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Master’s thesis

Reducing Emissions in the Transportation Sector:

A TIS Analysis of Hydrogen Trucks in the Norwegian Heavy-Duty Segment

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60stp

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2023

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MA Thesis, Centre for Technology, Innovation and Culture

http://www.duo.uio.no

Abstract

The chase to meet a zero-emission transportation sector is currently unfolding. However, the heavy-duty segment is proving more challenging than the passenger vehicle segment, where BEVs have already gained a significant market share, particularly in Norway. In the heavy-duty segment, multiple technologies develop simultaneously, and the needs differ from those in the passenger segment. For instance, trucks are operational for longer spans and often travel long distances. Additionally, profit margins are also something that must be considered. In this thesis, I will focus on hydrogen trucks in Norway. This includes fuel-cell electric trucks and trucks with hydrogen combustion engines – both of which are technologies that truck manufacturers are currently exploring. The activity in Norway regarding hydrogen trucks is currently limited, which is why the *potential role* of this technology is mainly highlighted. Consequently, barriers are more prevalent than drivers. I will use the technological innovation system (TIS) approach as my theoretical framework and analytical strategy.

The functional pattern of hydrogen trucks in Norway, which is at the heart of any TIS analysis, is central to the thesis's research questions. However, technological development does not occur in a vacuum. Therefore, I will also introduce TIS context structures to the analysis, with four main categories: technological, sectoral, geographical, and political context structures. Essentially, I will map out the status of hydrogen trucks in Norway while considering these. Some of the most critical context structures include other technologies in the heavy-duty segment, The European Union, the Norwegian power sector, and hydrogen in the Norwegian maritime sector. These can be potential drivers for hydrogen trucks in Norway, depending on the development in the coming years. In particular, this relates to the development of supportive policies. However, some context structures mentioned can also function as barriers because they represent competing technologies.

The thesis is qualitative, and interviews with relevant actors represent vital data sources. Additionally, relevant documents, literature, and various strategies are also important data sources. Together, this comprises the main elements of my analysis and discussion base.

Acknowledgements

With this thesis, I conclude two years as a student at the TIK Centre. There are many people I want to thank. First and foremost, I would like to thank my supervisor, Tuukka Mäkitie. Your feedback, support, and insights have been vital throughout this process. Additionally, I would like to extend my gratitude to the SINTEF community, who provided me with a working space throughout this process and welcomed me into your environment.

I would also like to thank the community at TIK for creating a space with room to explore and ask questions. I have learned a lot from your lectures, seminars, and research, much of which has helped me develop the analytical skills needed to conclude this thesis. To my fellow students, I truly appreciate the time we have had together and the bonds we have formed. These past two years would not have been the same without you.

This project has been with me for two semesters, constantly evolving and growing, sometimes to a point where it feels like an entity with its own personality. Given the many people I have talked to along the way, this perception might hold some truth. A special thanks to the 11 informants who have prioritised me in your busy schedules – your knowledge and insights form a vital part of this thesis.

To my family and partner Henrik, thank you for your support. I am truly grateful to always have a team by my side.

Maria Aspen Neerland, Oslo, May 2023

List of abbreviations:

FC – Fuel Cell

FCEV – Fuel Cell Electric Vehicle

BEV – Battery-electric Vehicle

EU – European Union

LoZeC – Low and Zero-Carbon Technology

CAPEX – Capital Expenditures

OPEX – Operational Expenditures

TIS – Technological Innovation System

MLP – Multi-Level Perspective

SNM – Strategic Niche Management

TM – Transition Management

AFIR - Regulation for the deployment of alternative fuels infrastructure

TEN-T - Trans-European Transport Network

ETS - EU Emission Trading System

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1 Introduction

Hydrogen as an energy carrier has received increasing attention in the wake of the climate crisis. The colourless, odourless, and flammable gas can accelerate the decarbonisation of our energy and transport system – especially those parts that are hard to electrify directly, the so-called hard-to-abate sectors. In other words, hydrogen is regarded as a technology that can contribute to reducing emissions by 2030 and, further, reach net-zero by 2050 (DNV, 2022). In this master's thesis, I will look at the role of hydrogen within the heavy-duty segment, specifically heavy-duty trucks. My analytical focus will be on the performance of hydrogen trucks and activities, actors, networks, and relevant policies to this technology in Norway. This does not entail that I dismiss activities outside of Norway; this would be futile due to the interrelatedness with European society and the dependence on foreign manufacturers. Rather, this will function as an essential context for the efforts made in Norway concerning hydrogen within heavy-duty transport.

In the course of this thesis, there will be mentions of other technologies in the heavy-duty segment, such as batteries and biofuels. The maritime sector is also an important backdrop for the hydrogen activities that are currently carried out in Norway. This is linked to the political interest in hydrogen within this sector. In comparison, the utilisation of hydrogen within the heavy-duty truck segment has received less attention in Norway. Therefore, I have chosen to specifically focus on trucks not despite but because of the limited attention it gets compared to other uses of hydrogen. My ambition is to contribute to the knowledge base on hydrogen trucks, specifically in a Norwegian context. Reaching net-zero by 2050 is challenging, given the deep roots of unsustainable practices and technologies on which much of society is built. Based on this, I believe it is important to analyse a technology that could play a crucial role in reducing carbon emissions in the transportation sector, even though it is not devoted much focus in Norwegian policies as of now. For instance, there are several technological analyses on the maritime sector and alternative fuels, in which hydrogen is frequently considered (Bach et al., 2020; Mäkitie, Steen, et al., 2022; Steen et al., 2019). These contribute to much insight into the complexity of transitions in hard-to-abate sectors. This insight can further be used to develop insight into other sectors or segments – such as the heavy-duty segment.

In Norway, the electrification of the passenger vehicle segment is substantial, and many expect that this will eventually be the case for the entirety of the Norwegian transportation sector – including most of the heavy-duty segment. However, there are also those that point to the need for electrification *and* hydrogen, viewing them as complementary rather than competitive in the chase for a zero-emission transportation sector. In the heavy-duty segment, the goal is that 100% of new heavy vehicles, 75% of new long-distance busses and 50% of new heavy-duty trucks will be zero-emission by 2030. It is noted, however, that the diffusion of zero-emission technology in the heavy-duty segment is more difficult to predict because the technology development is uncertain and slower than in the passenger vehicle segment (Meld. St. 13 (2020–2021), p. 49)

The EU has a different approach to hydrogen in the transportation sector, with more expectations and ambitions for hydrogen in the heavy-duty and passenger segments. Due to the interrelatedness with the continent and the European market, it can be argued that Norway must eventually acknowledge the role of hydrogen in road-based transportation – despite the high level of electrification. The difference in ambition is also something I would categorise as a gap, providing additional motivation to study hydrogen in the heavy-duty segment. Furthermore, the focus on hydrogen within the maritime sector can sometimes block the political imagination of synergies between the two sectors. These will be essential topics in the analysis and discussion. Further, the European hydrogen ambitions are also something that is thoroughly discussed, and the diffusion of hydrogen trucks in Europe will likely be greater than in Norway because of these ambitions.

In this thesis, I will conduct a technological innovation system analysis, a TIS analysis, of hydrogen trucks in Norway. I have chosen this framework because it presents useful tools for studying novel technologies and their central dynamics and activities – i.e., the innovation system. To collect data, I interviewed relevant actors in different positions participating in the hydrogen truck value chain, either directly or indirectly. I have also utilised relevant literature and different documents, such as political strategies and reports from research institutes, to broaden my understanding of the TIS I am interested in and link this thesis to a scholarly field. The TIS framework has a set of elements that together make up the structure of how I will present and lay out the empirical findings (Bergek, Jacobsson, Carlsson, et al., 2008). In this thesis, I have started with defining the focal TIS, which is a term frequently used to distinguish it from other TISs. Further, I identify the relevant actors, networks, and institutions to the TIS before I embark on the most extensive step of the analysis: identifying the functional pattern, or the seven *functions* of the TIS. Data gathered from interviews and other relevant documents and literature are essential when identifying these functions. As the TIS does not exist in a vacuum, relevant context structures are also identified. Then, the relative strength of the functions is assessed to make way for the analytical discussion. This will be used to answer two research questions presented below.

1.1 Research questions

In this thesis, I will answer two main research questions:

1. *How do the functions of the hydrogen truck TIS perform in Norway?*
2. *What are the TIS's central blocking and inducement mechanisms, and how can policy address this?*

The first research question is explicitly related to the theoretical framework of this thesis by including the functions. These are at the analysis's centre stage, making this a natural focal point of a research question. In the second research question, the inducement and blocking mechanisms of the TIS are the main focus. However, this RQ also has a second part – remedies. In this context, remedies can be translated into supportive and/or technology-specific policies.

1.2 Structure of the thesis

The thesis structure is as follows: In Chapter 2, I present some relevant background to my chosen technology, i.e., hydrogen trucks. This includes the properties of hydrogen, how it can be produced, and its use in the transportation sector. I also introduce some important policy contexts for hydrogen, mainly the Norwegian and the EU hydrogen strategy. In Chapter 3, I introduce the theoretical background of this thesis. First, I position myself within transition studies and introduce some central contributions from this academic field. Second, I introduce the TIS framework and some relevant TIS analyses on hydrogen. In Chapter 4, the methodology I followed when gathering data is explained. Importantly, this is also where I explain my methodological choices. In Chapter 5, the TIS analysis is conducted. Chapter 6 is a continuation of the TIS analysis, where the functional pattern of the TIS, inducement and blocking mechanisms, and policy implications are discussed. In Chapter 7, I conclude my work and discuss the implications of the thesis, its limitations, and further research.

2 Empirical background

In this chapter, I will elaborate on some central qualities of hydrogen, how it can be used in the transportation sector, and how policies have developed in relation to hydrogen. Importantly, this elaborates on much of the hydrogen truck value chain. This also provides context to the TIS analysis later on.

2.1 The production of hydrogen

In this section, I will address the production of hydrogen. Hydrogen is the most abundant, lightest, and simplest element in nature. It consists of one electron and one proton and is a colourless, odourless, and flammable gas. It does not exist in its pure form in nature but can be produced in multiple ways, notably through natural gas reforming and water electrolysis. Although there are more ways to produce hydrogen, the two abovementioned are those that have reached technological readiness. Note that this does not imply cost-effectiveness, as the two options currently have very different pricing.

To distinguish between the different modes of production, hydrogen is referred to in terms of colour. The most used colours are grey, blue, and green hydrogen, depending on how it is produced and whether CCS is employed. Some have criticised the simplicity of these groupings, mainly because they fail to describe accurately how "clean" the hydrogen is. This is because the colour codes address the type of energy used in production and additional technology while not addressing the GHG emissions during production, from sub-systems or the life cycle of the equipment (Dawood et al., 2020). However, for the sake of clarity, I will be using the mentioned colour codes. Additionally, this was something my informants frequently referred to. Green hydrogen is the most relevant to the technology I am concerned with. This is seemingly due to a preference for green hydrogen in the transportation segment in general (Damman et al., 2020, p. 33). Consequently, I will elaborate more on this colour than the others, including the technology used to produce green hydrogen, namely electrolysers.

2.1.1 Green Hydrogen

Green hydrogen is produced through water electrolysis powered by renewable energy. In Norway, Norsk Hydro has been using this method to produce hydrogen since 1926 in their ammonia factory at Notodden (Norsk Hydro, n.d.). The product of utilisation is pure water, and hydrogen is produced by splitting water into hydrogen and oxygen through an electrolyser. The process is emission-free as the electrolyser is powered by renewable energy, such as hydro power, wind power, or solar energy (Damman et al., 2020). Consequently, if hydrogen is produced through electrolysis powered by non-renewable resources, it is no longer classified as green.

Mainly, there are four electrolysers on the market, differentiated by their operating temperature and electrolyte material: Alkaline Electrolysers (AEL), Proton Exchange Membrane Electrolysers (PEMEL), Anion Exchange Membrane Electrolysers (AEMEL), and Solid Oxide Electrolysers (SOEL). The latter two are the least mature, with few demonstrated plants so far. AEL is the most mature technology of the four, with roots from the early 20th century, therefore having the widest market diffusion. AEL is based on a liquid caustic electrolyte and a cheap metal coating, with an operating temperature of 60-80°C and an energy efficiency of 65-82%. However, PEM electrolysers have also become a viable option in recent years. The technology is less mature but has the same operating temperature and energy efficiency as AEL, using a polymer as an electrolyte. While being a more expensive technology than AEL, PEMEL works at a high current density, requires less space, and makes it easier to compress hydrogen – all of which can reduce costs (Damman et al., 2020; Reksten et al., 2022).

A recent cost analysis published by SINTEF predicts a capital cost reduction of PEMEL and AEL leading up to 2030, with PEMEL seeing the steepest price reduction due to currently being more expensive. The capital cost reduction is closely related to scaling benefits, as the scale-up of plant size up until the 1-10 MW range will result in a price decrease. The learning rate of AEL and PEMEL leading up to 2030 is also predicted to be substantial, with estimates at 25-30%. This prediction is far higher than earlier estimates. It is noted, however, that this price analysis does not consider the potential shortage of raw materials. This can affect PEMEL in particular, as some of the critical components in the technology use precious metals that have a predicted increase in demand. A significant reduction in the use of these metals, or a substitution, is required if PEMEL are to reach commercial scale (Reksten et al., 2022).

As of now, the production of green hydrogen is limited. This is due to several reasons, such as electrolysis being an energy-demanding and expensive process. The energy aspect is particularly constraining, as renewable energy is currently a scarce resource. In sum, the energy content of the output hydrogen is always less than the input fuel, i.e., electricity. This can pose a major barrier to green hydrogen. In the future, when renewable energy sources are more abundant, the energy loss intrinsically linked to green hydrogen production will be less of a concern. Lastly, green hydrogen is more in line with the EU taxonomy and seems to be the preference of most EU countries with hydrogen ambitions (DNV, 2022).

2.1.2 Grey Hydrogen and Blue Hydrogen

Today, most hydrogen at an international scale is produced using natural gas reforming, also known as grey hydrogen. This process can be summed up as converting hydrocarbons and alcohols by chemical processes into hydrogen. The process has three by-products: water vapour, carbon monoxide, and carbon dioxide (Damman et al., 2020). In other words, the process has prominent greenhouse gas emissions intrinsically linked to it. That is, unless carbon capture and storage (CCS) are not utilised, which would then be blue hydrogen.

First and foremost, the difference between grey and blue hydrogen is, in theory, straightforward. Grey hydrogen is produced from natural gas reforming *without* carbon capture and storage (CCS), while blue hydrogen employs CCS. In other words, CCS is a promising way of reducing emissions linked to natural gas reformation. This could be a profitable business case for nations with natural gas resources, such as Norway, either by producing blue hydrogen on-site and exporting it or by exporting natural gas. However, there are some obstacles linked to blue hydrogen production as well. In some cases, such as Germany, public and political scepticism of CCS has been high. Seemingly, there has been an inertia to commit to CCS as a climate mitigation technology, something that has been a barrier to investments. Combined, this has weakened the business case for blue hydrogen (Damman et al., 2020; Reigstad et al., 2022).

Secondly, there has been a debate about whether blue hydrogen should be categorised as low emission. Suppose blue hydrogen is to be in line with the EU taxonomy, for instance. In that case, a combination of hydrogen production technology and carbon capture with high conversion and CO_2 capture rates is crucial. According to research conducted by DNV, this can be delivered in some regions with natural gas infrastructure, but far from all (DNV, 2022). For blue hydrogen to be considered low emission, the vast majority of the CO_2 emissions from producing hydrogen with natural gas reforming, at least 90%, need to be captured and stored. The methane emission rates from the supply chain also need to be less than 1% (Reigstad et al., 2022).

2.2 How can hydrogen be utilised?

The use of hydrogen itself is zero-emission, as it only emits water vapour and heat. As described above, production is what constitutes the level of emissions. Today, hydrogen is mainly used as a chemical feedstock or an industrial raw commodity. This can be categorised as industrial hydrogen, and the use includes fertiliser production, petrochemical refining, metal work, food processing, generating cooling in power plants, and semiconductor manufacturing. Hydrogen has also been employed by NASA since the 1960s as a fuel (Dawood et al., 2020).

The potential of hydrogen beyond its current use has been known for a long time, and the term “hydrogen economy” was launched in the 1970s. It can be used for storing excess energy by converting it to hydrogen, as an energy carrier, and as a “charger” to batteries comprised of fuel cells. It can also be stored and held in tanks, moved through pipelines, and converted between gaseous and liquid states. Additionally, hydrogen is the lightest element in the universe, with high energy density compared to weight, which makes it advantageous in settings where weight is of importance. The energy density compared with volume, on the other hand, is low, which can lead to challenges related to storing and transporting (Dawood et al., 2020; DNV, 2022). Many argue that the decarbonising potential of hydrogen is in the hard-to-abate sectors, where direct electrification is either impossible or ineffective. Sectors usually considered hard-to-abate are typically the high-heat heavy industry, aviation, maritime shipping, and to a certain degree, heavy-duty road transport. Additionally, blue and green hydrogen is set to replace grey hydrogen in the abovementioned industries that utilise hydrogen today, as this is necessary to reduce emissions from these industries. However, due to significant energy losses and low- and zero-emission hydrogen costs, many have been wary of investing in the hydrogen value chain (DNV, 2022).

2.2.1 Hydrogen in the transportation sector

When the potential of hydrogen is considered within the transportation sector, hydrogen fuel cells are, in most instances, the object of discussion. Fuel cell technology is not a new invention

– it has been around since the early 20th century and has since the 1960s been utilised in spacecraft (Dawood et al., 2020). There have also been substantial R&D investments in fuel cells throughout the decades, which is also the reason why hydrogen as a fuel and energy carrier has been highly anticipated (Suurs et al., 2009). There are different types of fuel cells, with proton exchange membrane fuel cells (PEMFC) being most common in vehicles, but the principle of how they work is mostly the same. Firstly, three elements are required: an anode, a cathode, and an electrolyte. Secondly, electricity is produced by converting hydrogen to electrical and heat energy. What mainly differentiates fuel cells are the electrolyte type and temperature (Damman et al., 2020; Manoharan et al., 2019).

There is also interest in hydrogen combustion engines, as opposed to diesel combustion engines, in the truck segment. While the focus has primarily been on hydrogen fuel cells throughout the years in the transportation sector, several truck manufacturers are currently exploring possibilities of adapting combustion engines to operate on hydrogen. While the R&D investments in fuel cells are considerable, the investments in combustion engines are also substantial and have been going on for decades. This can make the technological readiness of combustion engines an advantage compared to fuel cells – at least in the short term before fuel cell production increases, consequently decreasing the price. Other advantages of hydrogen combustion engines include tolerating fuel impurities better than fuel cells (Yip et al., 2019).

Fuel cell vehicles are often regarded as electric vehicles (EVs), which is why it is often referred to as FCEVs. Battery-electric vehicles (BEVs) also fall into this category. However, the well-to-wheel efficiency of the two options is different. While FCEVs have an overall efficiency of 25-35%, BEVs can reach 70-90% (DNV, 2022, p. 88). Regardless, FCEVs were considered a viable option in the transportation sector for a long time, especially before BEVs reached the technological maturity they have today. In the 2000s, Norway had a project with FCEVs – the Hynor project. This was a collaboration between Statoil and Norsk Hydro with the aim of establishing a hydrogen 580 km corridor for FCEVs from Oslo to Stavanger. This aim was to generate experience and create market development with hydrogen refuelling infrastructure and FCEVs. From 2006-2009, a total of five stations were opened. However, Statoil and Norsk Hydro put their efforts on hold in 2009 for various reasons. One of the main obstacles in the project was that the (few) producers of FCEVs prioritised other geographical markets for introducing this technology, and experiments from other countries indicated a limited technology maturity. The financial crisis of 2008 also impacted the decision to step back.

Additionally, the BEV market took off from 2010-2011, enjoying a higher level of maturity aimed at the same market segment. In 2011, Statoil decided to pull out of the project and close its stations by 2012. Another actor later possessed the stations, but the exit of Statoil constituted a loss of large-scale industry resources for hydrogen refuelling infrastructure in Norway (Damman et al., 2020; Langeland et al., 2022).

Many anticipate that hydrogen can be of more use within heavy-duty road transport, such as trucks, than in the private vehicle segment, where batteries will likely dominate. This is also signalled by multiple manufacturers within the heavy-duty segment implementing hydrogen in their portfolio. For instance, Daimler and Volvo have launched a joint venture to produce fuel cells for their vehicles and trucks (AB Volvo, 2021). In general, hydrogen in the heavy-duty segment also benefits from the increasing restrictions imposed on diesel trucks, which are set to be phased out eventually. On the other hand, there is uncertainty about the share of hydrogen trucks in the future transportation sector. For some time, it has been considered the only option to decarbonise the heavy-duty segment. A complicating factor in this is the fact that battery-electric trucks are developing simultaneously. Therefore, predicting the future share of battery-electric trucks versus hydrogen trucks is not easy. However, on longer distances, i.e., long-haul heavy transport, hydrogen will likely have a share due to the range limitations of batteries (DNV, 2022, pp. 88-89).

