by hydrogen, the total cost of this scenario is €1,96 billion.

4.2.4 Scenario 4: Hydrogen + Electricity

For this scenario, the LH_2 needed for the hydrogen need from scenario 3 is used (Roland Berger, 2021). The additional 1.3 million m^3 to fill the electricity need is omitted as the plant will use power from the Dutch energy grid instead in this scenario (Roland Berger, 2021). This makes the total need of 5.350.000 m^3 of liquid hydrogen. If using a 160.000 m^3 ship to transport liquid hydrogen, 35 shipments a year of liquid hydrogen should suffice to fill Tata's supplies. In this scenario, Tata Steel would require 395,6 kilotons of liquid hydrogen annually, given its density of 71,1 kg/m³ (Agyekum et al., 2023). Based on Giddey et al. (2017), the annual electricity requirement for producing the green hydrogen, which costs 45 MWh per ton to produce, amounts to 17,1 TWh in this scenario. This amount of electricity means that there is an electrolysis need of 1952 MW, which at a cost of €1400/kW would be an investment of just more than €2,7 billion, which spread out across the 20-year lifespan would be €163.644.000 a year in capital investment costs (Knop, 2022; Lichner, 2024). According to Agyekum et al. (2023), with transportation costs estimated at €440 per ton of hydrogen using LH2, the annual cost to transport the required 380,000 tons of hydrogen in this scenario would amount to €174 million. The energy required to produce hydrogen, like ammonia at a price of €60 per MWh, results in a yearly production power requirement of 17,1 TWh (ICE Endex, 2024a). This translates to an annual production cost of €1 billion for LH2 in this scenario (ICE Endex, 2024b). Next to these costs, 5,6 TWh will need to be bought to fill the electricity need at a total price of €336 million, with the price of electricity being €60/MWh (ICE Endex, 2024a). This brings the total cost of this scenario at €1,67 billion.

	100% NH_3	NH_3 + ELECTRICITY	100% LH_2	LH_2 + ELECTRICITY
MANUFACTURING ENERGY	10 MWh/t	10 MWh/t	45 MWh/t	45 MWh/t
MASS DENSITY	677 kg/m^3	677 kg/m^3	71,1 kg/m^3	71,1 kg/m^3
ENERGY DENSITY	4,33 MWh/m^3	n.a.	2,53 MWh/m^3	n.a.
HYDROGEN DENSITY	107,7 kg/m^3	107,7 kg/m^3	71,1 kg/m^3	71,1 kg/m^3
ANNUAL HYDROGEN EQUIVALENT NEED	533.000 t	380.000 t	533.000 t	380.000 t
TOTAL ENERGY NEED	n.a.	5,6 TWh	n.a.	5,6 TWh
AMOUNT NEEDED (VOLUME)	4.820.000 m^3	3.530.000 m^3	7.862.400 m^3	5.564.000 m^3
AMOUNT NEEDED (WEIGHT)	3.250.000 t	2.390.000 t	559.000 t	395.600 t
BOIL-OFF	n.a.	n.a.	4%	4%
ENERGY REQUIREMENT	32,5 TWh	23,9 TWh	25,2 TWh	17,1 TWh
WIND TURBINES NEEDED	465	342	343	245
SPACE NEEDED	1395 km^2	1026 km^2	1029 km^2	735 km^2
SHIP SIZE	160.000 m^3	160.000 m^3	160.000 m^3	160.000 m^3
SHIPMENTS	31/y	23/y	49/y	35/y
SHIPPING COST PER H_2 EQUIVALENT	€180/t	€180/t	€440/t	€440/t
CAPITAL COSTS	n.a.	n.a.	€201.370.000	€136.644.000
TOTAL SHIPPING COST	€95.940.000	€68.400.000	€245.967.000	€173.800.000
COST OF PRODUCTION	€2.275.000.000	€1.673.000.000	€1.512.000.000	€1.026.000.000
COST OF ENERGY	n.a.	€336.000.000	n.a.	€336.000.000
TOTAL COST	€2.370.940.000	€2.077.400.000	€1.959.337.000	€1.672.444.000

Table 7: Overview of the economic analysis (Author, 2024)