Hydrogen refuelling stations (HRS) are necessary for hydrogen in the transportation sector. There are, essentially, two categories of refuelling stations: those that produce hydrogen on-site and those that are dependent on hydrogen produced off-site. In both instances, there are many shared components. A list is provided below, derived from Apostolou and Xydis (2019, p. 4):

Shared components HRS	
1	Hydrogen compressor for high-pressure storage inside the station's main H2 tanks.
2	Hydrogen storage tanks, either for compressed or liquified hydrogen. The former is the most common in HRS due to the additional expenses of liquefying hydrogen.
3	Hydrogen gas booster that regulates pressure to 350 bar or 700 bar during the refuelling procedure.
4	Cooling unit to reduce hydrogen gas temperature.
5	Safety equipment, including pressure relief valves, hydrogen sensors, and waterless fire suppression.

6	Mechanical and electrical equipment.
7	Dispensers that supply the vehicles' H_2 high-pressure tanks from the station's compressed storage tanks.

Table 1: Components HRS (Apostolou & Xydis, 2019)

In the case of on-site hydrogen production, a hydrogen production unit and a purification unit are also required. The latter ensures that hydrogen meets the standard for supplying fuel cells, which requires a hydrogen purity above 99%. In the off-site HRS, hydrogen is delivered from a central production unit through road transport, rails, ships, or pipelines. In road transport, hydrogen is stored in tube trailers as compressed gas to more than 180 bar pressures and delivered by heavy-duty trucks. In these stations, the mode of deliverance is, therefore, a central aspect. Regarding costs, on-site hydrogen production constitutes an additional cost compared to off-site hydrogen production. Off-site HRS are also more flexible as they can be sized based on demand. In terms of required infrastructure, this will vary depending on the segment and the number of vehicles or trucks (Apostolou & Xydis, 2019).

2.3 Hydrogen policy

In the following sections, I will elaborate on some policies relevant to new applications and ambitions of hydrogen. Mainly, I will focus on the Norwegian and the EU hydrogen strategy.

2.3.1 Central policy developments in Norway

The Norwegian government´s hydrogen strategy discusses the possibilities of hydrogen in Norway, both at a national and international scale, systematically. The 56-page strategy includes aspects of hydrogen - from the technology to production, storage, safety, cost, pilots, and end-use. The strategy also considers the potential role of hydrogen in different sectors, including transport, industry, power, and R&D. There is also an emphasis on the price and competitiveness of hydrogen, which will be decisive in the uptake of hydrogen in the mentioned sectors. However, there is little concrete mention of how a price reduction and, thereby, competitiveness can be achieved; other than that, this depends on technology development outside of Norway. However, pilot projects and consequential technology learning, public procurement as a stimulator for innovation, and pre-existing political targets and strategies for emission reductions are mentioned as factors that can contribute to maturing hydrogen technology. In maritime politics, for instance, there is a political target that all vessels in the world heritage fjords of Norway ought to be zero-emission within 2026. According to the strategy, this is an example of an already established target where hydrogen can be a part of the solution (Ministry of Climate and Environment & Ministry of Petroleum and Energy, 2020).

The report has received some criticism, most notably that there are few points of direct governmental action beyond public funding of pilot projects. Public funding for hydrogen and other pilot projects with sustainability ambitions comes from actors such as Enova, Innovation Norway, the Norwegian Research Council, or PILOT-E. The latter is a collaboration between the institutions mentioned. The strategy also emphasises the development of and demand from the European market. For instance, it is stated that largescale production of blue hydrogen in Norway is not realistic – instead, gas from the Norwegian oil shelf could be used to produce blue hydrogen on-site (Ministry of Climate and Environment & Ministry of Petroleum and Energy, 2020, p. 48). In sum, critics say that the strategy resembles a sum-up of already-known facts or a status report rather than an actual hydrogen strategy (Pedersen, 2020).

Perhaps as a response to the criticism, the strategy is further elaborated in the whitepaper *Energi til arbeid* (Meld. St. 36 (2020–2021), p. 107). In this whitepaper, the government is more transparent about concrete ambitions for hydrogen in Norway leading up to 2025 and 2030. For instance, within 2025, the government wants to establish five hydrogen hubs for maritime use, 1-2 industrial projects combined with hydrogen production, and 5-10 pilot projects to stimulate technology learning and cost reduction. Within 2030, the goals are related mainly to making hydrogen a feasible option for competing with fossil fuels.

A growing number of pilot projects involving hydrogen and ammonia are set to take place in the coming years – many of which have received funding from various public organs, such as the public agency Enova and the EU. Those that have gotten funding from the EU can typically be categorised as an IPCEI (Important Project of Common European Interest). Many also anticipate that hydrogen will see a cost reduction leading up to 2030 and an increase in carbon taxes that will further the position of emission-free technologies (Damman et al., 2021).

The Norwegian Research Council granted a total of 310 million to establish two new research centres on hydrogen in the early months of 2022: HYDROGENi, led by SINTEF, and Hyvalue, led by NORCE (Ministry of Petroleum and Energy, 2022). In the hard-to-abate maritime sector, hydrogen, either in its pure form or converted to ammonia, methanol, or synthetic fuel, is one of the few viable options to reduce emissions significantly. In June of 2022, Enova awarded

1.12 billion NOK to five hydrogen hubs along the Norwegian coast and seven hydrogen- or ammonia-powered vessels. This was a tremendous policy development with the potential to accelerate the uptake of hydrogen within the maritime sector by providing the necessary infrastructure and end-users to this infrastructure. Furthermore, the funding was also a strategic move from the perspective of expanding national industry due to the presence of several Norwegian shipyards and the importance of the maritime industry (Hovland, 2022; NHF, 2022a). As of spring 2023, a final investment decision (FDI) from the companies that received the funding is yet to be taken. As the funding is first and foremost to invest in new technology, it is unclear whether there will be any operational support, for instance, to produce and sell hydrogen at a competitive price, i.e., contracts for difference.

2.3.2 Central policy developments in the EU

In July 2020, the Commission published *A hydrogen strategy for a climate-neutral Europe* (European Commission, 2020). The strategy must be seen as a continuation of the targets and ambitions presented in the *European Green Deal* (European Commission, 2019). It is one of many strategies developed by the EU to reach carbon neutrality in Europe by 2050. In the wake of the covid-19 pandemic, the EU launched multiple funding schemes to recover the member countries' economies and promote innovation. After the Russian invasion of Ukraine in February of 2022, the EU also launched its strategy, *REPowerEU*, to accelerate the transition to renewable energy and, thereby, liberate themselves from the dependence on Russian fossil energy. This initiative awarded another 200 million EUR to the Clean Hydrogen Alliance through the Horizon Europe Programme (Clean Hydrogen Joint Undertaking, 2022).

The EU Hydrogen strategy presents multiple goals and phases of the European hydrogen development while differentiating between different hydrogen types. The strategy clarifies that renewable hydrogen, i.e., hydrogen produced through water electrolysis powered by renewable power, is at the top of the priority list. This is referred to as green hydrogen in the thesis. Low-carbon hydrogen from other sources is also needed in the short and medium term. This includes fossil-based hydrogen, most notably from natural gas, with high carbon capture rates. This is referred to as blue hydrogen in this thesis. In Phase 1, from 2020 to 2024, the aim is to install at least 6 GW of renewable hydrogen electrolysers and produce up to 1 million tonnes of renewable hydrogen. This phase is characterised by creating incentives for the uptake of hydrogen on the supply and demand side while creating a regulatory framework for the hydrogen market. Renewable hydrogen in this phase could also be used to decarbonise existing hydrogen production. In the second phase, from 2025-2030, the aim is to install 40 GW worth of electrolysers and produce 10 million tonnes of renewable hydrogen. It is also stated that hydrogen needs to become an intrinsic and integrated part of the EU energy system. Increasing the use and production of renewable hydrogen aims to make it cost-competitive with other forms of hydrogen, but demand-side policies will be needed to accelerate the uptake. In general, there is a need for funding and support from the EU to scale up the European hydrogen ecosystem. This phase is presented as the phase where new applications of hydrogen are accelerating, such as in the steel-making industry, in railroad transport, in trucks and buses, and to some degree maritime use. Hydrogen will also increasingly be used as a flexibility tool in the renewable energy system. Lastly, the third phase is rather broad, lasting from 2030 to 2050. In this phase, renewable hydrogen technologies should have reached a level of maturity that makes them applicable to all hard-to-abate sectors where electrification is not an option. This also entails that renewable energy production must be massively scaled up, as large-scale hydrogen production would require a substantial amount of energy (European Commission, 2020, pp. 3-7).

In sum, the strategy's targets are to develop various ways to promote hydrogen in the EU economy. This includes establishing an investment agenda, a supportive framework of market rules and infrastructure, a link between the EU and the international hydrogen community, and supporting R&D and pilot projects on hydrogen (European Commission, 2020, p. 21-23). In addition, several other EU organs are mentioned in the strategy: *InvestEU, Sustainable and Smart Mobility Strategy, European Clean Hydrogen Alliance, and ETS Innovation fund*. The *European Clean Hydrogen Alliance* is essential in this context. It sets out to connect different actors and stakeholders in the value chain and stimulate investment, production, roll-out, and use of clean hydrogen (European Commission, n.d.). The alliance has also created a pipeline of investment projects, which was one of the main objectives of the alliance.

In many ways, the Norwegian hydrogen strategy is interrelated with the EU hydrogen strategy. The European market is an essential prerequisite for a hydrogen economy in Norway, as stated in the 2020 strategy. In January of 2023, Norway and Germany released a joint statement regarding a feasibility study of cooperation in establishing a hydrogen export chain. Germany would function as the importer and Norway as the exporter. The prospect of transporting CO_2 from Germany to Norway for storage was also the subject of the feasibility study. In a transition phase, blue hydrogen based on natural gas with CCS will be necessary. When renewable infrastructure is in place, green hydrogen is the eventual goal, the statement reads (Office of the Prime Minister & Ministry of Petroleum and Energy, 2023).

3 Theoretical framework

3.1 Transition studies

This thesis is in line with transition studies, focusing on sustainability transitions within the transport sector. Transition studies is a relatively new field built on various scholarly fields such as evolutionary economics, innovation studies, science and technology studies, sociology, and the history of technology. Transition studies are heterogeneous in the sense that the focus and the topics of the field vary significantly, from long-standing sustainability debates at the macro level to behavioural changes among individuals on the micro level. In earlier work within the field, articles were often concerned with sustainability transitions in electricity and transport. Nowadays, other societal domains are also investigated, such as waste management, water, heat, agriculture, buildings etc. Several characteristics make studies on sustainability transitions a complex field, such as multidimensionality, the presence of multiple actors with conflicting interests, and uncertainty in technological development and trajectory, to name some (Köhler et al., 2019).

Concepts such as the socio-technical regime and niches are especially recurring within transition studies. The core idea behind the socio-technical regime is that scientific knowledge, engineering practices, and process technologies become socially embedded, which in return makes them intertwined with societal structures and institutions. Together, this provides direction to incremental change along established pathways of development in the regime (Markard et al., 2012, p. 957). A niche can be defined as specific markets or spaces where actors are prepared to work with specific functionalities, invest in new technology and grow new markets while accepting “teething” problems such as higher prices (Hoogma et al., 2002, p. 4). Transitions studies also have several established frameworks, the most prominent ones being transition management (TM), strategic niche management (SNM), the multi-level perspective (MLP), and the technological innovation system (TIS). MLP tend to focus on macro-dynamics and regime-niche interactions, while TM and SNM often focus on micro-dynamics, such as specific niches or experiments. TIS is a meso-level perspective focusing on niche dynamics

(Hekkert & Suurs, 2012). Each framework has prominent scholars at the forefront and is often concerned with similar topics from different perspectives. Broadly speaking, transition studies focus on sustainability transitions within different socio-technical systems and how these transitions come about. Note that there are multiple systems. The energy sector, the transportation sector, and the water sector are all examples of socio-technical systems (Markard et al., 2012).

Within the framework of MLP, there are multiple levels to consider when looking at innovation. There are the socio-technical regime and technological niches, but there is also a third level: the socio-technical landscape. This is an exogenous overarching level concerned with deep cultural patterns and macro-political development (Geels et al., 2017). Therefore, changes on this level are rather slow and can often be decades in the making. On the other hand, changes on this level are what create the so-called windows of opportunity for niches to accelerate into the socio-technical regime (Geels & Schot, 2007).

Strategic Niche Management, or SNM, is one of the earlier strands of work in transition studies. Scholars such as Hoogma and Kemp have been influential within this framework. SNM can be described as a tool for creating protected spaces for and controlling the phase-out of novel technologies where the aim is experimentation and learning (Kemp et al., 1998). There are multiple aims of strategic niche management, including; mapping the institutional and technological conditions needed for the success of new technologies; learning about the social desirability of different options; stimulating the development of new technologies; and building a necessary network of actors to promote the diffusion of new technologies (Kemp et al., 1998, p. 186). SNM is not only a policy tool for government or local authorities – private industry and non-governmental organisations are also well equipped to manage and run such projects. However, it is noted that institutional adaption and being an enabling actor should be an essential prosperity of policies to cultivate niches (Kemp et al., 1998).

Transition management forwards the idea of active intervention and is an approach to dealing with complex and persistent societal problems, such as climate change or energy transitions. It views sectors as complex and adaptive societal structures in which transition management can function as a reflexive and evolutionary governance process. To address complex problems, a range of stakeholders needs to be involved in a collaborative and adaptive process of change.

It highlights the need for various solutions, which can be achieved through experimentation (Kemp & Loorbach, 2006).

The fourth approach, technological innovation system, is the analytical approach I will apply to my case in this thesis. I will further elaborate on this in section 3.2.

3.1.1 The focus of transition studies

As the “socio” in the socio-technical regime implies, there is a social dimension to the logic and doings in the regimes, which mainly manifests itself in user practices (Bergek et al., 2015). A sustainability transition is a relatively complex process that leads to a fundamental shift within various socio-technical systems towards more sustainable modes of consumption and production (Markard et al., 2012, p. 956). Studying transitions, in general, is a challenging task. They develop over a long period of time and include extensive and complex processes in broad societal structures, often over large geographical areas (Hekkert & Suurs, 2012). Nowadays, these transitions come about because of so-called grand challenges, such as rapid climate change, poverty, ecological degradation, etc. The underlying logic of these transitions is that the current system is inadequate in dealing with challenges of this magnitude. Innovations, such as novel technologies and new business models, are essential drivers of change in the socio-technical system (Markard et al., 2020).

How these transitions come about is not a straightforward answer, and there are many challenges in accelerating sustainability transitions. For instance, two necessary conditions for the diffusion of a sustainable, often radical, innovation is the complementarity between multiple innovations and altercations in the system architecture (Markard et al., 2020). These conditions can easily be summarised but are challenging to arrange for. They often require extensive and complex policy coordination to stimulate a whole system transformation. Additionally, sustainability transitions tend to have conflicting values with existing business models and other systems. The lack of social acceptance and resistance from incumbent actors in the current socio-technical regime can also represent substantial barriers to sustainability transitions (Markard et al., 2020). In turn, this can create lock-ins and promote path dependence.

Lock-ins are a subject that is prevalent within transition studies, as this is essentially inherent to the current socio-technical system. However, the degree of lock-in varies depending on the context in which it is applied and whether it hinders or reinforces a specific technology (Klitkou et al., 2015). In their highly cited article, Kemp et al. (1998) ask how electric vehicles, which could offer a range of environmental benefits, struggled to get a foothold in the contemporary transport regime. The answer, they argued, was that "[…] there is not just one barrier to the introduction of alternative vehicles but a whole range of factors that work against the introduction and diffusion of alternative vehicles" (Kemp et al., 1998, pp. 175-176). This demonstrates how sunk-in costs and path dependency are strong forces in a socio-technical regime.

3.2 Technological Innovation System

As a framework for the analysis, I will employ the framework of the technological innovation system, commonly referred to as TIS. Even though this framework can be applied to most technologies, it is often used on novel technologies. Consequently, it is one of the leading frameworks within transition studies (Markard et al., 2012). Two of the most influential accounts of the TIS framework are Bergek et al. (2008) and Hekkert et al. (2007). However, the TIS framework itself is built on earlier work on technological systems, the functions approach, and the innovation systems approach (Bergek, 2019; Hekkert et al., 2007). The concept of technological systems is something most TIS analysis is based upon and can be defined as a network of agents interacting in a particular industrial or economic area under an institutional infrastructure (Carlsson & Stankiewicz, 1991).

The concept of a function can briefly be described as the contribution of a set of components to the TIS, which leads to the development and diffusion of new products and processes. The innovation system approach assumes that innovation, and subsequently technological change, is both an individual and a collective act that depends on institutional networks in both the private and public sectors. The activities and interactions within and between these networks contribute to the diffusion of new technology. Understanding technical change, therefore, entails "[…] creating insight in the relations between incumbent technology and the incumbent (innovation) system in relation to the emerging technology and the emerging innovation system" (Hekkert et al., 2007, p. 415). The dynamic between incumbent and emerging innovation systems is often of a competitive character – a competition where the incumbent systems have the upper hand (Kemp et al., 1998). However, it is essential to note that there is always agency involved in these interactions: "Through their actions, a multitude of actors conditioned by institutions and technologies, create and support the events that contribute to the development of the innovation system at large" (Hekkert & Suurs, 2012, p. 157).

Even though there are (many) more similarities than differences between the two TIS approaches, the main thing that separates the two is the categorisation of some of the steps within a TIS analysis: Hekkert et al. (2007) make a distinction between *knowledge development* and *diffusion* in identifying central TIS functions, while Bergek et al. (2008) make no such distinction, instead combining the two and adding a step called *positive externalities*. Although the differences are minor, they can affect how the functional pattern is analysed and understood (Bergek, 2019). In this thesis, I will use the approach of Bergek et al. (2008). That said, it is necessary to elaborate on the steps of a TIS analysis – with contributions from both sets of authors.

3.2.1 Defining the TIS

First and foremost, there is a need to identify the TIS's scope or starting point. This includes making some critical decisions: (1) whether to focus on a knowledge field or a product/artefact, (2) the breadth of the study, and (3) whether or not to focus on a spatial domain (Bergek, 2019). A knowledge field and an artefact can be broad or relatively narrow, depending on the goal of the analysis. Therefore, it is up to the researcher to set the analytical boundaries of the TIS. Additionally, it is common for a TIS analysis to be spatially limited or have a geographic context (Bergek et al., 2015).

Second, the structural components of the TIS need to be identified (Bergek et al., 2008; Hekkert et al., 2007). These can be divided into three main groups: actors, networks, and institutions. First, firms, research institutes, public agencies etc. are examples of what can be regarded as actors. In the literature on systems of innovation (SI), on which TIS is a continuation, the actors are regarded as the *players* of the game (Edquist, 2005). Further, networks, which also represent structural components, can be formal as well as informal. Some are orchestrated with specific tasks in mind, while others can be more loosely organised, such as links between different organisations. Formal networks are easily recognised, while informal networks require more thorough investigation. Third, institutions can be understood broadly, including norms, culture, laws, regulations, etc. There have been some disagreements in the SI literature about what can be considered institutions. However, it is often regarded as the *rules* of the game. This implies that the actors or players of the game operate on the basis of these institutions (Edquist, 2005).

If a (new) technology is to diffuse, there is a need for institutional alignment. It is often the case that TISs that share similarities with the existing institutions have an easier time than those that are more ‘disruptive’ in nature (Bergek et al., 2008).

3.2.2 Mapping the functional pattern

This step might be the most comprehensive, as there are seven aspects to consider. However, this step does not entail considering how well the TIS fulfils its central functions, as this is a designated step within a TIS analysis (Bergek, Jacobsson, Carlsson, et al., 2008). In short, functions are essentially the conceptualisation of processes that facilitate innovation and influence the development of an innovation system. The rationale for doing this is that the performance of a TIS cannot be reduced to the presence or absence of system components – an approach that has been common in innovation studies (Mäkitie et al., 2018, p. 814).

As a starting point, one needs to consider the TIS knowledge base and the diffusion grade. There are different types of knowledge. For instance, scientific and technological knowledge differs from market, logistic, and design knowledge (Bergek, Jacobsson, Carlsson, et al., 2008). Nonetheless, they are equally important to consider. In relation to scientific and technological knowledge, R&D projects, investments, and patents are good indicators of the attention given to the TIS from these spheres. In terms of diffusion, this is where R&D meets the market and all the dynamics that go with this interaction (Hekkert et al., 2007).

The second function to consider is what Bergek et al. (2008) refer to as *influence on the direction of search*. For a TIS to develop, there need to be sufficient incentives for organisations and firms to enter it. This aspect can be assessed by factors such as optimism surrounding growth aspects, the extent of regulatory pressure, better performance of actor/product prices, and the expression of interest from leading actors (Bergek et al., 2008, p. 415). Essentially, the function identifies mechanisms that guide actors to spend resources within a particular technological field. It should be noted that this function often concerns supply-side actors along the value chain (Bergek, 2019).

The third aspect is *entrepreneurial experimentation*, arguably the most critical aspect of technology learning. Hekkert et al. (2007, p. 422) argue: “The entrepreneurs’ risky experiments are necessary to cope with the large uncertainties that follow from new combinations of technological knowledge, applications and markets”. This is also an indication of the performance of a TIS. Additionally, experimentation provides more exposure of a TIS to specific audiences, for instance, consumers, government, competitors, and suppliers. In turn, this can also reduce the uncertainty surrounding a new technology (Bergek et al., 2008; Hekkert et al., 2007).

The fourth aspect is *market formation*. As the TIS approach is common within transition studies, many markets still need to be created or are yet to be mature. It can therefore be fruitful to distinguish between three market categories: (1) nursing markets with a subsequential learning space, (2) bridging markets which are characterised by an increase in volume and participants/actors, and finally, (3) a mature mass market – if the TIS is successful. Measuring a market in terms of technology diffusion is often easier than answering what factors drive market formation (Bergek, Jacobsson, Carlsson, et al., 2008). As the three market phases illustrate, new technologies are often poorly equipped to compete with incumbent technologies. It can therefore be necessary to temporarily create competitive advantages, such as favourable tax regimes, feed-in tariffs or contracts for difference (Hekkert et al., 2007).

The fifth aspect is *legitimation*. This aspect is not to be underestimated, as this is crucial in relation to social acceptance and desirability, resource mobilisation, articulation of demand from relevant actors, and the accumulation of political strength. This is also important in relation to establishing formal institutions, such as suitable regulations and certifications for novel technologies. Legitimation is, however, something that must be earned, and whether the TIS aligns with the existing institutional framework is also a decisive factor. Intuitively, a TIS that does not require significant changes in the existing framework does not need to spend as much effort on legitimacy, as opposed to a TIS that is more destructive towards the established system. Mapping legitimation entails analysing legitimacy in the eyes of various actors and stakeholders and efforts made within the TIS to increase legitimacy (Bergek et al., 2008, pp. 416-417).

The sixth aspect concerns *resource mobilisation*. Resources in this context have multiple meanings: (1) human capital or competence through education in specific fields, entrepreneurship, management, and finance, (2) financial capital, and (3) complementary assets, i.e., complementary infrastructure, products etc. (Bergek, Jacobsson, Carlsson, et al., 2008).

Lastly, the seventh aspect is the *development of positive externalities*. Arguably, generating positive external economies, in a literal and non-economic sense, is a crucial aspect in developing and expanding a TIS. The entrance of new firms in an emerging TIS accelerates positive externalities in multiple ways. For example, it can resolve uncertainties that have hampered the development of the TIS and contribute to legitimacy. In addition, the greater the number and variety of actors increase, the more new and innovative combinations are possible. In a sense, this is an enhancing factor to the six abovementioned aspects (Bergek, Jacobsson, Carlsson, et al., 2008). However, this can also be a challenging function to incorporate when analysing novel technologies in the early stages of development, where positive externalities can often be absent or difficult to identify (Bergek, 2019). Consequently, this function will not be employed in the analysis.

3.2.3 Assessing the functionality of the TIS

The fourth step is concerned with assessing how well a TIS functions. This step might come across as normative, but the scope of this step is mapped out by the seven functions identified in the functional analysis (Bergek, Jacobsson, Carlsson, et al., 2008). Thus, it is a matter of considering whether the TIS is currently equipped to become a part of the dominant socio-technical regime and what it is characterised by. To assess the "goodness" of a TIS, as it is often referred to by Bergek et al. (2008), there are two main steps to consider: (1) the phase of development of a TIS and (2) comparisons between systems. Additionally, the strength of the functions is not only determined by the influence of structural components; exogenous factors at different levels (e.g., regime/landscape) or other innovation systems, such as regional and sectoral, may also have a vital influence on functions performance (Bergek, Jacobsson, & Sandén, 2008, p. 579).

A TIS's two main phases are the formative and growth phases. It is also possible to consider more phases, such as the stage of maturity and decline. The latter is often relevant when analysing a sustainability transition in which some unsustainable technologies are in decline. Such an approach is related to the life cycle of a TIS (Markard, 2020). However, TIS scholars are often concerned with the formation of new industries. Therefore, it often makes sense to consider the two former phases more thoroughly. In the formative phase, a rudimentary structure is formed, with the entry of some firms and/or organisations, the contours of institutional alignment, and some networks. There are also other, more concrete, indicators of the formative phase. For instance, the time dimension of a TIS is a crucial indicator, with many successful TISs often developing over a decade – if not several decades. There can also be uncertainties about the performance of the technology itself, price and performance, and the volume of economic activities. The latter aspect is often a fraction of the potential, with unarticulated demand and the absence of positive externalities being more pertinent. However, these characteristics are to be expected in a formative phase, and it is also necessary to eventually reach a growth phase. In the growth phase, economic activity increases, along with technology diffusion and market formation. In such a phase, the performance of the functions is subsequently stronger (Bergek, Jacobsson, Carlsson, et al., 2008).

Comparing TIS with the performance of similar innovation systems in other national and regional contexts can increase the understanding of the TIS performance. Perhaps most significantly, this can provide an understanding of what to expect from a TIS and identify critical functions. This could pave the way for specific policy goals to increase the functionality of the focal TIS, which can be seen as process goals (Bergek et al., 2008, pp. 419-420).

3.2.4 Blocking and inducement mechanisms & policy implications

When a TIS struggles to manifest itself in the dominant regime, there can be many reasons for this. Roughly speaking, this can stem from internal and exogenous factors – i.e., the context surrounding the TIS (Bergek et al., 2015). For instance, the dominant regime is often biased in favour of established TISs, making the entry of new TISs challenging – especially if it exhibits characteristics of “creative destruction”. Furthermore, the ideal functional pattern of a TIS is often affected by blocking mechanisms of different shapes and forms, making it all the more important to identify these mechanisms. On the other hand, there can also be inducement mechanisms that promote the development and uptake of a TIS. The two significant mechanisms of this kind are government R&D policy and the belief in growth potential. Thereby, identifying blocking and inducement mechanisms is the fifth step of a TIS analysis.

The sixth step concerns policy development, often specific to the TIS. Generally speaking, “[…] policy should aim at remedying poor functionality in relevant TISs by strengthening/adding inducement mechanisms and weakening/removing blocking mechanisms” (Bergek et al., 2008, p. 423). This is also why TIS analysis is a valuable tool for policymakers. In the following, I will elaborate on policies that have been suggested in other instances where novel technologies have been the object of analysis in section 3.2.5.

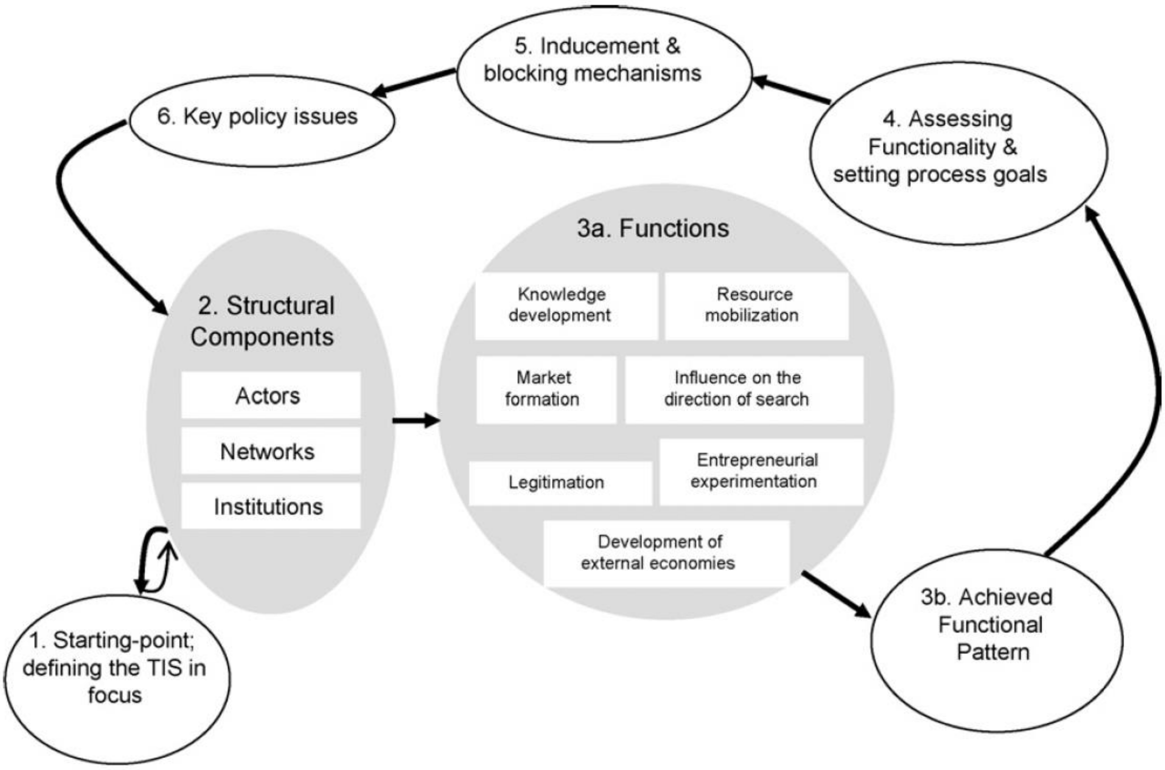

Figure 1 TIS scheme of analysis (Bergek et al., 2008)

3.2.5 The role of supportive policy

Much has been written about low and zero-carbon (LoZeC) technology in Norway. For instance, many contributions address hydrogen in the maritime sector amongst other low- and zero-carbon solutions (Bach et al., 2020; Mäkitie, Steen, et al., 2022; Steen et al., 2019). This has also been followed up with several policy recommendations, some of which will be presented here to function as a basis for the discussion on policy later on.

Many argue that state leadership, often in the form of technology-specific policies, is crucial to unlocking the potential of hydrogen because of the inherent risk it poses to private actors (DNV, 2022). This approach contrasts with much of the ideals that have been prevalent in policymaking for some time – that of technology neutrality. However, while technology neutrality is often suited to promote the most cost-effective options, it is likely insufficient to reach emission-reduction goals. Therefore, technology-specific policies are viewed as the ideal approach in relation to sustainability transitions (Azar & Sandén, 2011; Schot & Steinmueller, 2018).

The difficulties surrounding low- and emission-free hydrogen are often described as a chicken-or-the-egg dilemma. On the one hand, there is uncertainty about hydrogen supply for the end-user, which can halt investments in hydrogen-powered technology. On the other hand, committed users are pivotal to large-scale production (Damman et al., 2021; Mäkitie et al., 2021). In other words, creating hydrogen value chains is a financial risk that can be difficult to overcome. This is particularly demanding regarding private equity and investors, and attracting this type of capital will likely require significant government support. Currently, opportunities in hydrogen are seen as long-term and low-return, seemingly with a high-risk. Therefore, this is vital to balance risk and return (DNV, 2022, p. 27). The widespread diffusion of and heavy investment in battery technology in Norway could represent a technological lock-in, which could be a barrier to hydrogen technology and value chains (Damman et al., 2021, p. 5).

In a research note on how to enable the use of maritime hydrogen in Western Norway, Mäkitie et al. (2021) present arguments that are also valid in relation to the establishment of other hydrogen value chains. There is, for instance, a need to support early movers, i.e., those who invest in the hydrogen value chain in various ways, as these are the actors that create demand. In this value chain, infrastructure is crucial to create certainty for early movers. Ideally, investments in hydrogen technology and infrastructure should happen simultaneously, i.e., what is referred to as *synchronisation* by some scholars (Mäkitie, Hanson, et al., 2022). However, it is possible that infrastructure might have to precede hydrogen-powered vessels, which seems to be the case with novel technologies in general. There should also be links between different sectors to increase demand and promote commercialisation, establishing hydrogen hubs that can serve multiple purposes (Mäkitie et al., 2021).

In relation to government support, there are many mechanisms that could be utilised. Currently, the most common strategy of government funding programmes is to provide investment grants or loans to capital expenditures (CAPEX), i.e., the initial investment support. However, support schemes for operational expenditures (OPEX) will likely increase in the coming years. Contracts for Difference (CfDs) can be used as a mechanism in this context. This supplements operational costs with a strike price guaranteed to producers over a certain amount of time, essentially creating a price that is doable to the producer and end-user. These are technology push mechanisms (DNV, 2022, p. 35). However, due to the complexity of both hydrogen and hard-to-abate sectors, there are many who point towards technology-specific policies that take these complexities into account (Bergek et al., 2023).

3.3 The focal TIS and its context

A TIS does not emerge nor develop in a vacuum – a context surrounds it. Therefore, it is helpful to consider this context when analysing a TIS, with four main categories being identified as particularly important: technological, sectorial, geographical, and political context. These are referred to as context structures in which a TIS frequently interacts with (Bergek et al., 2015). Again, it is worth remembering that the TIS consists of a technology field, actors, networks, and institutions bound to interact with a broader societal structure (Bergek, Jacobsson, Carlsson, et al., 2008). For this reason, employing the term "focal TIS" when the contextual structures are being considered can be helpful, as many scholars do when conducting such an analysis.

As mentioned, the first steps of a TIS analysis entail mapping out the scope of the analysis – essentially establishing the focal TIS. Bergek et al. (2015) mentions two types of interaction between the focal TIS and the context: external links and structural couplings. The former relates to overarching influences that impact the focal TIS, but not vice versa. These can typically be macro-level developments, often called changes in the landscape level within innovation studies (Geels & Schot, 2007). External links can also be closer to the focal TIS than the landscape typically is, such as national policies, a shift in public discourse etc. The second kind of TIS-context-interaction, structural couplings, is more significant. This involves shared elements, such as actors, technologies, networks, and institutions, between the focal TIS and such couplings. An institution, for instance, does not exist for the sole purpose of promoting a single technology. Similarly, a firm may be engaged in and explore multiple technologies simultaneously. Frequently, there can be several structural couplings. This can constrain some TISs, especially emerging ones, as this can limit flexibility, funding, infrastructure, alliances, etc. On the other hand, a strong coupling is sometimes necessary to develop new technology, for instance, in terms of assets/infrastructure. Further, external links and structural couplings relate to the four *analytical* context structures mentioned earlier, as this is where they become apparent (Bergek et al., 2015).

When analysing a TIS relevant to a sustainability transition, it is difficult not to consider other TISs with the same locus or incumbent technologies, the latter often with an emissions-intensive nature. These types of TIS-TIS interactions constitute a technological context structure. These interactions can be of a competitive or complementary character, or even both, depending on the elements involved. For instance, market shares and strategic assets can be the objects of competition. On the other hand, the scale-up of one TIS can benefit the development of another. Sectoral context structures can have many of the same characteristics, as they also consist of multiple TISs. However, these are often at different maturity levels with different levels of institutional embedding. Additionally, a sector typically consists of the production, distribution, and use of technologies that fulfil a certain function for certain users. In terms of geographical context structures, there are many aspects that can be highlighted. For instance, looking at the specific national or local contexts relevant to a TIS can be useful. Often, these contexts can be geographical in a literal sense. It is also possible to look at embedding TIS structures in certain territories or the structural couplings among actors, networks, and institutions in different places. Multinational companies can also be based on multiple locations, constituting a relevant context structure. Lastly, the political context is often critical to facilitate large-scale transformation due to its significant influence on institutional alignment. Note that the geographical context is closely related to politics, as a political ideology can severely impact how a nation handles different technologies. For instance, technology neutrality can represent a barrier to the focal TIS, while a willingness to enforce technology-specific policies can induce it (Bergek et al., 2015).

3.4 TIS analysis on hydrogen within different segments

Much has been said and written about hydrogen in different sectors, as its use is rather versatile. In the following section, I will elaborate on some TIS analyses of hydrogen within the transport and maritime sector.

3.4.1 The Dutch Fuel Cell TIS

As mentioned in the background, fuel cells are often considered when hydrogen in the transportation sector is considered. Some TIS analyses have also been done on this, for instance, on the development of the Dutch fuel cell TIS from the first attempts of commercialisation in the 1980s and throughout the first half of the 2000s (Suurs et al., 2009). This analysis shows that the TIS did not have a linear development pattern, instead representing a constant back-and-forth interaction with different contexts and functions. The functions can reinforce each other over time, achieving the effect termed cumulative causation, which can be briefly summed up as interacting pattern functions. The distinction is also made between what Suurs et al. (2009, p. 9640) chose to label enactors and selectors. The enactors are actively involved in developing a TIS and foster positive expectations about its success. The selectors are usually involved in the TIS at a later stage, often due to the efforts of the enactors. The latter is also more prone to exiting a TIS as their interest is not fixed, while the former is more dependent on the success of the TIS, making the stakes higher for this group in comparison (Hekkert & Suurs, 2012; Suurs et al., 2009).

The analysis aimed to identify the motors of innovation of the fuel cell TIS, which was identified in two phases. The first phase was the *Science and Technology Push* (STP) Motor, driven by enactors. The development in the STP phase was primarily driven by knowledge development, with scientists and technology developers as the main enactors and the Dutch government representing the selector. With these roles, the enactors functioned as persuaders towards the Dutch government to secure government-backed resources for R&D. The resources were assigned due to an increased focus on clean energy technologies and an ambition of building national industry. In the 1990s, the selectors also started to include external actors such as the EU due to the increased attention fuel cell technology was getting on a global scale. A knowledge base was also forming, based not only on R&D but also on pilot projects and demonstrations. However, commercialisation was far from a reality, and as we know, fuel cell technology has still not achieved a wide market diffusion. This was mainly due to significant expenses and the need for effective technology demonstration (Suurs et al., 2009).

The second phase is termed the *Entrepreneurial Motor*. Outside the Netherlands, global companies were starting to take an interest in fuel cell technology. The research on the technology was increasing globally, incentivising big car manufacturers to enter the field. This also had spillovers to other parts of the value chain, with companies taking an interest in the decentralised storage of hydrogen and the refuelling infrastructure. Generally, there was more variety in terms of actors in the TIS. However, this also made the coordination more complex as several firms explored various technologies. The number of selectors was also increasing, with both local and national governments filling the role of the selector, in addition to the EU government (Suurs et al., 2009).

The analysis of the Dutch fuel cell is an example of how a TIS, especially an emerging one, constantly evolves in different directions, with different parts of the functional pattern reinforcing each other. It also shows how the expectation of emissions reduction can drive technology development, despite the technology struggling to provide promising results. On that note, fuel cells have yet to transition into a growth phase.

3.4.2 Comparing the hydrogen and battery TIS in Norway

In recent years, some TIS analyses have compared the development of batteries and hydrogen within the Norwegian maritime sector (Bach et al., 2020) and the passenger vehicle segment (Langeland et al., 2022). There is also TIS analyses on alternative fuels within the maritime sector, in which both hydrogen and batteries are discussed (Steen et al., 2019). These analyses showcase how batteries have an advantage compared to hydrogen, at least at the time of writing.

The advantage of batteries in the maritime sector comes from Norway's wide diffusion of battery-electric vehicles, making the core technology more mature and familiar than hydrogen. There are also many investments from public and private actors in batteries, strengthening the overall legitimation of the maritime TIS. According to Bach et al. (2020, p. 8), the position of batteries in Norway can be described as an *advanced niche market*. Another factor is the regulatory framework already developed with respect to battery-electric vehicles, representing a structural coupling that can positively affect the battery-electric maritime TIS as well. To a certain degree, it is possible to argue that there is a complementarity formation between the sectors (Mäkitie, Hanson, et al., 2022). On the other hand, just as in the maritime hydrogen TIS, there is a need for more standardisation in the segment, which leads to technological uncertainty.

On the other hand, the maritime hydrogen TIS is in an *early demonstration phase* (Bach et al., 2020). Access to public and private funding is increasing, in addition to the number of R&D and entrepreneurial projects, and political goals concerning hydrogen are starting to form. The maritime TIS also have positive synergies with the road-transport TIS of hydrogen. On the other hand, there is also an unwillingness to experiment with more than one emission-reducing technology at a time due to financial risk. This benefits the battery-electric TIS rather than the hydrogen TIS (and other technologies), despite the consensus that batteries cannot be the sole solution to emission reduction in the maritime sector. The cost of hydrogen and hydrogen powered-vessels, in addition to the lack of infrastructure, is also a significant barrier to the TIS.

In the passenger vehicle segment, battery-electric vehicles (BEV) have had an increasingly dominant position in Norway since the 2010s, especially when accounting for newly purchased vehicles. This results from a stable policy framework developing since the 1990s and the combination of easy-to-access power sockets to charge at home with increasing public charging infrastructure. There has also been a presence of powerful lobby groups, such as the consumer-focused Norwegian EV Association (Langeland et al., 2022). Both BEVs and FCEVs have enjoyed tax-related benefits compared to fossil-driven vehicles, although it has not led to an increase in FCEVs. This is mainly due to the lack of refuelling infrastructure, which requires a coordinated strategy. The hydrogen infrastructure also took a blow in 2019 when a refuelling station exploded outside of Oslo. The station operator, Uno-X, abandoned their plans to expand their hydrogen activity after the incident, despite their plans of a network of at least 20 stations. Consequently, the focus of FCEVs in recent years has mainly been heavy-duty transport. This could lead to spill-overs to the passenger vehicle segment in the future (Langeland et al., 2022).