4.2.5 Fossil fuels

Tata Steel currently consumes 4.6 megatons of coal annually (Roland Berger, 2021). The annual cost of this coal use totals approximately €828 million, calculated based on a coal price of around €180 per ton (Fitch Ratings, 2023). This fuel subsequently needs to be transported, as Tata steel gets its coal (partially) from mines in India (Tata Steel, n.d.). Varadhan and Ahmed (2022) have reported that Tata uses the port of Haldia to ship coal towards its locations, meaning that this port near Calcutta will be used as a reference port for the shipment of coal. According to the VesselFinder (2024) website, the shipping distance from the port of Haldia to the plant in IJmuiden is 14.873 kilometers. Coal can be easily shipped as it is a dry bulk good that does not need to be cooled or pressurized. The maritime transport of dry bulk goods such as coal is estimated as €0,0034 per ton per kilometer (Van der Meulen et al., 2023). Therefore, the annual cost to ship all the required coal from Haldia to IJmuiden is around €233 million, without including the costs of the Suez Canal. Additionally, Tata Steel's fossil operations include a natural gas consumption of approximately 2,2 TWh, as reported by Roland Berger (2021). With a gas price averaging 30 EUR per megawatthour (MWh), this results in additional cost of around €67 million annually (ICE Endex, 2024b). Lastly, Tata uses 0,6 TWh of electricity per year in the current situation (Roland Berger, 2021). At a market price of 60 EUR per MWh, like the one used for the green scenarios, this would be another expenditure amounting to around €36 million (ICE Endex, 2024a). Putting this all together, the fossil fuel system will cost around €1,16 billion annually in fuel costs.

To limit CO_2 emissions, the European Union has established the emission trading scheme (EU-ETS). The EU-ETS functions by creating a limited amount of allowances to emit CO_2 and establishing a market for companies to trade those allowances (European Commission, n.d.). It is an integral part of the climate policy of the EU as it provides a cost incentive to reduce CO_2 emissions, as well as a form of control against those emissions as it can reduce the amount in circulation (European Commission, n.d.). With its annual emissions of 12,6 megatons of CO_2, Tata steel would have to incur heavy costs if there was no free allocation of EU-ETS permits (Roland Berger, 2021). In May of 2024, EU-ETS prices were about €70 for a ton of CO_2 (Montel, 2024). At this cost, Tata steel would have to purchase EU-ETS permits worth €882 million in total, which would make both hydrogen and ammonia cost competitive immediately. Nevertheless, the EU-ETS system allows for the free allocation of permits to companies. For 2024, Tata steel has gotten 10,2 megatons of CO_2 permits freely allocated (Nederlandse Emissieautoriteit, 2021). Subsequently, it has to only actually pay for 2,4 megaton CO_2 which is an expenditure of €168 million. As such, the total costs for fossil fuel power are only €1.213.200.000 which is still considerably lower than for the green energy carrier scenarios. Nevertheless, with the prices expected to soar to almost €200 euros per ton, the EU ETS could evaporate the fossil fuel advantage if the free allocation is reduced (BloombergNEF, 2024).

4.3 Spatial factors

The spatial implications of ammonia entail both the environmental implications as well as the institutional implications of switching Tata steel to ammonia. This is in line with the definition of spatial planning by Voogd (2004), which combines both aspects.

4.3.1 Ammonia generation

Data for the yield of wind turbines was gathered by using data from the IEA 15 MW reference turbine into the Global Wind Atlas, which revealed that a 15 MW wind turbine can produce 70 GWh annually[1] (Davis et al., 2023; Gaertner et al., 2020; International Energy Agency, 2024). For these turbines, the optimal wind power density is calculated to be around 5 MW/km^2 which means that a single 15 MW wind turbine needs around 3 km^2 of space (Bulder et al., 2018). The energy need as calculated in the economic analysis is 32,5 TWh for the 100% ammonia scenario and 23,9 TWh for the ammonia + electricity scenario. To provide this electricity, 465 and 342 15-MW wind turbines would be necessary for the respective scenarios. If we observe the 3 square kilometers of space deemed optimal by Bulder et al. (2018), a windfarm ranging in size between 1000 km^2 and 1400 km^2 is needed to fill the annual ammonia need of Tata steel.

Figure 12: Drought comparison between 2023 and 2024 around Casablanca, Morocco (Joint Research Centre, 2024), Copernicus Sentinel-2 image courtesy of the EU

With the proposed wind farm being located at sea, there are issues with the access of fresh water which is usually used for electrolysis. This is further exacerbated by the fact that Morocco is an arid country which already suffers from severe droughts as of 2024 which is made clear in Figure 12 (Joint Research Centre, 2024). To account for both the remoteness to fresh water and the increasing water shortages on the mainland, it is key to research the two main options to electrolyze seawater. The first option is the desalination of seawater, which removes the salts from the seawater before it is electrolyzed. Researchers at the University of Wageningen found that, in a ‘real-world’ setting, an integrated electrolysis and desalination system that uses the residual heat of electrolysis can be a competitive hydrogen production method, especially considering the potential to export excess water towards the drying out mainland (van Medevoort et al., 2022). The second option to consider is the direct electrolysis of seawater which is another possible method to produce hydrogen at sea. Liu et al. (2024) have proven that the large-scale electrolysis of seawater in sea conditions is possible as well. Which option is chosen depends on the commercial readiness and costs at time of construction, although the integrated electrolysis and desalination system can provide fresh water to Morocco, which is an external benefit.

4.3.2 Ammonia and policy

At the start of this year, a new environmental act has come into effect, changing the entire legal framework for all spatial projects in The Netherlands. This project works with the assumption that Tata steel wants to be able to store one shipload at a time, which is 160.000 m^3 when using the reference ships of Agyekum et al. (2023) that were used in the economic analysis. OCI Nitrogen has gained a permit for a nitrogen terminal project in the port of Rotterdam, albeit under the pre-2024 regulations (DMCR Milieudienst Rijnmond, 2024). The approved tank is around 80.000 m^3 in size so Tata steel would need 2 of these to store a shipment of ammonia (DMCR Milieudienst Rijnmond, 2024). Ammonia is a gas that falls under ADR category 2.3, indicating that it is classified as a toxic gas, as well as ADR category 8, meaning it is also considered a corrosive gas (RIVM, 2024). Due to these classifications, the storage of large quantities of ammonia is deemed an environmentally harmful activity under Article 3.27, paragraph 1(a) of the Decree on Activities in the Living Environment (*Besluit activiteit leefomgeving*, 2024). Consequently, such storage requires a permit in line with Article 5.1, paragraph 2(b) of the Environmental Act (*Omgevingswet*, 2024). With it being clear that Tata steel would need a permit for the 2 ammonia storage tanks, the question is which instance will grant them the permit. Tata Steel is classified as a Seveso facility, which means that it is a facility that falls under the rules of the European Seveso-regulations on major incidents relating to dangerous substances (BZRO+, 2024; European Parliament and Council of the European Union, 2012).Its designation as a Seveso facility makes it a complex company under Article 3.50 and Article 3.51 of the Decree on Activities in the Living Environment (*Besluit activiteit leefomgeving*, 2024). As a result of this classification, the Province of Noord-Holland is the competent authority responsible for issuing the permit, as specified in Article 4.16, paragraph 1(b) of the Environmental Decree (*Omgevingsbesluit*, 2024). Although the Province of Noord-Holland holds ultimate responsibility for issuing the permit, the actual process is likely to be managed by the Omgevingsdienst Noordzeekanaalgebied, as stipulated in Article 13.12, paragraph 1 of the Environmental Decree due to the nature of it being an environmentally harmful activity (*Omgevingsbesluit*, 2024). A Dutch ‘omgevingsdienst’ is a public organization tasked with the issuance of environmental permits and supervision and enforcement related to external safety and the environment in a certain area, relieving the municipalities and provinces. Despite Tata Steel falling within the jurisdiction of Omgevingsdienst IJmond, Omgevingsdienst Noordzeekanaalgebied will handle the case because it is one of the six environmental services specially equipped to oversee the complex Seveso facilities (Ambtelijk voorstel, 2013).