4 Methodology

In this thesis, I have used qualitative methods to gather data. Above all, I have interviewed actors relevant to a constantly evolving TIS. When investigating a niche technology, many aspects can come across as ambiguous, even contradictory, at times. This is why I would argue that qualitative methods, particularly interviews, are fitting to approach this topic. Essentially, it contributes to nesting up aspects that can be hard to capture using other methods (Dunn, 2016). In the following, I will elaborate on my methodological choices during the data-gathering process and how I handled the data.

4.1 Case study as a research method

I would classify the subject I am interested in as a case, making this a case study. This is also in line with the logic of a TIS analysis, which aims to investigate certain aspects of a specific technology or knowledge field and its surrounding context (Bergek et al., 2015; Bergek, Jacobsson, Carlsson, et al., 2008). A theoretical background can be useful when it is time to draw conclusions from a case. This is where the term analytical generalisation is highly relevant and significantly different from that of statistical generalisation. The latter involves making generalisations based on a sample. This can, for instance, be a sample of the population. Analytical generalisation, on the other hand, involves using empirical data to probe into some theoretical concepts. This can, in turn, strengthen the validity of the findings or link them to something beyond the specific case (Baxter, 2016; Yin, 2014). I will elaborate on validity later in this chapter, more specifically, how I assess the validity of my findings.

Case studies are often used to answer “how” and “why” questions in research and deal with patterns and operational links that can be viewed over time. “How” and “why” questions are more explanatory than typical “what” questions, with the latter often exploring the prevalence of a phenomenon – therefore favouring survey or archival methods. This being said, there are two types of “what” questions. They can also be in the form of “what can be learned from…”, which can also be present in a case study (Yin, 2014, p. 10). For instance, one of my thesis's main objectives is to explore *what* the functional pattern of the heavy-duty hydrogen TIS is a case of. In my case study, I also investigate a phenomenon, i.e., a development of an innovation system, within its real-world context. This consists of various actors, networks, institutions, and contexts that impact the performance of the functional pattern. However, as is common to case studies, the boundaries of this system are not always evident. This is also illustrated in the general definition of a case study:

> A case study is an empirical inquiry that (1) investigates a contemporary phenomenon in depth and within its real-world context, especially when (2) the boundaries between phenomenon and context may not be clearly evident (Yin, 2014, p. 16).

In general, there are many misconceptions about case studies. For instance, some would argue that it is difficult to generalise from case study findings or compare different cases. In both instances, the underlying assumption is that some methods are better equipped to achieve this than others – most notably methods frequently used in the natural sciences, such as experiments and randomised controlled trials. On the other hand, one can also ask: what can be achieved through a single experiment? An experiment aims to test a phenomenon under different conditions, relating to theoretical propositions rather than whole populations. If applied correctly, the same can be said of case studies. As mentioned above, the goal is to make analytical generalisations rather than statistical generalisations. Concerning how comparative a case study is to other cases, it can be helpful to reflect upon whether this is a goal in itself. For example, a randomised controlled trial aims to measure the effect of different treatments or interventions. However, case studies can help answer the “how” or “why” of the results from these trials, something that also makes case studies equipped to follow up on such trials (Yin, 2014, pp. 17-23).

4.2 Research design

A case often has many aspects of interest, leading to multiple sources of evidence and data triangulation (Yin, 2014, p. 17). Additionally, both multiple- and single-case studies fall under the case study umbrella – although some make a distinction between the two. In my instance, I would categorise my study as an embedded single-case study, as illustrated on the next page. First and foremost, a single case study can be appropriate when the case has a critical, unusual, common, revelatory, or longitudinal character. My case has a revelatory character, as there is no study like it as far as I know Norwegian context. Secondly, when I describe my study as an embedded single-case study, this entails that my case, the heavy-duty hydrogen TIS, has multiple sub-units. These sub-units range from the structural components and functional pattern of the TIS, in addition to the context structure of the TIS (Yin, 2014, pp. 51-56).

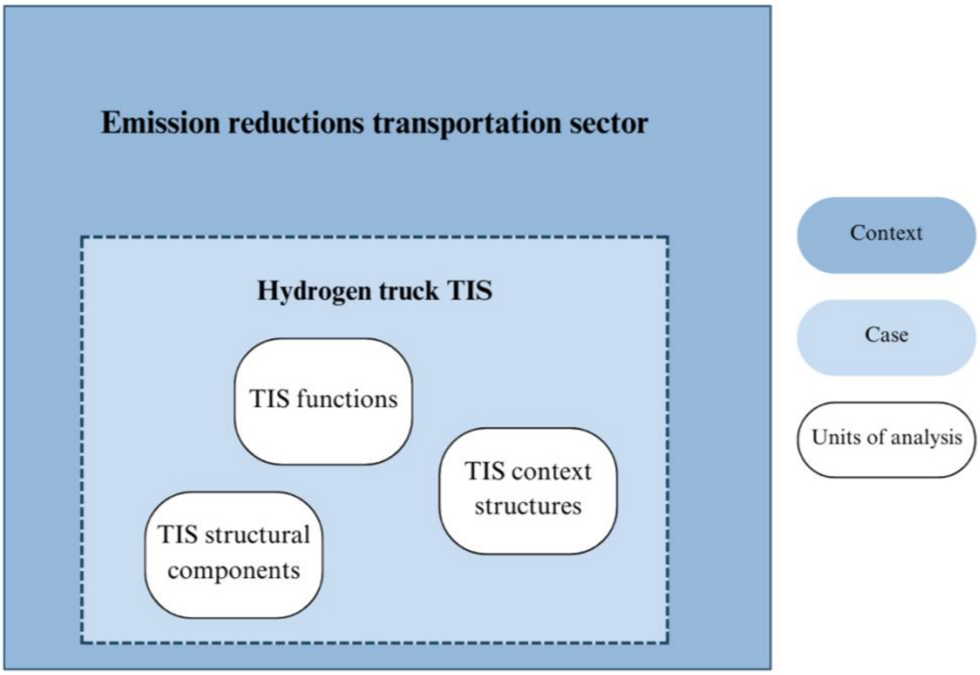

Figure 2: Embedded single-case design (Yin, 2014)

My thesis can be split into multiple phases. The first phase consisted of doing a broad search of the hydrogen situation in Norway while keeping in mind that I wanted to narrow down my thesis to a specific technology within the hydrogen ecosystem. I was open to many hydrogen technologies, and this could, for instance, be in the form of a production method, such as blue or green hydrogen, or in different end-use segments, such as high-heat and heavy industry, the maritime segment, or the heavy-duty segment. I eventually landed on the heavy-duty segment, and there were multiple reasons why. First and foremost, I wanted to write about something that was already operational to some degree. In other words, I wanted to write about a hydrogen technology that had some entrepreneurial experimentation connected to it. In the case of Norway, I found this in the logistics company ASKO –specifically, their branch in Central Norway. Even though their four hydrogen cars had only been operational since the spring of 2020 (in reality, 2021/2022 due to the covid-19 pandemic), this intrigued me and eventually led me to choose hydrogen within the heavy-duty segment as the object of my analysis.

4.2.1 Data collection

The second phase included a literature search within innovation studies. This led me to choosing TIS as my analytical framework. As opposed to MLP, which is another major framework within transition/innovation studies that I also considered, I felt like TIS could offer a way of analysing a system *innovation*, i.e., hydrogen in the heavy-duty segment. If I were to study the transition from fossil fuels in the transportation sector, a system *transition*, MLP would have been more suited. This further led me to search the available TIS literature, which was very fruitful due to the availability of TIS analysis already conducted on different hydrogen technologies and end-uses. The research questions result from a close dialogue between the literature and empirical findings, including political hydrogen strategies and various articles, during the research phase. Based on this, I would argue that the research questions are deductive in nature. As mentioned earlier, it was also important to me that the thesis focused on a particular use of hydrogen rather than hydrogen as an energy carrier in general. Consequently, the research questions were also limited in scope – something that is recommended in qualitative research. Then it was time to recruit informants.

I interviewed 11 people working in different companies, institutions, and segments relevant to my focus on hydrogen within heavy-duty transport. This did not entail that they exclusively worked with hydrogen for this particular use. Most of them did not. Using hydrogen to reduce emissions in different sectors is still a niche, limiting the selection of actors working to promote this technology – especially if the different end-use segments were to be separated. This led me to recruit various informants working with hydrogen in one form or another. That being said, some informants had professional backgrounds that aligned very well with the focus of my thesis. The first informant I recruited was an employee at ASKO (Informant A), a central person in their hydrogen project. The second person I recruited was very involved in a project to specifically promote the use of hydrogen within the heavy-duty segment in Norway (Informant C). Finally, one of my last interviews was with someone who worked on an EU-funded project to create a hydrogen corridor for the heavy-duty segment between Oslo and Hamburg, also involving Danish and Swedish regions (Informant J). These were the three informants specifically involved with hydrogen in the heavy-duty segment. Some of the remaining informants worked in research institutes or projects. Other informants were more involved with politics, funding of new technology, the Norwegian energy sector, the production side of hydrogen, and heavy-duty transport in general. A comprehensive list of my informants, with their names redacted and substituted for a code, is available below. On average, the interviews lasted between 30-60 minutes. These were recorded with the permission of the informants and later transcribed.

Table 2: List of informants and duration of interviews

Informant code	Firm	Duration of interview
Informant A	ASKO	75 minutes
Informant B	SINTEF	46 minutes
Informant C	H2 Truck	31 minutes
Informant D	Mobility Zero Emission Energy System (MoZEES)	36 minutes
Informant E	Enova	41 minutes
Informant F	Everfuel	55 minutes
Informant G	SINTEF	41 minutes
Informant H	Miljøstiftelsen ZERO	48 minutes
Informant I	Norwegian Energy Partners (Norwep)	44 minutes
Informant J	STRING Megaregion/Greater4H (STRING)	38 minutes
Informant K	Norwegian Road Transport Association (NLF)	54 minutes

4.2.2 The in-depth interview as a source of data

In-depth interviews are a common strategy for gathering data in many research projects, particularly qualitative ones. As mentioned above, I have also used this as a data collection technique in my thesis. In this section, I will elaborate on why the in-depth interview is a valid and valuable method to gather data.

There are many reasons to conduct research interviews. For instance, interviews can help fill a knowledge gap where other methods are not suited or not enough on their own. It also offers insight into complex behaviours and collects a variety of opinions, meanings, and experiences. Importantly, it allows a researcher to discover what is relevant to the informant (Dunn, 2016). In my case, I sought to get insight into the dynamics and central developments in an evolving niche. This made the experience and opinions of actors in this niche or located close to it a natural strategy for achieving this insight. Interviews were, therefore, the way to go about gathering this insight. As mentioned, I also read multiple TIS analyses throughout my literature search, many of which used interviews with relevant actors in the TIS to draw conclusions about the central development of the TIS and to assess the functional pattern. An example of this was the TIS analysis of the Norwegian maritime industry by Bach et al. (2020), where interviews with a number of relevant actors were used to gain insight.

The interviews themselves were semi-structured. This entails that the questions were organised around a set of pre-determined questions, while other questions emerged as the conversation went on (DiCicco-Bloom & Crabtree, 2006). In a semi-structured interview setting, the researcher is flexible and is not bound to the interview guide (Dunn, 2016, p. 158). In my case, the spontaneous questions were not too far off from the topics we were already discussing, although this helped me get a richer understanding of the informants' experiences. Many of these questions emerged when they were talking about particular projects they had been a part of, or they could be requests to elaborate on something mentioned earlier. In other words, I remained flexible throughout the interviews. This stands in contrast to the structured interview, which typically comprises a list of carefully worded questions that are asked in exactly the same order. This makes the interview question-focused, whereas I felt my interviews had more in common with conversation than this strict form of interview style. There was really no point for me to ask the same questions to every informant, as they represented different parts of the TIS I was interested in. In other words, I did not employ the same interview guide for every informant. Rather, I adjusted the questions in accordance with the background of the informants and, importantly, which company, project, or institution they represented. On the other end of the scale, there is the unstructured interview. This is more suited when digging into the individual's personal history, which is not the aim of my thesis (Dunn, 2016, pp.158-160). I, therefore, felt comfortable with the semi-structured approach.

The interviews were conducted using Microsoft Teams. This was the preference of most informants, regardless of whether we were located in the same city. I figured this was due to a post-pandemic mindset, in which many professionals had to become very comfortable communicating on digital platforms during the pandemic and discovered their convenience. I did not mind doing digital interviews and viewed this as time-saving measure. However, many qualitative researchers have been wary of using alternatives to the in-person interview. These alternative interview methods include the digital interview, e-mail and other asynchronous measures, and the telephone interview. Traditionally, they have not been seen as equivalent, and the in-person interview has for a long time been perceived as the gold standard because they enable both verbal and non-verbal cues to be considered (Novick, 2008; Thunberg & Arnell, 2022).

However, most researchers had to adapt to the pressing situation during the pandemic, which has resulted in a digital revolution in interviewing of sorts. Through a literature review of different methods used in research, Thunberg and Arnell (2022) discovered that there had been debates about whether the digital interview and even the telephone interview offer richer data than the face-to-face interview, also before the pandemic. To some informants, the flexibility of the digital interview could be experienced as more comfortable than the more direct face-to-face interview. For instance, the fact that they do not have to meet up with a stranger could lower the threshold of disclosing their experiences. Among other things, this increase in comfort level is why some researchers have argued that the digital interview could lead to richer data. I would not say that an increase in emotional comfort was why my informants preferred the digital interview. As I understood it, this was more of a convenience as the interview would not take up as much time. I would therefore argue that the comfort was more practical in nature. Nevertheless, I did not feel like the quality of the data suffered as a consequence of using Teams rather than meeting the informants in person.

4.2.3 Recruiting the informants

As I have stated multiple times, the informants were recruited due to their relevance to my project. This is the most common strategy for researchers: informants are selected because they can communicate their experiences and ideas relevant to the researcher’s interest (Dunn, 2016). However, this entails a rigorous research process to ensure you are talking to the “right” people (Bradshaw & Stratford, 2016, p. 123). Patton (2002) has developed seven purposive sampling categories, where I identify with two sampling strategies: criterion sampling and snowball sampling. The former is related to choosing informants because they meet a criterion: in my case, they worked with hydrogen on some level and/or heavy-duty trucks. I also employed the snowball method, which entails recruiting informants based on the recommendation of other informants (Bradshaw & Stratford, 2016, p. 124). In other words, criterion sampling was the primary strategy, whilst I employed the snowball method if the recommended informant also met the criterion. This allowed me to contact individuals that could otherwise be hard to reach.

When contacting informants, there are some things a researcher should be wary of. First, it is crucial to introduce oneself and establish your intentions. Second, it is essential to clarify how one obtained the contact information of the informant. Third, outline why the informant is relevant to the research. Lastly, indicate the interview length (Dunn, 2016). These were all things I made sure to disclose to the informant upon initial contact. I also repeated this at the beginning of each interview. This helped set the tone and steer the informants toward my interests – even though some were more involved with other things than hydrogen within heavy-duty transport.

Stating the length of the interview was also a helpful precaution. To some informants, this was also the necessary information to get them to agree to an interview in the first place. As stated earlier, many had busy schedules, which often made the time they were willing to set aside for an interview maximum of an hour, maybe even half an hour. This is also something Harvey (2011, p. 436) found when interviewing elites, and he experienced that many of the elite informants he had interviewed had a mindset of "how much can I tell you in 45 minutes". This is a balance where it is vital to stay realistic, and asking for too much time could lead to the informant declining participation. Finally, some informants were contacted via e-mail, while others via phone. I did not prefer one or the other, although reaching out via phone was the most effective alternative. Most informants I contacted agreed to an interview, while a few did not answer my e-mail. Overall, the response rate of informants was high. In addition to this, I also sent them an information sheet via e-mail on how their data would be handled. This also stated that their anonymity would be ensured. I will return to this process in this chapter's ethics and rigour section.

4.2.4 Recording and transcribing interviews

During the interviews, I took audio recordings that would be transcribed later. In addition to notetaking, this is a standard technique when doing interviews. Some combine the two, but I did not indulge in this. Many researchers find that audio or video recording allows for a natural flow in the interviews because the researcher is not preoccupied with notetaking and allows more time to prompt the following questions. Some even argue that this can detract from attentive listening (Dunn, 2016). I also found this something that made taking notes more or less excessive. If the interviews had been conducted in person, there is a good chance that I would have felt differently about this because the situation would probably have come across as more intense. Therefore, I imagine that note-taking could be a good buffer in such a situation. However, because of the digital format, things like body language and eye contact were dialled down, and I did not need to "seem busy" while the interview was ongoing. Additionally, I resorted to nodding and small conversational cues to show that I was paying attention to what was being said. This was also important due to the semi-structured format of the interviews, as I was planning on asking questions based on things the informant had previously stated.

The audio recording was agreed upon beforehand, but I also disclosed this at the beginning of each interview and asked if the informant was ok with it. Everyone agreed to this. However, I noticed that some informants were wary of *how* they articulated certain things because of the audio recording. This was not the case for every interview, but some informants referred to the recording during the interview. An audio recorder can remind informants of the formal situation of the interview and potentially inhibit an informant's responses. Altogether, this can make the informant less forthcoming (Dunn, 2016, p.169). This can be problematic because the data quality is not as good as it could have been. When these situations arose, I could have stopped the recording and resorted to note-taking. However, I figured that the informants who referred to the recording before they said certain things did so because they were mindful of being quoted on things that were too frank or harshly worded. This can, for instance, result from media training and previous experiences with questions from journalists. Therefore, I concluded that this did not pose a problem and that the audio recording was more valuable regarding data quality than the potential information I could have gotten if this was not present.

As stated above, I used audio recording during the interviews to be able to transcribe them later. This is a time-consuming task, and many recommend that this should be done as soon as possible after an interview. Transcribing one's interviews is also recommended, as this can function as a preliminary form of analysis (Dunn, 2016, p. 170). Even though there are many auto-transcript services available, I chose to do my own transcripts. There were multiple reasons for this.

First and foremost, this gave me a richer understanding of the information conveyed in the interview, i.e., a preliminary analysis as stated above. Second, by doing the transcripts myself, I was also able to write them out in a clear manner. I figured it would be easier to transcribe the data myself in a more condensed and precise way than using software that could not do this. This did not entail that I heavily edited the responses of the informants. However, most people use filler words or take some time to articulate their answers, which I "cleaned up" during transcription. Many researchers argue that the transcript should be a verbatim record of the interview and should therefore include the things I chose to remove manually (Dunn, 2016, p. 170). However, I did not see a point in this. This can be useful in studies where discourse and semantics are of more importance, but in my project, I was essentially concerned with what the informants said rather than how they said it.

4.3 Data analysis

When the interviews were transcribed, I used the software NVivo to code the interviews following my theoretical framework. At a later stage, these codes were used to conduct the analysis. Data coding is an overall strategy within qualitative research to make sense of the data in relation to the research question. The purpose of coding could be described as data reduction, in the sense that the researcher group large amounts of data into key themes (Cope, 2016; Elliott, 2018). In essence, a code symbolically assigns an attribute to a portion of data, in this instance language-based data (Saldaña, 2020). Essentially, using NVivo allowed me to group quotes from different informants describing the same themes, which functioned as vital preparation for the analysis.

I used the concepts and categories from TIS to code my data, specifically those used to assess the functional pattern of a TIS. In total, I had nine main codes: one for each TIS function, one for the TIS context structures, and one for the structural components of the TIS. The latter two also had sub-categories. The TIS context structures were divided into four codes: political, sectoral, geographical, and TIS-TIS interactions. The structural components were divided into three codes: actors, networks and institutions. In other words, I had a set of prespecified, or a priori, codes that I later used to categorise my data. Many researchers prefer to do this the other way around, letting the codes emerge during the coding process. Some argue that the researcher should always be open to emerging codes, as prefigured codes do not necessarily allow the participants' views to shine through (Elliott, 2018). In my project, however, it would be counterproductive not to use the concepts from TIS as codes. This doubled to sort the data and lay the essential groundwork for a theoretically anchored analysis. Additionally, using a priori codes allowed me to move through the data quicker than emerging codes, which can be time-consuming.

In qualitative research, analysing the data entails observing and discerning patterns in the data material and constructing meaning that captures their essence (Saldaña, 2020). How I have understood the TIS functions, structural components, and context structures is vital to how the data were coded and later analysed. Importantly, the innovation system framework itself is an analytical construct that the analyst is familiar with, while the informant is not (Bergek et al., 2008). As the informants did not have the same theoretical understanding of the innovation system that I did, this necessitates some overlap in their answers. When conducting the analysis, this was consequently a back-and-forth process due to these overlaps. This also led me to employ other data sources to complement the findings. Essentially, this entails a process of triangulation that is important when conducting research (Bradshaw & Stratford, 2016). Additionally, I later assess the strength of the functions, rating them on a scale from *weak, intermediate,* to *strong*. This was done on the basis of my findings and represents my interpretation of the focal TIS. Lastly, this was addressed using policy. Figure 3 showcases the analytical process, inspired by Bach et al. (2020) with some modifications.