The new environmental act attaches two spatial regulations which need to be considered. The most important of these is the site-specific risk. site-specific risk refers to the mortality chance for an unprotected person who is continuously present outside the boundary of the location where an activity is conducted which arises as a direct consequence of an unusual occurrence caused by the activity being performed at that site, according to art. 5.6 of the decree on the quality of the living environment (*Besluit kwaliteit leefomgeving*, 2024). Within the area in which this site-specific risk is larger than 1 on 1 million annually, no vulnerable land use may take place according to art. 5.7. of the decree on quality of living environment (*Besluit kwaliteit leefomgeving*, 2024). (very) vulnerable locations are classified in appendix VI of the same decree, among these are for instance houses, schools, shops, and offices (*Besluit kwaliteit leefomgeving*, 2024). These contours were inherited from the previous regulations, which makes the site-specific risk contours from the OCI ammonia terminal in Rotterdam also applicable to this study as this terminal is the same size as the tanks to be built for Tata steel (Antea Group, 2022). In the risk report by Antea, the sitespecific contours have a diameter of around 1,8 kilometers at their largest point, meaning that in the case of Tata steel, both tanks need to be 900 meters removed from vulnerable locations at a minimum.

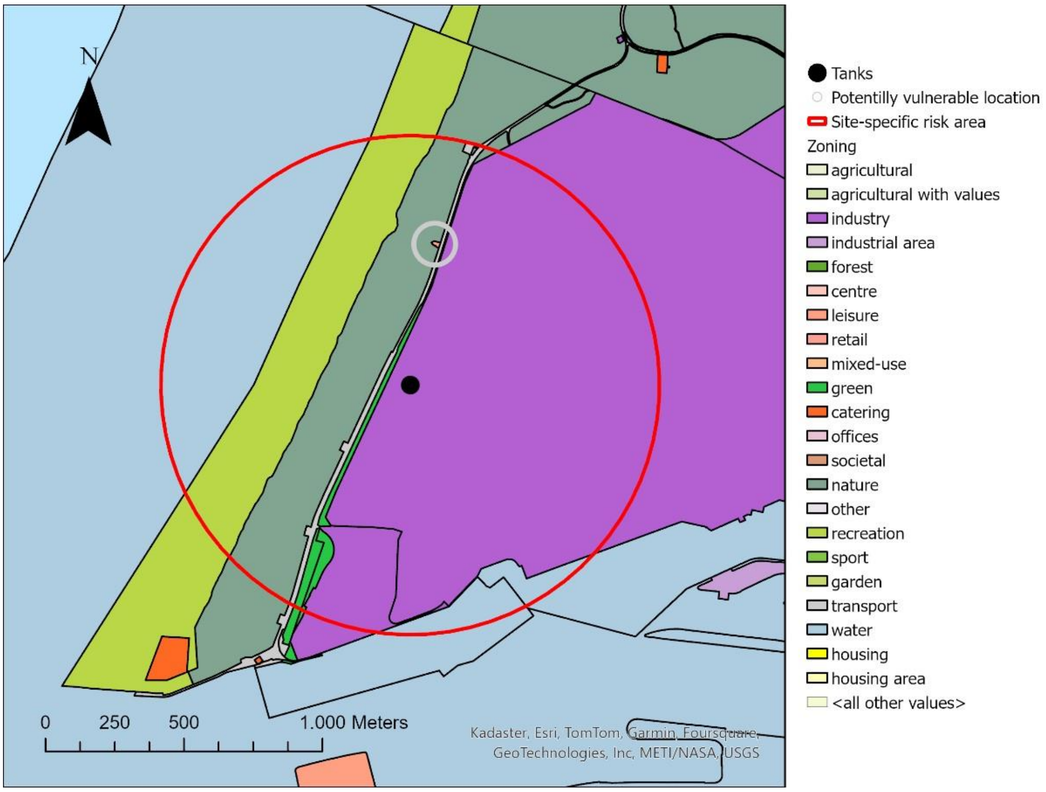

Figure 13: Vulnerable locations within the site-specific risk area (Data sourced from: Beheer PDOK, 2024)

Figure 13 shows the vulnerable locations within 900m distance from a potential ammonia tank location at the west of the Tata steel site.Within this radius, only one potentially vulnerable location has been identifies, with a kitesurfing club being located at the caution sign. Considering that buildings with a sporting function are deemed mildly vulnerable when there are not a large amount of people during the day according to Appendix VI of the decree on quality of the living environment, there is a significant chance that they are allowed within the site specific risk area (*Besluit kwaliteit leefomgeving*, 2024).

The second spatial regulation focuses on attention areas for fire, explosions, and toxic clouds (*Besluit kwaliteit leefomgeving*, 2024). Art. 5.12 para. 3 and para. 4 of the decree on the quality of the living environment states that the attention area for toxic clouds consists of the range wherein people die because of a high concentration of toxins during a specified period, limited to 1500 meters (*Besluit kwaliteit leefomgeving*, 2024).

Within these 1500 meters, the relevant authorities must ensure that there are protective measures against these risks in the attention areas according to Art. 5.15 of the decree on quality of the living environment (*Besluit kwaliteit leefomgeving*, 2024). These measures can range from additional awareness by increasing communication to spatial interventions like water curtains to limit the spread of an ammonia cloud (Informatiepunt Leefomgeving, 2024).

The consultancy bureau Roland Berger (2021) mentions that Tata steel can, in the most optimistic timeframe, rebuild to a partial direct reduction system in 8 years. Nevertheless, the most time-consuming part of the process is the permission process, which is expected to take at least three years. This is in line with the conclusions of Scholten et al. (2021) who concluded that large projects in the energy sector usually range from 8 to 11 years. To make the construction of a fully ammonia powered steel plant possible around 2040, the time that the permission process consumes must be reduced.

5 Conclusion and discussion

The main research question of this thesis was: "*How can the role of ammonia be understood in the energy transition for Dutch industry and the energy system as a whole?"*. An answer to this question has been studied by conducting a literature review, an empirical analysis and a case study on Tata steel. This research was guided by a TES-analysis of constraining and enabling factors posed by the regime to the ammonia niche. The sub-questions will be answered first before the answer to the main question follows based on the sub-questions.

Sub-question 1: 'Is the usage of ammonia for industry technically feasible?' Ammonia is already being produced and used for more than a century, so therefore the technology to manage the transport and storage of ammonia is already well-developed. Nevertheless, there are some important limiting factors to the implementation of ammonia for industry. First among these factors is the difficulty to make green ammonia production energy-efficient, for second-generation ammonia this issue stems both from the initial electrolysis of hydrogen as well as the energy intensive Haber-Bosch process which overall grants ammonia a return on energy investment of only 42 – 52%, although cracking is included in that process. The second disadvantage of ammonia is its hazard to health and environment. Ammonia is an acute respiratory toxin that can irritate the respiratory system when inhaled and even lead to lung damage and death in extremely high concentrations. Besides this, ammonia is a corrosive substance that can irritate and burn skin and eyes. Furthermore, it poses a large threat to nature, especially aquatic because it dissolves well in water. Lastly, it is considered a flammable gas even though it is not extremely flammable outright, with it needing to be preheated before it can ignite. Ammonia can be used in multiple ways, ranging from vehicular fuel to fuel cells. Specifically for the case of Tata steel, ammonia is usable for steel production in an equivalent way to hydrogen by utilizing direct reduction, making it possible to use without cracking. A major concern for the use of ammonia is the possibility of increased NO_x, N_2O, and unburned ammonia emissions, which can negate its environmental benefits. The low efficiency of current green ammonia production means that a lot of space is needed to generate the electricity necessary for this production. Additionally, ammonia necessitates a lot of water to produce, which often provides problems as the areas with the highest renewable energy potential are usually arid. The electrolysis of seawater is possible, but it is still technology in development. Ultimately however, ammonia usage for industry is proven to be feasible on a technical level as it is both applicable for various uses and a proven material for which handling technology already exists. Nevertheless, for its potential to clean industry to truly blossom, NO_x, N_2O and unburned ammonia emissions need to be reduced and for some uses, optimal blends need to be researched.