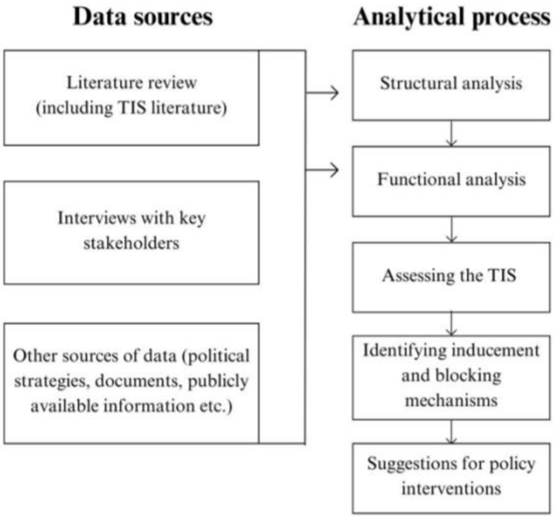

Figure 3 Analytical process (Bach et al., 2020)

4.4 Ethical considerations

Because I chose to record the interviews, I had to notify Sikt about the project and apply for permission to collect and process personal data. Sikt is a public agency that handles research and ethics-related inquiries in Norway. This is standard practice when conducting to ensure that the rights of the informants are well taken care of. In my project, I did not handle sensitive data, nor did the informants belong to a vulnerable group. I have, therefore, chosen to include the name of the firm or institution they are a part of. As mentioned, the information I wanted to gain through interviews is their professional view on topics relevant to this thesis. Therefore, the employer of the informants seems like relevant information to give some context to their views. When directly quoted, for instance, it can be advantageous to know whether a public funding agency, such as Enova, or a consortium for hydrogen, such as H2 Truck, employs the informant. Their name, however, is not disclosed. Any personal information I got access to through the interviews is not included in this thesis as this does not serve any purpose for the research questions.

Good research practice includes informed consent. This entails that when the informants are approached for an interview, they know what they agree to (Dowling, 2016). With this in mind, I sent an e-mail before the interviews with an information letter describing the project's aim, how they could go about if they wanted to withdraw their consent or insight into their data, and how and how long their data would be stored. The letter also stated that they would remain anonymous, except for the firm or organisation they were employed by. At the end of the letter, there was also a consent form that the informants signed. The information letter was developed using a template from Sikt and approved with my application.

Lastly, quotes from informants are frequently referred to in the analysis. However, all interviews were conducted in Norwegian, meaning the quotes were translated. The translation was done using software. To avoid losing meaning in translation, I have constantly asked myself whether the translation reflects how the message was conveyed in Norwegian. Overall, I would say that this does not pose an issue, as I am confident in the translation of the selected quotes.

4.4.1 Rigour and critical reflexivity

Ensuring rigour in qualitative research entails certain things. Firstly, it means establishing trustworthiness. This can be done by involving the interpretive community of the researcher, which is the academic context I find myself in, and the participant community. My interpretive community is innovation studies, as the academic work I consume, in addition to my supervisor and fellow students, is related to this academic field. It also involves a triangulation process, which was mentioned in section 4.3. This is a process in which multiple sources, methods, investigators, and theories are consulted. Lastly, it involves acknowledging limits to the transferability of the research (Bradshaw & Stratford, 2016, pp. 125-128).

In the research process, I have engaged in what is referred to as critical reflexivity. This is a process of self-scrutiny concerning the role of the researcher, or the self, and the social setting in which one operates. Two things, in particular, can be helpful to reflect upon: power and subjectivity (Dowling, 2016). For instance, I was conscious of the somewhat asymmetrical relationship between the informants and me. When I recruited the informants, I was aware that I was new to a field some of them had been working on for years – maybe even decades. This, combined with the fact that I was a student, could represent an imbalance of power in the interviews. Power is present in all social relations and contexts and cannot be eliminated. This includes the research situation I was in. Whether this affected the quality of my data is difficult to estimate, although I did not experience this as a barrier. Many informants were used to talking to students and showed interest in my project. I also adjusted the interview guide according to the informants role and made sure to be well-prepared. This indicates that the asymmetrical relationship did not pose a problem. It is, however, something to be aware of and continuously assess during the research process. Subjectivity is also an important aspect in this regard. Because qualitative methods often involve social interaction, I must be aware of the biases, meanings, and interpretations of the world that I, as a researcher, bring with me (Dowling, 2016, pp. 35-40).

5 Analysis

5.1 Defining the focal TIS

As mentioned throughout this thesis, the object of analysis is hydrogen trucks – either in the form of FCETs or hydrogen combustion engine trucks. Although multiple truck sizes exist, hydrogen trucks in this thesis are often synonymous with long-haul heavy-duty trucks. This is because long-haul trucking of heavy goods is the application in which hydrogen trucks can be the most sensible option to reach zero-emission in the long term. This is opposed to (smaller) trucks that have a more local-based operational pattern, where electrification is currently the preferred option to reduce emissions. In other words, I have decided to focus on a product rather than a knowledge field, which is also possible when doing a TIS analysis, and an application for the technology – long-haul heavy-duty trucks. The diffusion of this product, or technology, is currently limited. This does not mean that the analysis of such a product is fruitless; more often than not, TIS analysis focuses on novel technologies (Bergek, Jacobsson, Carlsson, et al., 2008). Additionally, it is common to choose a geographical focus for a TIS analysis:

> While TISs are generally global in character, there may be reasons to focus on a spatially limited part of a particular system in order to capture other aspects, perhaps those most relevant for a particular set of actors in a regional or national context (Bergek et al., 2008, pp. 412-413).

In my case, I have chosen to focus on hydrogen trucks in Norway specifically. Firstly, there is much interest in hydrogen in Norway. For instance, hydrogen has been a frequent topic in political debate in recent years. In addition, the ambitions of reducing emissions have been a dominant focus amongst policymakers and the population, which once again has put hydrogen on the agenda. The Norwegian hydrogen strategy is a testament to this, in addition to recent grants to pilot projects with hydrogen in the maritime sector and research centres on hydrogen (Hovland, 2022; Ministry of Petroleum and Energy, 2022). Secondly, this decision has a practical dimension, as it is easier for me to access informants in Norway than in other countries. However, many of the informants I interviewed underscored that the European hydrogen market is an important context in terms of pilot projects and other measures to promote hydrogen. In addition, the European market is an essential customer for Norwegian hydrogen producers and companies specialising in certain technologies in the hydrogen value chain.

First and foremost, there are multiple actors in Norway that specialise in hydrogen production. The majority of the market for hydrogen is currently limited to its existing use within various industries, and carbon-intensive grey hydrogen is still very much dominant – both in Norway and globally (DNV, 2022, p. 12). In terms of hydrogen in the heavy-duty segment, green hydrogen currently seems to be the preferred option, at least according to the informants. The utilisation of grey hydrogen was not considered an option, as this would weaken the legitimacy of hydrogen applications in Norway (Informant B, H2 Truck; Informant J, STRING). Some informants also noted that the EU has taken a sceptical approach towards blue hydrogen. However, this is starting to change because of geopolitical developments, and blue hydrogen seems to be accepted in a transition phase – particularly in heating where natural gas is currently utilised (Informant J, STRING; Informant I, Norwep). However, green hydrogen is generally favoured in transport. For instance, the envisioned maritime hubs along the Norwegian coast are all set to produce green hydrogen (Hovland, 2022). As the multi-use of these hubs is relevant to hydrogen trucks as well, this increases the notion that green hydrogen seems to be preferred within the transportation sector. Because of the reasons listed above, green hydrogen will primarily be the method of production of the hydrogen truck value chain in this analysis.

5.2 Defining the structural components of the focal TIS

The structural components of a TIS include actors, networks, and institutions. In this section, I will identify the key actors and networks relevant to the focal TIS, in addition to formal and informal institutions. However, the structural components identified in this section are relevant to many other technologies that utilise hydrogen – not just hydrogen in the heavy-duty segment specifically. To start this off, I will formulate a value chain for the focal TIS. This will mainly include actors in the structural components of the TIS.

5.2.1 Actors: the value chain of the focal TIS

As mentioned above, green hydrogen is the main mode of production considered in this TIS analysis. There are multiple companies in Norway that are relevant in terms of green hydrogen production. This includes both new entrants who exclusively engage with hydrogen and incumbent actors who have multiple business ventures. The former includes companies such as Norwegian Hydrogen, Everfuel, Hyfuel, Glomfjord Hydrogen, Meråker Hydrogen, H2 Marine, and GreenH, to name some. The latter includes actors who have a strong presence in the Norwegian industry, like Statkraft, Hydro, Equinor, Aker Solutions/Horizons and so on. Additionally, an intrinsic part of green hydrogen production is electrolysers. One of the most prominent actors in Norway in terms of electrolyser technology, and green hydrogen in general, is NEL ASA. Other companies focused on electrolyser technology with a presence in Norway include Hystar and Hydrogen Pro. Further, green hydrogen also makes Norwegian power companies and grid capacity essential parts of the value chain.

Companies specialising in hydrogen refuelling stations are also a part of the value chain. Importantly, this also includes efforts to transport the hydrogen from production sites to the refuelling stations. Several firms are operating in Norway that specialises in hydrogen refuelling stations. This includes companies like Everfuel, Hynion, and Vireon. NEL ASA is also a technology provider of refuelling stations with close relations to Everfuel. Vireon, on the other hand, is a subsidiary of Norwegian Hydrogen.

The manufacturers of hydrogen trucks are at the centre of the value chain. There are multiple vehicle and truck manufacturers engaged in developing hydrogen trucks. Notably, these are European or Asian companies, such as Volvo, Daimler, MAN, Quantron, Nikola, Toyota etc. Therefore, the technological development of hydrogen trucks is not happening in Norway. However, this does not mean Norwegian actors and companies have no role in this development. For instance, R&D from Norwegian research institutes can be utilised when developing fuel cells or other technologies in the TIS value chain.

There are also actors that specialise in hydrogen safety, such as Hyex Safety. This is a vital part of the value chain regarding regulations, as safety is extremely important to manufacturers and the public. The Directorate for Civil Protection and Emergency Planning (DSB in Norwegian, as I will hereby refer to it) is also vital in this regard, although with a broader mandate than the former.

The end-users of hydrogen trucks, i.e., companies who utilise trucks in their operational pattern, are also important actors. In theory, this can include most companies that own one or more trucks. In practice, however, multiple aspects currently make some companies better equipped than others to integrate hydrogen trucks into their operations. Mainly, this concerns limited resources in smaller companies. In Norway, the logistics company ASKO, with its Central Norway branch, is the only actor that has utilised hydrogen trucks in its operations. On the other hand, there are other companies that have shown interest in hydrogen trucks. This includes actors such as the Norwegian postal service, PostNord, Rema1000, Coop, and Bama (H2 Truck, n.d.). However, this has not yet materialised into any public agreements or contracts as of May 2023.

Lastly, research institutions are important in many parts of the value chain. There is much research on hydrogen in Norway through various research institutes and universities. SINTEF is the most prominent independent research institute in Norway. It is also a leading actor in hydrogen research, including electrolysers, fuel cells, hydrogen technology, -storage and -quality, CCS, and various materials (Informant 2, SINTEF). In 2022, 200 million NOK over the span of eight years were awarded from the Norwegian Research Council to form a new Research Centre for Environmentally Friendly Energy (in Norwegian referred to as an FME – forskningssenter for miljøvennlig energi) dedicated to research on hydrogen and ammonia: HYDROGENi, coordinated by SINTEF. The research centre has 50 partners from industry and academia, both within Norway and from Europe, and is set to educate 35 PhDs/Postdocs and 100 master/bachelor-candidates (SINTEF, 2022). In addition, the NORCE-led research centre HyValue was awarded 120 million NOK[1] over the span of eight years in the same grant from the Research Council (Ministry of Petroleum and Energy, 2022; University of Bergen, 2022). This marked two significant developments in the R&D on hydrogen in Norway and is in line with the targets established by the Norwegian government in the whitepaper *Energi til arbeid* in the years leading up to 2025 (Meld. St. 36 (2020–2021), p. 107).

Besides the two mentioned FMEs, there are also other research institutes that conduct research on hydrogen in Norway. Institute for Energy Technology, or IFE, is a Norwegian independent research institute. At IFE, there is much research on hydrogen, for instance, through their fuel cell and hydrogen technology test centre IFE Hynor (IFE, n.d.). The Centre for International Climate Research Oslo, or CICERO, is another actor that conducts research on hydrogen, specifically on the consequences of hydrogen leakage into the atmosphere (CICERO, 2021). The FME Mobility Zero Emission Energy System, or MoZEES, is another ongoing research centre that conducts research on hydrogen in Norway (FME MoZEES, n.d.). According to the website of the Norwegian Research Council, there is a significant number of hydrogen research projects that have been awarded funding throughout the years. When searching for projects involving hydrogen in their research archive, a total of 4.5 billion NOK has so far been distributed to 767 projects between 2004 and 2023 (The Norwegian Research Council, n.d.).

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[1] 15 million NOK annually in the span of eight years

Additionally, there are many projects and research on hydrogen within universities, as research institutes have close ties with universities. Thereby, Norwegian universities are also important partners in such projects, including those mentioned thus far.

The value chain is mainly comprised of companies with business interests, with the exception of R&D institutions. However, there are also other actors relevant to the TIS that have overarching functions. This includes political institutions and funding agencies. The Norwegian Government is, of course, an essential actor. Among the ministries, the Ministry of Climate and Environment, the Ministry of Petroleum and Energy, and the Ministry of Transport are the most relevant to the focal TIS. As hydrogen within the transportation factor is in a preliminary phase, it depends on national policy to support and accelerate the value chain. Strategies and whitepapers are vital documents that affect the actors in the value chain in multiple ways. The non-governmental organisation (NGO) and environmental agency ZERO are also prominent in relation to hydrogen. Their main target group are decision-makers in politics and business.

As discussed in the background chapter, there are also multiple public agencies that provide funding for new technology in different stages. To repeat, these include the Norwegian Research Council, Innovation Norway, Enova, and PILOT-e, which is a collaboration between the three (Informant E, Enova). Out of the three, Enova is the most significant to the TIS value chain. In turn, Enova is subject to the Ministry of Climate and Environment.

5.2.2 Networks

There are several networks relevant to the focal TIS. Some key networks are identified here, mostly formal in character. Although identifying informal networks in a TIS analysis is common, this has not stood out in the data material. I would argue that the formal networks identified lay the base work for informal networks. Therefore, informal networks are not explicitly considered in this section but rather treated as an inherent capability of formal networks.

First and foremost, the Norwegian Hydrogen Forum (NHF) is a strong lobbyist for hydrogen and ammonia in multiple sectors. This also includes hydrogen in the heavy-duty segment. NHF also promotes the role and interests of Norwegian hydrogen producers and technology developers abroad. Their primary task is to be a link between public authorities, the policy apparatus, politicians, and actors in the hydrogen value chain to ensure good framework conditions for hydrogen and ammonia. The Nordic Hydrogen Partnership is another network that connects hydrogen activities in the Nordic region more closely. NHF is one of the members of this partnership, creating an additional layer to the forum.

The H2 Truck consortium is another example of a lobbyist for hydrogen in the heavy-duty segment. The consortium aims to connect actors in different parts of the value chain, including providers of hydrogen and refuelling stations, truck manufacturers, and end-users. The main geographical area the consortium is focusing on is Eastern Norway (Informant C, H2 Truck). H2 Truck is also involved with the EU-funded project Greater4H. The official partners are, however, Oslo municipality and Viken County municipality. They are also partners in the H2 Truck consortium. Greater4H, on the other hand, is a regional collaboration under the STRING Megaregion umbrella to realise a hydrogen corridor between Oslo and Hamburg for heavy-duty applications. In other words, Norwegian, Swedish, Danish and German regions are involved in the project.

Another network specifically working with hydrogen in heavy-duty transport is the HyWay Alliance Trøndelag. This network is working towards establishing a hydrogen infrastructure that can serve 80% of all land-based heavy-duty transport in Norway by 2035. This alliance has several members, most of which are located in central Norway and Trøndelag. The hydrogen producer in the project is Meråker Hydrogen, while the hydrogen distributor is Everfuel (Meråker Hydrogen, n.d.).

Lastly, the Norwegian Truck Association (NLF) is also relevant to the focal TIS and its value chain, representing potential end-users. The association has 2600 member companies, whereas 30-40% of these members have five cars or less. This is an actor located close to the truck segment with much insight into the dynamics and interests in the segment as a whole. The association has several regional networks in Norway and is also connected to the Nordic Logistics Association, which operates in Brussels and speaks on behalf of the Nordic transport sector. In sum, NLF works for the framework conditions of Norwegian transporters. Among other things, this includes aspects like the competitiveness of and the regulations imposed on the segment, and they are generally very outspoken about which solutions are doable for their members. NLF also promotes other means of reducing emissions that are not directly technology related. The main implication is not to drive more than necessary. This includes aspects like maximising space utilisation, i.e., driving fewer trips while maximising freight load per trip. In relation to this, bigger trucks are more suited. Reducing the number of trucks on the roads is also a safety aspect (Informant K, NLF).

5.2.3 Institutions

In this section, I will assess some key institutions relevant to the focal TIS that have emerged in the data material and through research. Rules, regulations, support policies, and procurement practices constitute formal institutions, while norms and social acceptance are typically regarded as informal institutions (Steen et al., 2019, p. 24).

The rationale in policy aimed at stimulating innovation and new technology is, in many instances, technology neutrality (Azar & Sandén, 2011). For instance, the Norwegian hydrogen strategy of 2020 emphasises that much of the development of the hydrogen economy relies on market forces. This show somewhat of a technology-neutral rationale, as the underlying logic is that the market will push forward the best-suited solution. On the other hand, there have been signals that hydrogen, in its pure form or as a feedstock for other fuels, will have a role in transitioning to a zero-emission maritime sector. The same cannot be said for hydrogen in the heavy-duty segment, where there is no clear ambition in terms of policy. In this segment, hydrogen competes with battery-electric trucks for market shares: seemingly, there is an “either-or” narrative between the TISs.

To an extent, it can be argued that this technology neutrality is Enova's rationale as well. In their current agreement with the Ministry of Climate and Environment, which lasts four years, there are two subgoals: reduce emissions leading up to 2030 and contribute to developing new technology leading up to 2050. This is, therefore, the most important thing to Enova, and they do not have any preferences as to how this should happen. However, technology neutrality often means that the most cost-effective option is chosen. Therefore, Enova can be generous if a technology shows good emission-reducing potential but poor price performance and market maturity (Informant E, Enova). Therefore, Enova can also provide technology-specific support policies that align with many of the arguments presented by Azar and Sandén (2011).

New hydrogen applications, in general, require new regulations and standards – so-called hard regulations. This is, consequently, something that must be aligned if the TIS is to accelerate. In terms of safety standards, this is particularly important. Accidents with new technologies can severely impact the reputation of those technologies – even if accidents with established technologies occur more frequently. To a certain degree, hydrogen is associated with danger. Hydrogen, like natural gas, can be dangerous if it ignites accidentally and causes fires or explosions. On the other hand, the difference between natural gas and hydrogen is that hydrogen is more reactive, leading to a wider flammable range. When hydrogen is applied beyond its current use, many new users will also handle it. Risk perception will likely vary, with sensitivity increasing when the public is near the actual use of hydrogen. This is also a business risk to investors (DNV, 2022, pp. 20-21).

Risk perception is also an important explanatory factor when looking at the aftermath of the hydrogen refuelling station explosion in Sandvika in 2019, as briefly mentioned when presenting other TIS analyses on hydrogen. The explosion occurred on the 10th of June, and by the end of June, it was clear that two wrongly installed bolts were the culprits. In other words, human error was the main cause of the accident (Jensen, 2019). However, the incident also affected other hydrogen facilities. For instance, numerous operational bans were imposed, and several inspection rounds had to be conducted (Informant A, ASKO; Informant D, MoZEES). Some of these processes lasted for months. Uno-X also abandoned its plans to expand its hydrogen infrastructure, and the station never reopened. Essentially, this was a setback for the Norwegian hydrogen infrastructure.

Established norms and regulations in a sector are factors that can affect the development of a TIS (Bergek et al., 2015, p. 57). The transportation sector is set to undergo several changes to reduce CO_2 emissions. Therefore, how the commercial actors in this sector relate to this is very relevant. However, reducing emissions is something that is familiar to these actors. There have, for instance, been several European emissions standards since 1992, with the Euro 6 standard being the current one. The main targets of the emission standards are nitrogen oxide (NOx) and particulate matter ($PM_{2.5}$ and PM_{10}) from diesel and gasoline, as these pollutants affect local air quality. The heavy-duty segment has successfully reduced many of these pollutants, while lighter vehicles have been harder to regulate (Hooftman et al., 2018). The Euro 6 standard is something actors in the Norwegian transportation industry have been highly adaptive to, and 97-98% of all freight transport is currently by this standard (Informant K, NLF). This bears witness to an industry that can adapt to regulations from authorities.