Sub-question 2: 'Is the usage of ammonia economically feasible?' In the case study, a comparison was done between ammonia and hydrogen as energy carriers from a wind park in Morocco to the Tata steel plant in IJmuiden. Compared to the costs of fossil fuels, both green energy carriers currently come at a premium of 5075%. For the case of Tata steel, hydrogen is proven to be a more economical energy carrier, with both hydrogen-based scenarios ending up less costly than ammonia by a margin of €100 million – €600 million based on which scenarios are compared. This difference can be attributed to two main reasons. Firstly, the wind farm in Morocco for the case study is relatively nearby, meaning that the lower shipping costs of ammonia were not too deciding for the final cost, with its savings being vastly outweighed by the higher energy demand for ammonia. Secondly, as the direct reduction process relies on hydrogen, there is a continuous demand for it, meaning that it will not be kept in storage for longer periods of time. Therefore, the lower boil-off rates of ammonia had only limited effects on the outcome. In a case where ammonia would be kept on hand longer (30> days) as a stockpile against intermittency for example, it would become more competitive with hydrogen. Nevertheless, with the outcome of this case study and the knowledge that ammonia is, for the foreseeable future, reliant on the same electrolysis as hydrogen, it is clear that ammonia cannot challenge hydrogen for industrial uses where there is a high turnover of hydrogen/ammonia. For longer term storage and transport, it might paint a different picture in favor of ammonia. It can be more suitable than hydrogen for incidental use if electricity is in short supply for instance as it allows the strengths of ammonia to shine. Ultimately however, with future improvements in hydrogen and ammonia synthesis, the gap between these technologies can tighten as the storage and transport costs begin to play a bigger role compared to energy costs, especially if the latter continues to drop. Compared to fossil fuels, both green energy options are still costly, although this gap will shrink due to the pressures from both sides, with the lowering costs of electrolysis and ammonia synthesis reducing the energy carrier costs while the market pressures with the decreasing EU-ETS supply will pull up the price of fossil fuels. This question can ultimately be concluded with a 'yes' but not necessarily for this specific case, as it might fit smaller industrial plants better.

Sub-question 3: 'Does ammonia fit within the Dutch spatial fabric?:'
In this study, a policy analysis was conducted to establish if Tata steel could switch to ammonia within the new spatial regulations of the environmental act. Additionally, the spatial effect of the energy generation and electrolysis were touched upon. Lastly, constraints were identified with the permission process in the Netherlands. The analysis of the spatial and environmental factors concerning the electricity generation in Morocco revealed that the wind farm would take up to 1400 km^2 in surface area if Tata steel were to switch to a fully ammonia powered plant tomorrow. Moreover, the environmental concerns of electrolysis in a water scarce area were researched, which revealed that an integrated system of desalination and electrolysis could both deliver green hydrogen and fresh water, thereby alleviating the drought problems. In the Netherlands, the legal possibility of the construction of two 80.000 m^3 ammonia tanks on the site of the Tata steel plant was researched. The new environmental act provides clear and certain legal context for the storage of ammonia and provides a clear overview of relevant authorities. According to the policy analysis, the main regulation

with spatial implication, the site-specific risk, did not provide a large constraint to the construction of the two tanks, with the radius of 900m only potentially affecting a single building. The other spatial regulation is the attention area, in which additional safety precautions must be taken due to the toxicity of ammonia. With this attention area having a range of 1500m, precautions need to be taken for a few locations to minimize risk, which should not prove as an insurmountable barrier. Lastly, the key barrier to the speedy adoption of ammonia is the permission process, with delays hindering its construction. For Tata steel, ammonia does fit within the Dutch spatial context. Tata steel is however quite remote and in a sparingly built-up area, which does not reflect the Dutch context everywhere. Building truly large-scale ammonia storage is with these regulations only feasible in a few other large industrial clusters like Chemelot, the port of Rotterdam, or Moerdijk for instance. For smaller scale industries, particularly near residential areas, the rules surrounding ammonia might become more challenging.

Sub-question 4: 'Can the regime accommodate a transition to ammonia?': The TES-analysis was aimed at the identification of constraints and opportunities in the regime-niche relation for ammonia. Following the TES-analysis, it seems that ammonia can fit reasonably well within the current regime. As mentioned in the introduction, ammonia has the potential to be a 'bridge' between the molecular present and the electrical future. According to the technical feasibility, it does have the potential to fill currently fossil fuelled roles without drastically affecting the operations. Its established supply chain also is a benefit as there is an immediate way to ship and store ammonia on a large scale, while hydrogen transport is still in development. Ammonia is still a fuel in development, but it seems promising for various industrial uses. On an economic basis, ammonia is not a directly feasible alternative to fossil fuels, mainly because the EU-ETS free allocation system reduces the cost of using fossil fuels. Within a regulation standpoint, ammonia benefits from being a relatively well-established and well-studied substance, which helps with the legal certainty surrounding its use. Ultimately, ammonia can fit within the current regime reasonably well, with the main barriers being a low technological readiness and its lack of economical competitivity with fossil fuels.

Sub-question 5: 'In what time frame can ammonia be a solution?': Green ammonia is currently still in development as an energy storage medium. The initial literature review points to green ammonia being commercially ready between 2030 and 2040. With ammonia-powered industry only being tested at an experimental level, there is also time needed to conduct more research and development. Besides this, time is needed to redesign and modify industrial facilities which can easily take more than a decade in itself. Moreover, the necessary infrastructure needs to be developed to produce, transport and store ammonia. Lastly, ammonia needs to reach economic viability, meaning that electricity prices should drop considerably and EUETS prices should rise in tandem. Considering this, ammonia can be estimated to be a widely applicable solution in the 2040's, meaning that it can still help contribute to the Netherlands' climate neutral goals for 2050.

Sub-question 6: 'Does ammonia have advantages over hydrogen?': Ammonia has been compared to hydrogen multiple times in this thesis. Arguably the point can be made that ammonia can be seen as a part of the larger hydrogen niche, filling in roles that hydrogen cannot. Based on the technical analysis, ammonia is easier to transport and store, at the cost of its toxicity. The main comparison has been conducted in the economic analysis, which proved that the relatively cheap transport and storage of ammonia did not weigh out the benefits of hydrogen, which is less costly to produce. Ammonia is less suited for continuous usage as compared to hydrogen. Nevertheless, ammonia and hydrogen can coexist, with ammonia mainly having strengths for the long-term stockpiling of fuel between seasons for more incidental use due to its low boil-off and cheap storage. This is strengthened by the legal nature surrounding ammonia, making it mainly applicable in large installations on a few relatively remote industrial clusters. Ultimately, ammonia is perhaps best used as a specific role within the hydrogen economy for stockpiling and long-range transport, where its strengths over hydrogen shine the most.

Following these sub-questions, it is clear that ammonia can technically help fossil fuel based industries switch to a zero-emission process while still using molecular fuels. The TES-analysis also showed that ammonia is also viable within the new regulatory system in The Netherlands, provided it is in a fairly remote location. Additionally, the technologies and infrastructure for ammonia could be ready around the 2040's. Despite all its promises however, ammonia will probably be relegated to a smaller role as a long-term stockpile fuel as it is not economically competitive with hydrogen for continuous use in industrial processes. Nevertheless, this role is still crucial as it allows for a more intermittency-proof energy system. Ultimately however, ammonia can best be understood as a smaller niche within the larger hydrogen niche, filling in a few dedicated roles to which it is most suited.

5.1 Policy recommendations

Although ammonia will mostly fill a comparatively small role, there are still some key recommendations for urban planners and policymakers. First among these is the reduction of the time it takes to get a permit. Firstly, limiting the option to appeal for critical energy infrastructure projects can potentially boost the permission process (Tiekstra, 2024). This might prove contentious however as forcing through infrastructure for a toxic gas can upset affected people. A LNG-terminal in Eemshaven used a more elegant approach by starting construction before the permit process had ended, which saved a considerable amount of time (Sanders, 2024). The main risk with this method is that there needs to be some form of insurance if the permission process fails.

6 Discussion

This thesis aimed to view ammonia as an energy carrier from a spatial planning perspective. With the majority of studies on the subject being strictly technoeconomical in nature, I aimed to add to both spatial planning discourse and to bring a new perspective into the field of green ammonia as an energy carrier.

6.1 Future research

In this research, a modified PESTEL-analysis, the TES-analysis was used to identify constraining and enabling factors within the regime-niche relation. As both the PESTEL and TES models overlap quite well with the definition of a socio-technical regime of Schot and Geels (2008) this could be an interesting analysis method for future research in planning and transition management.

This thesis established that ammonia can probably not play a key role in the energy transition for industry due to its economic disadvantage compared to hydrogen. Nevertheless, a case study on a stockpiling function could be an interesting avenue for research as it fits better with the strengths of ammonia according to the findings in this thesis.

6.2 Reflection

Looking back on the research process, there are some key limitations that can be identified. Firstly, the thesis was far too broad in the beginning, which led to valuable research time wasted on dead ends. Secondly, being a spatial planning student, some of the more technical data was hard to grasp and understand immediately, which led to some miscalculations early on.

Focusing on the methodology, using a case study has provided some much needed context-dependent data. Nevertheless, relying on a case study naturally means that the lessons learned can only be used to a certain general extent.

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