5.3 Mapping the functional pattern

The most important step of a TIS analysis is identifying the functional pattern. This process also distinguishes the TIS analysis from other forms of innovation system analysis. In this section, I will analyse the seven functions identified by Bergek et al. (2008). Above all, this is the manner in which I present my empirical findings gathered from interviews and relevant literature. Importantly, the focal TIS, and thereby the functions, is an analytical construct. Therefore, the empirical findings are sometimes repeated in several functions, although discussed from different angles. This is particularly apparent in the functions of influence on the direction of search and market formation, as both functions are concerned with incentives in one form or another. Additionally, many of the influencing context structures are hard to separate from the functions when analysing these. Where it is natural, I have chosen to include some context structures when analysing the functions – despite the presence of a separate section devoted to analysing these.

5.3.1 F1: Knowledge development and diffusion

There are several dynamics to consider in the function of knowledge development and diffusion. In this function, limiting the activities to a Norwegian context is difficult. Norway does not specialise in trucks, and there are no Norwegian car manufacturers. This technology development happens in other countries. However, this is not to say that Norway has no activity in terms of hydrogen research. As illustrated when discussing the actors of the focal TIS, several research institutions focus on this. Rather, it means that the focal TIS and the European hydrogen truck TIS are hard to separate in this function, as they are very much interconnected.

As discussed in the TIS value chain, several research institutions in Norway are engaged with R&D on hydrogen. The newly established FMEs HYDROGENi and HyValue are significant arenas for knowledge sharing and the development of hydrogen in the coming years (Informant D, MoZEES). However, whether these research centres are focused on hydrogen within heavy-duty applications is not apparent from their websites. The maritime sector seems to be the end-use in which their focus is currently directed.

That being said, SINTEF, the coordinator of HYDROGENi, is one of the most prominent actors in terms of heavy-duty hydrogen applications identified during the span of this thesis. Their research on fuel cells and electrolysers, for instance, are important contributions to the TIS value chain. They were also closely involved with the only hydrogen truck project in Norway that has currently materialised – that of ASKO Central Norway.

> We started in an early phase, so not many of the suppliers had commercialised. Many of the manufacturers were the result of entrepreneurial companies that consisted of highly qualified technical personnel, typically researchers and engineers. SINTEF was a door opener to help us into those environments (Informant A, ASKO).

By describing SINTEF as a door opener, the quote illustrates that the knowledge developed at this research institution is vital in a real-world context to accelerate hydrogen uptake. SINTEF also assist with economic feasibility studies for other actors and has previously done multiple TCO (Total Cost of Ownership) on behalf of the Norwegian Hydrogen Forum (Informant B, SINTEF). These resources are, in turn, a result of decades of work on hydrogen technologies. SINTEF is also an important actor in relation to the European hydrogen truck TIS. In March of 2023, it was announced that SINTEF would coordinate the most recent project of H2Accelerate, an ambitious project aiming to roll out 150 FCETs on European highways from Daimler Truck, Volvo Group, and Iveco. This also includes a refuelling infrastructure that will service these trucks. The funding for the infrastructure comes from Connecting Europe Facility (CEF), while the Clean Hydrogen Partnership granted 30 million EUR to the roll-out of the 150 FCETs (H2Accelerate, 2023).

The Greater4H project is also relevant to this function. The project is twofold: One part of the project focuses on the hydrogen corridor, while the other part focuses on soft measures to accelerate the uptake of hydrogen in the heavy-duty segment. The soft measures were described as such: “This involves research on hydrogen, how to increase demand, and how to design pilot projects with trucks” (Informant J, STRING). In other words, this is part of the knowledge development and diffusion of the focal TIS – specifically in the Nordic region and Germany. The project has also received much attention from the EU Commission, and the informant experienced a strong hydrogen agenda in the union. In general, private-public projects have a high standing in the EU, especially when multiple regions across national borders are involved. The private part of the project, i.e., the hydrogen corridor, is also funded by the EU. In total, the project received 12.4 million EUR through CEF.

> When we applied for EU funding, we experienced high amounts of interest in our project, and there is a strong hydrogen agenda in the EU. They also have their own initiatives put together by various parliamentarians and generally set themselves quite ambitious goals, also specifically in heavy transport (Informant J, STRING).

The Greater4H project is a good example of a project that aims to create and diffuse knowledge while also materialising. As the project also involves Norwegian regions, it was a common reference point for many of the informants. The EU is a vital actor in many functions related to the focal TIS, including this function. Over the years, R&D on hydrogen under the EU umbrella has been substantial, making for a large knowledge base. This also reflects the observation of a strong hydrogen agenda in the quote above.

5.3.2 F2: Influence on the direction of search

In this function, I will address mechanisms that steer actors and firms towards entering the TIS. Additionally, some central barriers are identified. In this section, much of the focus is directed towards the supply-side actors. For this reason, the findings are not limited to operations in Norway.

As mentioned, Norway has a target of reducing 55% of emissions by 2030, along with many other countries. This, in turn, has severely influenced our time's political targets and rhetoric. This is, first and foremost, a driver for many decarbonising technologies – not just hydrogen. However, in recent years there have been many signals from the government that Norway is mature for hydrogen as a decarbonising technology. The hydrogen strategy published in 2020 is a testament to this. Regardless of the criticism it has received for being cautious, it is the first of its kind in Norway. This is certainly a significant development in terms of hydrogen. In other words, there have been signals that hydrogen is a political priority, something that can be regarded as a driver in this function. However, are these political signals sufficient to incentives firms to enter the focal TIS?

At the beginning of the value chain, there are the actors that produce green hydrogen. This is expensive for several reasons, one of which is that electrolysers are expensive. This is reflected in the price per kilo of hydrogen. In turn, this makes green hydrogen difficult to sell on a commercial basis, making the current use of it limited. Meanwhile, a price reduction requires a larger production quantum, which can only be triggered by increased use. The chicken-or-the-egg dilemma is often used as a metaphor for hydrogen, as it describes whether infrastructure or end-users come first. However, this is not just a chicken-or-the-egg dilemma but a matter of scale (Informant G, SINTEF). As described in the empirical background, if the production of electrolysers were automated, this would lead to a reduction in price per unit, which could lead to more extensive facilities that produced hydrogen in larger quantum. Thereby, green hydrogen could be sold at a more reasonable price to the end-user (Reksten et al., 2022). Fuel cells, which significantly drive up the price of fuel cell trucks, are also suited for automated production. This means that the same principle can be applied to this technology (Informant G, SINTEF). However, in a preliminary phase, many argue that there should be support schemes in place to make green hydrogen more competitive, as the scaling up of electrolyser facilities is something that will take time. Additionally, policies that facilitate the scale-up of renewable power production by the time it is needed are, in turn, necessary for the scale-up of green hydrogen production (Informant H, ZERO).

With the Enova funding to the five maritime hydrogen hubs, it is possible to see synergies with heavy-duty trucks, heavy industry, and other commercial actors, such as taxis (Informant F, Everfuel). To those who produce hydrogen in Norway, diversifying their portfolio of potential end-users is in their best interest to ensure that the hydrogen will be utilised. This can also contribute to a cost reduction. The hydrogen hubs were initially meant for maritime use, as this was what Enova explicitly set as a requirement to get funding in the first place. Since then, they have now adjusted this requirement so that at least 50% of the hydrogen produced shall go towards maritime use – which opens possibilities for other segments to also benefit from the hubs (Informant G, SINTEF). An important *if* in this context is that there have not been any final investment decisions yet concerning these hydrogen hubs (Informant H, ZERO; Informant E, Enova).

Currently, hydrogen trucks are not an off-the-shelf commodity. However, truck manufacturers are increasingly interested in fuel cell technology and hydrogen combustion engines. Regarding European truck manufacturers, Volvo and Daimler have launched a joint venture with fuel cell systems, mainly for use within long-haul heavy-duty, called Cellcentric. Both manufacturers will use these fuel cells in their trucks and other applications (AB Volvo, 2021). Together with Iveco, Daimler and Volvo will also be providing fuel cell trucks for the H2Accelerate Truck project, in which the goal is to introduce 150 fuel cell trucks on European roads in the coming years (H2Accelerate, 2023). Iveco, together with Nikola, is also the truck manufacturer involved in the Greater4H project through collaboration with GP Joule. This German power company will provide hydrogen refuelling stations to the German regions involved. The collaboration with the truck manufacturers will most likely be in the form of a leasing agreement (Informant J, STRING). Other manufacturers, such as MAN, DAF, and Scania, are more comprehensive about hydrogen and focus more on different technologies – such as biogas (Informant K, NLF). This is despite Scania being the only manufacturer that has delivered hydrogen trucks to Norway and is producing two more that will be delivered to ASKO in 2024. Although hydrogen will probably not dominate Scania's manufacturing pattern in the coming years, they have implemented it in their strategy. This signals that the technology can potentially be a more significant part of their portfolio in the future (Informant A, ASKO).

Despite the fact that several truck manufacturers have announced that they will have hydrogen trucks in production this decade, the diffusion of such trucks will not necessarily have a broad geographical reach. For instance, The H2 Truck project aims to introduce 100 hydrogen trucks on Norwegian roads by 2025. However, there are several delays in the hydrogen truck value chain (Informant J, STRING). The manufacturers also have preferences regarding where their trucks will be operated. This preference is skewed towards the strategic customers located close to the manufacturers in proximity. To counter this, the H2 Truck project has therefore chosen to focus on the Eastern region of Norway, as this is the region with the highest density of trucks. This can offer a more cohesive infrastructure that can benefit the preliminary phase of hydrogen trucks (Informant C, H2 Truck).

In late 2022, the Government launched their infrastructure strategy for battery-electric fast chargers (Ministry of Transport, 2022). This was especially relevant to battery-electric trucks, as the market for fast chargers to passenger cars is commercialised, while the former is not. In this strategy, hydrogen is rarely mentioned. When mentioned, it is in connection to passenger cars, not heavy-duty trucks, as many argue are the more reasonable use of the technology. Multiple informants argued that the strategy should have been a combination of battery and hydrogen infrastructure (Informant C, H2 truck; Informant G, SINTEF). This would allow for better space utilisation, as many of the "best" spots are already taken (Informant F, Everfuel).

> I have emphasised in every possible context that there should be a program for building a hydrogen infrastructure and that it must be in place for anyone to be interested in investing

> in trucks. However, it is a bit of a challenge. The politics could be even more explicit, more aggressive, and set clearer ambitions for what to do (Informant C, H2 Truck).

This sentiment, namely that the Norwegian policy and ambition level concerning hydrogen in the heavy-duty segment is inadequate, is shared among many informants. In turn, this is off-putting both to the potential end-users of trucks and actors involved in the subsequent infrastructure. In this function, the incentives for actors on the infrastructure side are particularly relevant. As elaborated in the structural components of the TIS, a few actors are on the infrastructure side of the focal TIS present in Norway. The refuelling infrastructure, however, is sparse. If this were to expand, it would be necessary with an adequate number of end-users. Once again, I return to the Greater4H project; this is an example of a project that incentivises firms on the infrastructure side of the value chain to enter the focal TIS, while also providing end-users that can utilise this infrastructure through GP Joule's collaboration with Iveco. There are also additional benefits to this private-regional partnership. For instance, this reduces the bureaucracy of establishing hydrogen refuelling stations, which can be time-consuming because of regulatory frameworks. Additionally, it also offers a political legitimacy that can influence how other actors perceive the hydrogen value chain. Everfuel is one of the companies that has received funding for building eight refuelling stations in the Swedish and Danish regions of the project. Hynion provides the two refuelling stations in Norway. However, the Hynion stations are privately funded – something that was a prerequisite if the Norwegian regions were to join as well. This is due to Norway standing outside of the Connecting Europe Facility (CEF) arrangement, which is the public agency funding the refuelling stations in the other regions (Informant J, STRING).

Many actors in the value chain of the focal TIS are in contact with Enova. There is, however, one group that seems to be more or less absent as of now:

> There are various actors who are in contact with us regarding hydrogen. You have those who have vehicles to sell, those who will build stations, those who are interested in hydrogen in general, and those who are potential truck owners. The last group has not been in contact with us as much. There are probably many reasons for this, but we do not hear much from them about their interest in hydrogen trucks. This is something we could have supported (Informant E, Enova).

As the quote mentions, the reasons for this are likely multifaceted. For many truck owners in Norway, hydrogen comes across as something that lies far ahead in time (Informant K, NLF). There is a need for policies that affect the entire value chain if the uptake of hydrogen as an emission-reducing technology is to expand (Informant H, ZERO). In terms of the focal TIS, this includes increased production of renewable power and green hydrogen, the establishment of hydrogen refuelling stations to establish a comprehensive network, making the Norwegian market appealing to manufacturers of hydrogen trucks, and incentivising end-users to adopt the technology. The latter will be discussed further in the function of market formation.

5.3.3 F3: Entrepreneurial experimentation

As Hekkert et al. (2007) argue, entrepreneurial experimentation might be the most important to accelerate the uptake of new technologies, as vital technology learning happens in this function. However, this is arguably limited in terms of the activities within this function of the focal TIS. As stated earlier, ASKO is the only company in Norway with operational hydrogen trucks. Therefore, much of the focus in this section will be on the experiences of ASKO that are relevant to this function. There will also be a focus on why entrepreneurs have a hard time experimenting with hydrogen trucks, i.e., barriers to the entry of entrepreneurs in the focal TIS.

ASKO Central Norway, a regional branch of ASKO, received funding from Enova in 2016 to launch its hydrogen truck project. Before this, they had a smaller project where hydrogen in the form of a small fuel cell unit supplemented some of the power used for the cooling unit and rear lifters. SINTEF was also involved in this project, while the Swedish company PowerCell provided the fuel cell unit. One important context is that ASKO is the logistics company of NorgesGruppen, the most prominent actor in the Norwegian grocery retail market, with a market share of 31%. They have also established a target that their transportation is to be emission-free by 2026 (NorgesGruppen, 2021). By being part of NorgesGruppen, ASKO also has bigger profit margins than other logistics companies, consequently having more opportunities to experiment with new technology. I would argue that ASKO is an incumbent actor – something that is of importance concerning their efforts to experiment with hydrogen trucks. The board of NorgesGruppen have also decided that investments in environmental solutions and technologies do not have to be profitable. This makes for considerable room to experiment (Informant A, ASKO).

As of 2023, ASKO has four hydrogen cars and has ordered two more that will be delivered in 2024. They also have The first four cars result from a collaboration between the Swedish truck producer Scania, who has been the sole supplier of ASKO for 20 years, and the fuel cell company previously known as Hydrogenics – now under the Cummins umbrella. In other words, Scania delivered cars ready for a fuel cell system, and Hydrogenics installed this system. This, in turn, demanded extensive coordination on the part of ASKO. The trucks also needed a refuelling infrastructure. This was not available then, which led ASKO to build a hydrogen infrastructure with an electrolyser and refuelling station at its base in Trondheim. The electrolyser is powered by solar panels on the roof of the operative base. In other words, the company has gone to great lengths to launch its hydrogen pilot.

> It has been exceptionally demanding since we have carried so much of the responsibility that we are used to suppliers having. That is, Scania has taken full responsibility for their part of the vehicle, and so has Hydrogenics, but it is the connection between them that is so exceptionally important. When there is not a finished product being delivered from a factory, the necessary testing that one does before providing a product to a customer has not taken place at all (Informant A, ASKO).

In addition to describing the coordination challenges, this quote hints at another prominent factor in the project: the challenges of untested technology. The fact that the covid-19 pandemic significantly overlapped with the project did not help this matter, as vital technical personnel were unavailable. The project was also affected by the explosion in Sandvika in 2019, which led the DSB to impose a temporary production halt on the electrolyser at ASKO's operative base that lasted nine months. Prior to this, ASKO had tried to engage DSB in their project – with little response. The accident was, therefore, the trigger for their involvement and interest in the project. In other words, while the project officially started in 2019, it was delayed by almost three years due to unforeseen events. Because of these prolonged periods of inactivity, the fuel cell systems in the trucks also started to degenerate, something that caused multiple errors and a reduction in power output: "A fuel cell system that has barely been used does not like to stand idle for so long" (Informant A, ASKO).

Although there was no shortage of challenges, the company had considered this before starting their project. The informant stated: "We would have been very naive if we had not anticipated teething problems" (Informant A, ASKO). They also highlighted that this is an essential part of technology learning, and even though they would have preferred to discover these problems at earlier stages, this was not futile. As briefly mentioned, the fuel cell provider of the four trucks, Hydrogenics, was also bought up by the multinational company Cummins. This was a positive experience for ASKO, as they had extensive experience with heavy vehicles and the automotive industry while also having a more thorough approach to troubleshooting the fuel cell systems. “They search for the root cause, not just the symptoms” (Informant A, ASKO).

The ASKO branch I interviewed was a pilot for the central unit. The informant was positive that if they could operate the trucks normally for a more extended period, they would also be able to show that hydrogen is a viable solution on longer distances. Then, hydrogen could be an option for other branches in ASKO – as long as their operational pattern covers certain geographical distances. The fact that ASKO Central Norway covers a large geographical area, in addition to the proximity to SINTEF Trondheim and the resources located there, was why this branch was chosen for a pilot project to begin with. The Central Norway branch covers a geographical area of 1000 kilometres from north to south. This is something that distinguishes their operational pattern from other branches. In comparison, ASKO branches located in the East of Norway, i.e., more densely populated areas, do not have as large areas to cover, with most of their customers located in an 80-kilometre radius (Informant A, ASKO). This is something that underscores the initial definition of hydrogen trucks in this thesis; their use in a preliminary phase is mainly in long-haul applications.

Most of the informants were asked: What do you think are the most significant barrier to hydrogen within heavy-duty transport? This was particularly interesting due to ASKO being the sole actor conducting a pilot project. Although many of the answers were related to the barriers to market formation in general, there were also some who commented on the lack of actors willing to experiment with hydrogen in their operations. The most prominent reason is the low-profit margins in the segment, making the willingness to take risks related to experimenting with new and uncertain technologies low.

> If our members who own three cars were to buy a new car with a new technology that is not yet proven to be reliable or where the cost of operation is much higher compared to a diesel truck, it would be a completely different matter for them than for the large transport companies that have hundreds of trucks (Informant K, NLF).

This was also a shared sentiment in H2 Truck, which interacts with multiple actors in the transport and trucking segment. This is not to say that there is little action to decarbonise, as other decarbonising technologies are starting to gain a foothold in the segment. Another important factor is the lack of refuelling infrastructure, which makes hydrogen inaccessible regardless of whether one is willing to pay the additional cost for a truck or not. In comparison, ASKO's efforts to implement hydrogen in their operations by coordinating the production of their trucks and building the necessary infrastructure are much more than one can expect from other actors in the segment (Informant C, H2 Truck). Altogether, this creates a risk aversion among truck owners that are hard to overcome without clear political signals, a realistic infrastructure strategy and (very) favourable support schemes.

5.3.4 F4: Market formation

In this section, I will present my empirical findings relevant to what drives market formation, or lack thereof. Furthermore, this will indicate which phase of market formation the focal TIS is in, which will be discussed further when assessing the functions. Importantly, this function is focused on what drives companies to adopt certain technologies in their operations rather than what drives supplier companies to enter it (Bergek, 2019).

Companies that own one or several trucks are of crucial importance in this function, as they are the end users. At the same time, they are not actively advocating for hydrogen in the truck segment. This is, as mentioned, due to low-profit margins and the impression that hydrogen is somewhat inaccessible – which is not an unreasonable impression as there is neither an available infrastructure nor trucks.

> Our members live in the present. They transport goods from A to B at the lowest possible cost. At the same time, there are authorities saying that emissions must be reduced and that they need to invest in new technology that is both more expensive and possibly not yet available (Informant K, NLF).

This quote illustrates the dilemma of emission reduction versus profit margins, and to small transport companies, this can be quite an overwhelming task. This is an area where NLF assists with TCO calculations that can make the economic decision-making basis more explicit to their members. In a business cycle survey conducted on the members of NLF in November of 2022, 44% answered that they were open to new technologies that were not combustion engines. In other words, the will to test new technology is not the problem. Rather, lacking access to supporting infrastructure and higher investment prices pose serious barriers to many companies (Informant K, NLF).

However, NLF does not currently have much focus on hydrogen because they try to focus on solutions that can be implemented relatively easily and at the lowest possible cost to the end user. Their agenda is not to push for hydrogen in the trucking segment. Rather, it is to promote solutions that are doable for the majority of their members. This is not to say that NLF will not be an essential asset in the function of market formation if hydrogen becomes more widely available. As the informant's quote reflects, their members live in the present. Consequently, the organisation must mirror this, as they would not speak for their members if they did not consider their interests: "We should be positive towards the green shift, but we also need to be realistic about what we can do and achieve today" (Informant K, NLF). As of now, I would argue that networks such as The Norwegian Hydrogen Forum, the H2 Truck consortium, and the Greater4H project are currently of higher importance in this function to advocate for hydrogen trucks. The Greater4H project is in a unique position in this sense because, in addition to advocating for hydrogen trucks, it is an important coordinator in establishing the necessary infrastructure for said trucks.

As mentioned earlier, it can be challenging to attract truck manufacturers to the Norwegian market (Informant C, H2 Truck). To return to the case of ASKO once again, they experienced great difficulty finding a manufacturer willing to produce their trucks. This search started in 2016, with extensive coordination between Scania and Hydrogenics/Cummins to realise the project (Informant A, ASKO). However, the challenge of acquiring trucks for the Norwegian market demonstrates that the company may not have an easier time today, despite a rising number of manufacturers producing hydrogen trucks. The relationship ASKO had already established with Scania, with the company being the sole provider of ASKO's truck fleet, seemed to be the decisive factor in this case. This underlines that even if there was an actual demand for hydrogen trucks, there is no automaticity in that this would lead to a situation in which one can purchase such trucks. To indulge in regional and international cooperation, therefore, appear as a key driver to actors wanting to purchase hydrogen trucks. In other words, being part of bigger and more strategic projects can appeal to manufacturers. Examples of this are, again, the Greater4H and the H2Accelerate project.

In the truck segment, about 15-20% of the operations are currently proving hard to electrify due to the need for flexibility that can be hard(er) to achieve with battery-electric solutions (Informant H, ZERO). This is where hydrogen could prove useful, as it has more similarities with diesel trucks regarding refuelling style. While charging a 900-kWh battery pack, which is the battery capacity that is likely required on long-haul distances, would take 45 minutes or more, refuelling 70-80 kg of hydrogen at 700 bar would take 10 minutes – the same amount of time it would take to fuel a diesel truck (Informant A, ASKO; Informant J, STRING). Furthermore, the range of hydrogen trucks is also improving, with some manufacturers arguing that their trucks will have a range of 500-1000 kilometres. This is an important development in terms of standard settings, as this establishes a market for hydrogen trucks in which they can meet certain requirements that other technologies cannot. In this context, the zero-emission aspect of hydrogen is of vital importance. If one looks at it pragmatically, there are two paths to reach zero-emission in the transportation sector: battery-electric and hydrogen. In terms of long-haul heavy-duty transport, many argue that hydrogen is the most sensible alternative (Informant G, SINTEF).

It is easy to point at transporters when discussing the need for emission reductions in the transport sector, as they have operational patterns that emit CO_2. However, some informants also pointed to the role of actors that buy transportation services and cargo. This group of actors can easily be forgotten, as they are not emitting CO_2 directly. On the other hand, the cargo they are purchasing has emissions linked to it. “There are always high expectations for the transporter to do something. But the transporter's activity is triggered by someone creating a need for it. They drive around for a reason, not because it's fun. The customer needs to be held more accountable” (Informant A, ASKO). Considering this aspect, it is possible to argue that the transporters of cargo are left with an unproportionate part of the bill to reach zero-emission. If the entirety of the Norwegian truck fleet is to be replaced with zero-emission technology, this is likely not economically sustainable for an industry with low-profit margins alone. In some instances, it is possible for the buyer to choose whether they want their cargo to be transported with lower emissions, and there are companies that exclusively deliver zero-emission transportation services. However, since much of the truck fleet is diesel-based, this is far from the standard (Informant K, NLF).

An important reason why hydrogen is not utilised on a bigger scale is the fact that it is currently cheaper to emit CO_2. That being said, carbon prices will increase by 2030 in Norway. However, they are currently set at a level that makes diesel much more favourable to the end user than hydrogen, making commercialisation even slower. Consequently, the hydrogen infrastructure and utilisation suffer from the slow increase in carbon prices. If the market for hydrogen trucks is to accelerate before the price of emitting CO_2 increases, this would require generous support schemes and incentives to stimulate the interest of truck owners. Many informants brought up contracts for difference (CfDs) as a policy tool suited to reduce the price of hydrogen for the end-user while also guaranteeing a certain price for the producer (Informant H, ZERO). In turn, this would need a political agenda to stimulate a market for hydrogen in the transportation sector, such as the one in the EU.

5.3.5 F5: Legitimation

Legitimation is an important function of social acceptance and desirability of the TIS, which in turn is important to mobilising resources. This is also a function that is closely related to political strength. In the focal TIS, there are some reoccurring themes regarding social acceptance. This is mainly related to hydrogen safety, especially in light of the Sandvika accident in 2019. In terms of political legitimation, which can lead to the mobilisation of various resources, this can be challenging to discuss without considering other TISs. This is especially important in a Norwegian context due to the strong political momentum of battery-electric technologies in the transport sector. In particular, this can affect the legitimacy of hydrogen trucks, leading to a restricted focus on decarbonising the transport segment.

The Sandvika accident was by several informants described as something that put the hydrogen industry in Norway on hold. The delays ASKO experienced because DSB had to conduct controls of the hydrogen facility, as briefly mentioned in the function of entrepreneurial experimentation, are a testament to this. This ban seemed to have its root cause in social structures rather than technical difficulties with the electrolyser and refuelling station, as the safety aspect of hydrogen became more prominent after the accident. The approach taken by DSB was considered conservative in the hydrogen community: There were seemingly few knowledge-based decisions involved in the ban on multiple hydrogen facilities, some of which had been operating for many years without problems (Informant D, MoZEES). In other words, this shows how social factors can influence the regulatory framework in a significant way. The cause of the accident was also revealed shortly after, which boiled down to a wrongly installed bolt. This made the length of the ban all the more frustrating to ASKO – who was confident in their process with their technology provider NEL (Informant A, ASKO).

Another aspect of the accident was that the industry was made more aware of the social acceptance of hydrogen (Informant G, SINTEF). As mentioned earlier, hydrogen is sometimes associated with danger. For instance, hydrogen has a lower ignition point than other fuels, making it more prone to an explosion in the case of an accident. On the other hand, hydrogen has been utilised in different industries for many years. This also means several industries are competent in safely storing and handling hydrogen in large quantum. Instead, the new element is the use of it and who handles it. To counter this, minimising the risk of accidents is of high priority to technology suppliers.

> The risk and consequences of potential accidents are analysed with hydrogen, as with everything else. However, let's think about the manufacturers. It will be important to design the systems so that the consequences are no greater in the event of an accident than for regular vehicles (Informant B, SINTEF).

The quote highlights two important aspects concerning hydrogen safety and legitimation: the implementation of risk calculations in the design of hydrogen applications and the fact that existing technology is used as a parameter for safety standards. Both of these aspects are critical, although the latter explicitly showcases social acceptance. “No hydrogen-powered products on the market will be less safe than the dominant technology. This principle is something that technology suppliers pursue” (Informant G, SINTEF). Humans are surrounded by risk in multiple forms – many of which are in the form of existing technology. For instance, when there is a diesel fire in a tunnel, and harmful gases are emitted, this does not lead to public debates about the safety of diesel. Because we are used to it, this risk does not pose a major concern in the day-to-day life of most people (Informant D, MoZEES). Therefore, it is easier to establish legitimacy by implementing the same or even stricter safety standards as existing technology.

As mentioned previously, the accident also led to Uno X abandoning its hydrogen ambitions (Langeland et al., 2022, p. 149). In other words, the accident also had a major impact on a company's investment decisions that, at the outset, were positive about expanding its hydrogen activity. The accident highlights that the risk tolerance with new technology is lower than with established technologies.

However, as stated above, safety does not seem to be a concern among truck manufacturers and technology suppliers. Neither is the social acceptance of a certain technology decisive of how safe it is. Rather, it is an expression of risk tolerance and how the public perceives the technology. Therefore, it is reasonable to assume that increasing exposure to hydrogen also increases the public's and, importantly, investors' risk tolerance (Informant D, MoZEES). That being said, public acceptance of hydrogen in the aftermath of the accident, in particular, is difficult to measure. Seemingly, the consequences mainly affected the will to invest in hydrogen infrastructure and technology, at least in the transportation sector. Therefore, it is difficult to say whether this accident actively worsened the public perception of hydrogen in Norway (Informant E, Enova).

In the EU, hydrogen has a high standing in transitioning to a zero-emission transportation sector. Multiple informants have highlighted the importance of the EU in relation to the focal TIS, something that the informant in the Greater4H project also underscored. However, hydrogen trucks in the Norwegian transportation sector have seemingly been less important to the government than battery-electric trucks. In this context, it is also important to acknowledge that battery-electric trucks have achieved more technological readiness than hydrogen trucks. This is not only due to the development and wide diffusion of BEVs but also the widespread use of batteries in other applications (Informant H, ZERO). The importance of battery-electric transportation is, for instance, illustrated through the infrastructure strategy for fast chargers, where fast chargers for trucks are mentioned as something that will need government subsidies to be commercialised (Ministry of Transport, 2022). Currently, there is no equivalent to this in terms of hydrogen trucks in Norway.

In the 2020 hydrogen strategy, it is emphasised that hydrogen in long-haul trucking could be a potential business case for hydrogen. On the other hand, it is also noted that the technological development of hydrogen trucks is uncertain, especially considering that alternative technologies are also developing rapidly. The way Norway can contribute to developing the technology is, first and foremost, through pilot and demonstration projects (Ministry of Climate and Environment & Ministry of Petroleum and Energy, 2020, p. 34). Several informants said that the government's approach towards hydrogen trucks needs to be more offensive to establish a market. As of now, the political legitimacy of hydrogen trucks, especially compared to hydrogen in the maritime segment or battery-electric trucks, is not particularly strong.

Since the Greater4H project includes multiple regions, it was also possible to see a difference between the regions' level of involvement and ambition. The German region, for instance, is more involved in the project than the Norwegian region. This is in line with Germany having an ambitious hydrogen policy overall, in addition to Land Schleswig-Holstein being the main coordinator of the project. However, this does not fully explain the more modest approach the Norwegian region in the project has: “At a political level in Norway, I think there has been a barrier that there hasn't been very much recognition for hydrogen. There is a great deal of scepticism about it” (Informant J, STRING Megaregion). Additionally, there is not just scepticism that seemingly prevents hydrogen from being seriously considered as an alternative in the transportation sector; there is also the fact that Norway, and consequently the Norwegian regions involved in the Greater4H project, are far ahead in the electrification of the transport fleet (Informant H, ZERO).

5.3.6 F6: Resource mobilisation

This function is crucial to enable activities within a TIS. Resources for various parts of the TIS value chain will be important in this section. This is because it is necessary to mobilise resources to the entire value chain to establish a market where one can operate and fuel a hydrogen truck.

The empirical background chapter mentions that private investors are wary of investing in hydrogen technologies. This is because of the notion that the dividend of these technologies is long-term and low-return (DNV, 2022). In other words, this is a barrier to private funding. In much TIS literature, private funding is described as cyclical and sensitive to market downturns (Bergek, 2019). In relation to the focal TIS, public funding was crucial in most projects involving hydrogen, and private capital was rarely mentioned. As stated earlier, Norway has multiple public agencies that fund various hydrogen projects. Agencies within the EU system can also be an important funding source for actors in the focal TIS (Informant F, Everfuel). Concerning financial funding for hydrogen trucks and infrastructure in Norway, Enova is the most crucial agency. In ASKO’s project, the Enova funding was a triggering factor in starting the project in the first place (Informant A, ASKO). This is seemingly a tendency in most projects involving hydrogen – something to be expected considering the perceived risk of investing in hydrogen.

If the hydrogen economy can accelerate, this will likely attract more private capital, as many of these resources seek new investment opportunities in the energy transition. For instance, the EU taxonomy strongly focuses on sustainable investments. This pushes new entrants and incumbent actors toward sustainable business models and investments (Informant F, Everfuel). Many of the actors mentioned in the structural components of TIS are also listed on various stock markets to raise capital. However, the stocks are often volatile and sensitive to change, reflecting this section's opening statement about the notion of hydrogen technology as low return.

As mentioned, Enova is an essential actor in the focal TIS. A part of Enova’s mandate in the energy transition is to provide funding for technologies that are in a pre-commercial stage. This can be funding for purchasing technologies with a different cost profile than conventional technologies or supporting pilot projects with new technologies. The former aspect, i.e., technology with an additional cost than conventional technology, is required, as state aid is illegal in Norway. Importantly, Enova's funding has a professional rather than a political rationale. This does not imply that the Norwegian Government's overall policy development is not considered. Instead, it means that experts rather than politicians govern the direction and nature of their funding. Regarding the focal TIS, most parts of the value chain are eligible for Enova funding. They have also funded several hydrogen projects throughout the years. Concerning the focal TIS, this is most notably refuelling stations (Informant E, Enova).

To many informants, Norway's currently available funding schemes were regarded as insufficient to engage many truck owners (Informant B, H2 Truck; Informant G, SINTEF). Additionally, Enova is technically able to expand its funding from the 40-50% limit that is currently the norm. For instance, this was done when announcing a public tender for public charging stations in Northern Norway, where up until 100% of the investment cost could be covered. Another argument was that the cost of establishing refuelling stations was minor compared to that of purchasing the trucks. If public agencies covered a bigger share of the investment cost, this could create a solid foundation for the market formation of hydrogen trucks (Informant G, SINTEF). Some also pointed to neighbouring countries, such as Sweden. The Swedish Energy Agency has funded 13 hydrogen refuelling stations, covering 100% of the investment costs. There are also plans for investment support for a number of additional stations (NHF, 2022b).

Many were also sceptical of the fact that Enova only supports investment costs. In contrast, operational costs are often the most demanding aspect of hydrogen technology.

> Support is given for investment, and a plan for operation is created for some time, but then one fails to establish a market that is good enough, fast enough, or large enough. I think this is the cause for a good portion of failed projects. There should be more flexible arrangements based on trust, results, and ongoing evaluation to get the commercial ball rolling (Informant A, ASKO).

New competencies are also required to accelerate the adoption of hydrogen in the heavy-duty segment. Although hydrogen has been used in multiple industrial settings for decades, new uses of hydrogen require educating new users. Existing competence in handling hydrogen can be utilised, but it is vital to develop new kinds of expertise to drive hydrogen uptake in this segment. In particular, the Norwegian hydrogen industry is estimated to need dedicated engineering expertise in process technology and automation. Additionally, there is a need for competency enhancement and further development throughout the hydrogen value chain. This includes the production, storage, distribution, and use (Normann et al., 2023). In the focal TIS, some of this competence must also come from the technology providers themselves. For instance, the necessary learning with the personnel set to operate hydrogen trucks will likely be baked into the trucks' price. Additionally, a reason why many producers want their hydrogen trucks close in proximity in a preliminary phase is because of the necessary service and follow-up that will follow new technology (Informant C, H2 Truck).

As illustrated in the function of legitimation, safety is highly prioritised when introducing new technologies, and hydrogen is no exception. As Norway has much experience with hydrogen from industrial use, certain actors specialise in this. There are also ongoing research projects focusing on hydrogen safety. One example is Hytunnel, a project that FME MoZEES is involved with that focuses on hydrogen safety in tunnels and confined spaces – such as parking houses and garages. This is particularly important in relation to existing ventilation, which can be reflected in the design of hydrogen vehicles, trucks, and trains operating in tunnels. Calculating the hydrogen release is particularly important to one group: emergency correspondents. In the project that Informant D was involved in, firefighters were engaged in order to increase their knowledge about hydrogen safety when accidents occur. In general, the involvement of emergency personnel in such experiments was essential to the project. In general, such collaborations between academia and vital personnel are necessary for the knowledge diffusion of hydrogen safety. This is also one of the things that can provide the competence needed when the uptake of such technologies starts to accelerate, i.e., technology learning.

In the example given above, vital personnel correspond to emergency respondents. However, vital personnel also include the personnel set to handle hydrogen in new applications. Another aspect of competence development was also highlighted: industry involvement in hydrogen research projects. “Almost more projects involve industry than those that don't. We also use information from them in experiments we plan, and it is generally a great advantage to have projects with industrial partners” (Informant D, MoZEES). This entails that collaboration between upstream and downstream actors in the hydrogen value chain is important in creating competence on both ends. This can also be true in the function of knowledge development and diffusion.

5.4 TIS Context Structures

5.4.1 Interactions between the focal TIS and other TISs

The focal TIS is embedded in the transportation sector, which currently consists of several TISs. A vital aspect of this is that the sector needs to reduce emissions, something that has created momentum for low- and zero-emission technologies. Consequently, this will also be the focus of this section. Thus far, battery-electric trucks have been mentioned several times and a narrative of competition between the focal TIS and the battery-electric truck TIS is apparent. Several informants addressed and were highly critical of the competition narrative between the TISs. Other technologies, such as biogas and biodiesel, already have a strong presence in the truck segment and will therefore represent important context structures as well.

The Norwegian passenger vehicle segment is world-class regarding EV use. This development can be attributed to cheap hydropower and the possibility of installing home chargers which, in part, circumvents the need for building extensive charging infrastructure (Langeland et al., 2022). Because of the increasing electrification in the passenger vehicle segment, the electrification of other parts of the transportation sector has also started to develop. For instance, the development of battery-electric buses and trucks has started to take off, and there are a number of routes and operational patterns that are currently being served by batteries. Based on this, there are also high expectations surrounding the development of heavy-duty electric trucks that can operate over long distances. The national charging strategy is a testament to these expectations. Specifically, the rapid charging infrastructure for heavy-duty trucks is something that this strategy addresses, as this is an underdeveloped market compared to the passenger vehicle segment. In short, there are currently not enough battery-electric trucks for it to be interesting for commercial actors to build an infrastructure for these trucks. Consequently, the battery-electric trucks and heavy vehicles that are currently in operation mainly cover short distances while utilising charging facilities at their home base. Enova's funding will be important to develop this area – both to establish a wider use of battery-electric trucks and a market for rapid chargers (Ministry of Transport, 2022, p. 37).

Despite the challenges of rapid charging infrastructure, battery-electric trucks' technological development and readiness have come longer than hydrogen trucks. In December 2022, 387 battery-electric trucks were registered in Norway, with one rapid charger for heavy-duty vehicles. In 2030, the number of battery-electric trucks is imagined to increase to 23 000, with a rapid charging infrastructure of 1500-2500 charging stations. These numbers are, however, subject to uncertainty (Ministry of Transport, 2022, p. 17). In comparison, the number of hydrogen trucks in Norway per 2023 is four, all of which are owned by ASKO. There is no political ambition or strategy to expand the number of hydrogen trucks. That being said, both TISs have the same framework conditions in Enova. However, the interest in hydrogen trucks from the end-users has been marginal in terms of applicants for Enova funding (Informant E, Enova).

Many of the informants had strong opinions about this development. First and foremost, many were critical of the one-sided and uncritical focus on electrification in the heavy-duty segment. Some argued that the cost of establishing the necessary grid infrastructure to release energy at the precise moment and location it is required could ultimately be more expensive than utilising a combination of both hydrogen and batteries (Informant C, H2 Truck; Informant G, SINTEF). Power is “fresh produce”, while hydrogen is more flexible because it can be stored and produced at times when the power demand is low. This is often brought forward as an advantage of hydrogen because it causes less strain on the power grid during refuelling. If placed tactically, hydrogen production can limit the need for grid infrastructure in the areas of refuelling/charging stations, which can potentially be a more cost-effective option than expanding the grid infrastructure (Informant F, Everfuel). The logistics aspect of hydrogen trucks was also highlighted in the data material. A situation in which multiple battery-electric trucks need charging simultaneously, subsequently creating queues, was deemed unsustainable by many informants because of the queues this would create. This illustrates the logistical benefit of hydrogen in the heavy-duty segment.

It can be easy to get the impression that battery-electric trucks are an off-the-shelf commodity and that many companies are in possession of one or more of these trucks. However, this is not entirely true. The battery-electric trucks are, for instance, more expensive than diesel trucks, even with Enova support. In comparison, the technological development of biogas trucks is developing the most rapidly of the non-fossil technologies in this segment. Additionally, the emissions-reducing solution that the Norwegian Truck Association focused on these days was biodiesel – or HVO100, as it is also called. The reason is that this can be utilised in combustion engines that today are fuelled by diesel. If the use of HVO100 is to increase, this would require an available infrastructure and increased production. This solution could end up costing less for the truck owners as it would not require replacing their truck fleet with new technology – at least not in the short term. Therefore, HVO100 is something many actors in the truck segment are very positive towards. That being said, there is a divide among the truck manufacturers, with some focusing more on hydrogen and batteries, while others are currently most focused on biogas. Scania, which has been discussed multiple times thus far, fall into the latter category (Informant K, NLF).

On the other hand, HVO100 is controversial because of its dependence on arable land, thereby competing with food production. In other words, access to fuel is an issue in this instance (Sutherland et al., 2015). The situation is similar in terms of biogas. Biogas trucks are something Enova has supported for some time, with the same framework conditions as battery-electric and hydrogen trucks. However, as of May 31, 2023, Enova will no longer support these types of trucks. The main argument is that access to biogas is the challenge of scaling up production because of the dependence on raw materials of a certain quality. If biogas production is to scale up, the increased demand for raw materials will likely lead to a decrease in quality, creating a situation where the fuel is both lower quality and more expensive. To ensure the best utilisation of resources, Enova states that the market should decide where biogas is most sensible – without government subsidies disrupting competition (Enova, 2023).

5.4.2 Sectoral TIS interactions

Next, an important context structure to the focal TIS is sectoral interactions. In particular, hydrogen within the maritime sector can be of a competitive or complementary character to the focal TIS, depending on the policy and technology development in the coming years. These two TISs draw on much of the same resources, with hydrogen being the most obvious similarity. However, other assets, such as R&D, funding, technology development (e.g., fuel cells), safety regulations, storage of hydrogen etc., also represent areas where there are some shared or overlapping assets. This also entails that I treat the maritime hydrogen TIS as a sectoral interaction with the focal TIS due to the dependence on the same energy carrier. From the literature on context structures, sectors often correspond to established systems that serve an overall function (Bergek et al., 2015). In relation to the focal TIS, the main sectoral context structure would then be the transportation sector. However, other TISs in this sector have already been discussed, which is why I assess it as appropriate to discuss the maritime sector in this section. Additionally, the Norwegian power sector will also be presented as a relevant context structure.

In Norway, hydrogen within the maritime sector is gaining recognition as an alternative fuel that can contribute to decarbonising the sector, while hydrogen within the heavy-duty segment is not – at least at the time of writing. There are multiple reasons why and I will not claim that I am able to provide a comprehensive list of all the reasons. However, some aspects have stood out in the data material. First and foremost, Norway has much experience with shipbuilding, and there are several Norwegian shipyards and shipping companies. In terms of zero-emission maritime technology, this is an area where Norway can have a leading role globally. In other words, this sector offers an opportunity to develop the national industry while also being able to influence the technological development of hydrogen-powered vessels significantly. As mentioned earlier, the technological development of trucks happens elsewhere (Informant E, Enova). Additionally, hydrogen is likely necessary for the maritime sector to reach zero-emission – both as a fuel in itself or as a feedstock to create other fuels, such as ammonia or methanol. Batteries are an option on short-distance and local routes and are starting to diffuse within the ferry segment. However, the batteries would be too heavy on longer distances, ultimately affecting the cargo the vessels can carry (Informant H, ZERO; Informant G, SINTEF). In a sense, the situation regarding hydrogen trucks is somewhat similar, as weight is an argument that has been used in its favour when comparing hydrogen to batteries. However, some still believe batteries will be the only viable zero-emission option in the heavy-duty segment. According to an increasing number of actors, hydrogen is indispensable in transitioning to zero-emission in the maritime sector (Informant H, ZERO).

On the part of the Norwegian government, this has led to a focus on the maritime sector regarding hydrogen in recent years. These signals have created significant momentum for hydrogen as a low- and zero-emission technology, magnified with the Enova grants for maritime hydrogen hubs and hydrogen-powered vessels. In turn, this strong focus on maritime hydrogen can affect where resources are located, both in terms of funding and R&D. This can seemingly be a barrier for the focal TIS, as there is a risk of one-sidedly focusing on specific uses of hydrogen while neglecting others. On the other hand, the maritime hydrogen TIS can also positively affect the focal TIS. For instance, the maritime hydrogen TIS strengthens the legitimation of hydrogen as a fuel and energy carrier. As mentioned earlier, several "hydrogen hypes" have occurred throughout the decades that have not led to any significant expansion of its use. However, many seem to think it is now or never, as the pressure to decarbonise is intensifying (Informant I, Norwep). If green and blue hydrogen production were to increase, this could secure infrastructure for other uses of hydrogen as well. Additionally, increased exposure to and experience with hydrogen in new sectors can be beneficial in discarding the impression of hydrogen as a dangerous substance.

Whether there will be "room" for all envisioned uses of hydrogen in the years to come is not an easy question, as there is much uncertainty at play. For instance, the certainty of hydrogen supply is vital for those who operate or are set to operate hydrogen-powered vessels, trucks, or facilities. Many need confirmation that the "hydrogen economy" will materialise to make costly investments (Informant H, ZERO).

The Norwegian power sector and grid is also very relevant in connection to green hydrogen production. Many want access to this grid, not just actors in the hydrogen value chain. This can create significant competition for these resources:

> What we see now among those establishing charging stations or other energy-intensive companies is that they are having problems making the energy available. To draw a parallel, Elvia has spent 70 years building today's energy system and capacity based on hydropower, which represents around 70 TWh. During 2022, they received requests for grid connections representing 50% of the capacity they have spent so many years building up. This illustrates

> the enormous demand for energy, which we cannot meet with today's capacity (Informant F, Everfuel).

The Norwegian power grid TIS is, in other words, under pressure. There is different interest at play simultaneously, which makes for different interests in where these resources should be allocated. At the same time, it is vital that the Government have ambitions to scale up renewable power production as the demand for it continues to grow (Informant H, ZERO). In response to the energy crisis that started in the fall of 2021, the Government appointed an Energy Commission whose task was to review how Norway can remain in a situation of surplus power in the future (NOU 2023: 3). This is an example of the policy measures that are necessary if Norway is to reach its climate goals – although it has to be followed up with concrete action.

5.4.3 Geographical context structures

When considering geographical context structures, many aspects can be highlighted. This section will address some geographical context structures relevant to Norway. Additionally, the European geographic context is also addressed here, as this is an important context that partly explains why hydrogen within the transportation sector is more considered here.

Pre-existing structures of a geographical area are important contexts for TISs. The Norwegian power sector largely consists of renewable energy sources, with most of the energy mix comprising hydropower, while a smaller percentage comes from wind power. This energy mix is unique in a European context, as fossil fuels are much more integrated into the energy system in other European countries (NVE, 2023). For several years, Norway has also had a power surplus. Although this is changing, with rising energy prices and an increasing need for electricity in multiple industries, it has created a business case for and an interest in green hydrogen production in Norway. Natural gas resources are something that also has made blue hydrogen production interesting (Damman et al., 2020). These preconditions can be a springboard for many new business cases and ventures and serve as an important geographical context regarding national resources. Another factor that can be important in terms of geographical context is the fact that Norway is a large and elongated country with a relatively cold climate. For instance, this can have consequences for the range performance of batteries in the winter months. In general, the correlation between low temperatures and reduced battery performance is an argument that can be used in favour of hydrogen in the transportation sector (Informant F, Everfuel).

Regarding structural couplings to other geographical contexts, Europe is a vital backdrop to the focal TIS. For instance, Norwegian freight transport companies operate in Europe and vice versa, making different standards, ambitions, and practices in the transportation sector across nations problematic (Informant K, NLF). In March of 2023, the EU launched the *Regulation for the Deployment of Alternative Fuels Infrastructure* (AFIR). Among other things, this regulation states that there are to be hydrogen refuelling stations every 200 km along the core Trans-European Transport Network (TEN-T) and urban nodes by 2030. The regulation also states that there are to be charging stations dedicated to electric heavy-duty vehicles with an output of 350 kW every 60 km along the core TEN-T and every 100 km along the larger TEN-T network. This will be established from 2025 onwards, with complete coverage in 2030 (European Commission, 2023b). This regulation clearly states that the EU is in favour of both technologies. This will drive the need for support schemes to establish these networks, making investing in alternative fuel technologies – such as hydrogen – more attractive (Informant F, Everfuel).

In some parts of the EU, grid infrastructure is more problematic than in Norway. There are multiple reasons why, and it is beyond the scope of this thesis to go further into this topic. However, this geographical context structure can explain why hydrogen within the transportation sector is of higher priority in the EU than in Norway. In theory, direct electrification is more effective than converting electricity to hydrogen and, in the case of fuel cells, converting hydrogen back to electricity. Hydrogen combustion engines are, in turn, less effective than fuel cells (Informant G, SINTEF). This conversion process entails an energy loss that is often used in the disfavour of hydrogen. However, if the grid infrastructure and connection are weak, hydrogen can be a viable option due to the inherent flexibility in hydrogen production and storage (Informant D, MoZEES; Informant F, Everfuel). Weak grid infrastructure is also why some countries focus more on biogas and hydrogen for their heavy-duty transport than batteries. While direct electrification makes sense in many instances, socio-political and economic considerations can make this inexpedient compared to hydrogen. This is at least true in a phase before potential grid infrastructure updates, and expansions are made. In comparison, Norway has a stable and well-functioning grid infrastructure, making the situation in Norway less precarious than in other countries (Informant H, ZERO). While the grid infrastructure in Norway does not pose a problem as of now, there will likely be a need to establish more grid infrastructure in the decades to come.

Although Norway's power situation differs from that of many European countries, many informants have pointed out that it would be a mistake to ignore the developments in the European market: “Having a separate agenda in Norway for how the development progresses would be very inefficient. Believing that we should also be different in this area, while truck manufacturers in other countries follow market trends” (Informant G, SINTEF). In this context, “being different” refers to the diffusion of EVs in Norway. The market trend in question is hydrogen trucks, which in turn is created by signals from the EU that this will be an important technology to reduce emissions from the transportation sector. This is not to say that hydrogen trucks have been excluded as an emission-reducing technology in the Norwegian transportation sector. However, it implies that the EU is ahead of Norway in the understanding that both technologies are needed, as they focus on both batteries and hydrogen (Informant C, H2 Truck).

5.4.4 Political context structures

In this section, I will present the political context structures that affect the focal TIS in various ways. In the empirical background, I have already presented the Norwegian hydrogen strategy and the whitepaper that followed up this strategy with concrete targets for hydrogen hubs and projects, in addition to the hydrogen strategy of the EU. Therefore, the political context relevant to the TIS I will present in this section is general policies aimed at reducing emissions from the transport sector. I would classify much of this policy as external links, i.e., factors that influence the focal TIS, but not the other way around. This is especially true given the little focus on hydrogen trucks and subsequent infrastructure in Norwegian policies.

First and foremost, *Norway’s Climate Action Plan for 2021-2030* (Meld. St. 13 (2020–2021)) is relevant in this context, as it targets emissions reductions in multiple sectors. The transportation sector is not part of the EU Emission Trading System (ETS), and the targets for the non-ETS sectors are somewhat different from those included in this system. Agriculture, buildings, and households are other sectors not included in the ETS. Through the Climate Agreement with the EU, which is an agreement both Norway and Iceland signed in October 2019, Norway has committed to reducing 40% of the emissions in these sectors by 2030 compared to 2005 levels. However, the Norwegian government's climate plan for 2021-2030 sets a target of reducing emissions from sectors not covered by the ETS by 45% below 2005 levels by 2030. In other words, this is a more ambitious target than the Climate Agreement with the EU (Meld. St. 13 (2020–2021), pp. 34-36).

Moreover, the transportation sector is the most carbon-intensive of the non-ETS sectors, with approximately 60% of the emissions in these sectors stemming from transport. Therefore, if Norway fails to reduce CO_2 emissions from this sector, the reduction target of 45% in the non-ETS sectors will not be achieved. Some of the most important means of achieving CO_2 reductions in this sector include higher carbon prices, the use of public procurement to promote zero-emission technologies and increased use of public agencies supporting technology development and market introduction, such as Enova. Higher carbon prices are the most important policy tool, and in the years leading up to 2030, the price per tonne of CO_2 emitted will gradually increase to 2000 NOK. Note that this is based on 2020 price levels, i.e., not adjusted for inflation. The eventual goal is to halve the emissions in the sector (Meld. St. 13 (2020–2021), pp.54-64).

Undoubtedly, The EU is ambitious concerning hydrogen. This is reflected in policy development, some of which are presented above. The European hydrogen strategy presents ambitious and concrete goals for developing an EU hydrogen economy, which was also elaborated on in the empirical background chapter. However, many other countries also take an interest in hydrogen. Strategies such as The Inflation Reduction Act (IRA) in the US are a testament to this. This act is extensive regarding the US's efforts to reduce national carbon emissions. Concerning hydrogen, it utilises tax credits depending on the level of CO_2 emitted while producing the hydrogen – with lower emission levels being awarded. These tax credits have a ten-year horizon, creating incentives to invest in low-emission hydrogen sooner rather than later to maximise the advantage (Guha, 2023). In response to this act, the EU Commission has developed the *Net-Zero Industry Act: Making the EU the home of clean technologies manufacturing and green jobs*. This is currently pending approval from the European Parliament and the Council of the EU (European Commission, 2023a). The title of the Act hints that the IRA has made green investments in the European market less appealing compared to the US market, as the latter currently offers more favourable conditions. At least, it is likely that some investments in the EU market were put on hold when IRA was launched, as the support scheme created some uncertainty regarding where investments should be made in the short term (Informant I, Norwep). The race to reduce emissions within 2030 is intensifying, and the EU cannot afford to lose green investments at such a critical point.

6 Discussion

Thus far, I have defined the focal TIS, analysed the structural components of the TIS, and, most importantly, analysed the functional pattern of the focal TIS. Further, I have identified relevant context structures to the focal TIS. This will be vital for the next steps: assessing the functionality of the focal TIS, identifying inducement and blocking mechanisms, and specifying key policy. This is also where I will answer the research questions.

6.1 RQ1: How do the functions of the hydrogen truck TIS perform in Norway?

6.1.1 Assessing the functionality of the TIS

In this section, I will assess the performance of the six functions, thereby addressing RQ1. To do this, I will summarise some of the main empirical findings while grading the functions on a scale from *weak*, *intermediate*, and *strong*. This is listed in the table available below. Again, this is inspired by Bach et al. (2020), which uses the same grading scale to assess the findings.

Function	**Assessment**	**Strengths**	**Weaknesses**
(F1) KDD	Intermediate	• Increasing R&D on hydrogen in Norway • Momentum for hydrogen research, with established actors that can guide entrepreneurs and coordinate pilot projects	• Little explicit focus on hydrogen in heavy-duty applications
(F2) IDS	Weak	• Incentives for green hydrogen production • Potential synergies with the maritime sector • Potential spill overs from the focus on hydrogen trucks and infrastructure in the EU • Regional collaborations, some of which includes Norway • Prices of CO_2 set to increase	• Seen as competing with battery-electric trucks in Norway • Weak political signals regarding the desirability of the technology • Lack of infrastructure development • Norway is not an attractive market to truck manufacturers in a preliminary phase
(F3) EE	Intermediate	• ASKO's pilot project providing vital technology learning	• Few actors with the financial capacity to go through such projects

		- Increasing exposure to the technology	- Insufficient support schemes to incentives experimentation - Limited activity in Norway
(F4) MF	Weak	- Growing market for hydrogen trucks in the EU	- Unarticulated demand profile - Small profit margins leading to limited ability to purchase with new technology - Cargo owners not held responsible for CO_2 emissions
(F5) LEG	Intermediate	- Experience with hydrogen from other sectors - Hydrogen safety is of highest priority among manufacturers - Increasing acknowledgement of hydrogen as a decarbonising technology	- Public perception and investors are sensitive to accidents, illustrated by the Sandvika explosion - Regulatory agencies are unexperienced with hydrogen in the transportation sector - Hydrogen trucks lack political legitimation in Norway
(F6) RM	Intermediate	- Available support schemes from public agencies - Competence from other industries using hydrogen	- Lack of efforts to overcome the chicken-or-the-egg in Norway regarding hydrogen trucks - Competing with other technologies for resources

Table 3: Assessing the functional pattern

(F1) Knowledge development and diffusion: This function is assessed as *intermediate*. There is some research on hydrogen within heavy-duty applications in Norway, for instance in relation to fuel cells. In terms of establishing a knowledge base on hydrogen in Norway, the newly established research centres are important. Some of the actors and networks mentioned in this function can also contribute to knowledge diffusion of the focal TIS by coordination various projects. Consequently, this is a good example of R&D meeting the market (Hekkert et al., 2007). The reason why this function is assessed as intermediate is because much future research on hydrogen in Norway will likely be on maritime applications. However, this can be positive for hydrogen in the heavy-duty segment since parts of the value chains overlap.

(F2) Influence on the direction of search: I assess this function as *weak*. This function mainly concerns incentives for supply-side actors (Bergek, 2019). First and foremost, there are incentives to produce green hydrogen in Norway. In turn, the actors who produce green hydrogen are interested in diversifying their portfolio of end-users, which can benefit the focal

TIS in the future. A combination of weak political signals for the desirability of hydrogen trucks and infrastructure development, in addition to the trouble of getting trucks to Norway, weakens the strength of the function altogether. On the other hand, there are efforts to establish a comprehensive network of hydrogen refuelling stations for heavy-duty applications along strategic European corridors. This can create synergies with Norwegian regions, although this is currently not the case. Moreover, hydrogen trucks are competing with multiple technologies simultaneously, some of which have many more incentives for the entrance of new actors. Without much political guidance on establishing an infrastructure, the current situation is off-putting to many actors along the value chain of the focal TIS.

(F3) Entrepreneurial experimentation: This function is assessed as *intermediate*. The reason why is mainly the pilot project of ASKO, which created vital technology learning with hydrogen trucks for the company itself and other actors in the value chain. The latter includes technology providers and regulatory authorities. On the other hand, few actors are in the position of conducting such experiments, which are often perceived as risky. With the current support schemes, incumbents seem to be the only actors equipped to go through such projects. This stagnates experimentation, which is arguably very important to the growth of a TIS. The reason why is that this function can contribute to reducing uncertainty around a certain technology and increasing technology learning (Bergek et al., 2008, p. 146).

(F4) Market formation: This function is assessed as *weak*. I would argue that the focal TIS is in the nursing market stage. However, this can look different in different geographical contexts. In a European context, efforts are made to create a niche market for hydrogen trucks that align with the logic of strategic niche management, i.e., protected spaces for and controlled phase-out of hydrogen trucks (Kemp et al., 1998). This is not the approach by Norwegian authorities, which creates ripple effects on multiple fronts. For instance, the interest of potential end-users in hydrogen trucks is low. This is due to a lack of infrastructure, immature technology in terms of market performance, and low-profit margins in the segment overall. When posing emission restrictions on the segment, the latter is often not adequately considered. Additionally, other technologies are more appealing to many truck owners. Biogas trucks, and to a certain degree, battery-electric trucks, have achieved more technological readiness than hydrogen in this segment. HVO100 is also something the segment is positive towards. Therefore, the *demand profile* of the end users is not yet articulated regarding hydrogen trucks (Bergek et al., 2008, p. 416). Additionally, the services of Norwegian transporters are arguably too cheap if they are to replace their truck fleet with new technology. There is a missing link between what the transporters are expected to do with limited means and what the cargo owners should pay for emissions.

(F5) Legitimation: This function is assessed as intermediate. Hydrogen has become more vital in reaching zero-emission, affecting its legitimacy in general. However, hydrogen must still overcome scepticism related to some of its inherent capabilities. A highly relevant term in this context is what Bergek et al. (2008, p. 417) refer to as “liability of newness”. This describes the struggle of new technologies to overcome scepticism in a preliminary phase. Legitimation is how new technologies can overcome this, which in turn is established through targeted and dynamic actions by various actors. That said, hydrogen in the transportation sector has less legitimacy than hydrogen in the maritime sector. This is mainly because hydrogen in maritime applications is perceived as necessary, while hydrogen in the transportation sector is perceived as excessive. Seemingly, there is currently little room for hydrogen trucks in Norway due to the high expectations of batteries. Nevertheless, there are still some drivers of the legitimacy of hydrogen trucks, mainly the political recognition it gets from the EU. Additionally, the maritime application of hydrogen is not a barrier for heavy-duty applications per se. Instead, it could be how hydrogen trucks achieve political legitimation in Norway. Combined, this contributes to a higher rating of this function.

(F6) Resource mobilisation: This function is assessed as *intermediate.* There are available support schemes, although insufficient to incentivise most potential end-users and infrastructure providers in Norway. Operational support is also something that is missing from this function. Arguably, the funding and ambition level for hydrogen in the heavy-duty segment is modest compared to that of other European countries. Private funding is currently limited, although some companies involved with hydrogen, such as refuelling companies, are listed on Euronext Growth or other financial markets. That being said, the market for hydrogen technology is highly volatile and sensitive to various developments. Regarding human competence or capital, some of this can be “inherited” from sectors with experience with handling hydrogen. Additionally, multiple hydrogen projects involve the industry and academia, which can benefit both parties. On the other hand, there is a need for dedicated hydrogen competence that is not just derived from existing industries.

6.1.1 The phase of development and comparisons between TISs

I have now assessed the relative strength of all the functions, or lack thereof. The second step of assessing the “goodness” of the functional pattern is to consider the phase of the TIS development and compare TISs (Bergek et al., 2008). These aspects will be discussed rather simultaneously.

First and foremost, I would argue that the TIS is in a formative phase. The description of the formative phase by Bergek et al. (2008) strongly correlates with the TIS's observed characteristics, making this categorisation rather unproblematic. The few hydrogen trucks present in Norway and the earlier categorisation of the TIS in a nursing market stage also underscore this conclusion. In the following, I will elaborate on this, building my arguments on some of the main characteristics of the formative phase. I will also connect some central aspects of the background material, theoretical framework, and analysis to establish a more holistic picture of the phase of development. Further, I will address aspects of other TISs that can be compared to the focal TIS.

Regarding the time dimension of a TIS, this is rarely shorter than a decade (Bergek et al., 2008). This aligns well with the data and background material, demonstrating that the development of the focal TIS, i.e., hydrogen trucks and the subsequent value chain, has been lengthy and far from linear. For instance, the concept of hydrogen in heavy-duty applications has been prominent for years and was long thought of as the only decarbonising option in this segment (DNV, 2022). The data material illustrates this through the interest of ASKO in hydrogen, with the project applying for Enova funding in 2016. Before this event, the company was interested in hydrogen, with a smaller pilot project. From a broader point of view, however, many have predicted that the hydrogen economy will take off for decades at this point, with the transportation sector as one of the main potential growth areas. In a Norwegian context, this is illustrated by the Hynor project in the mid-2000s, which aimed at introducing FCEVs in the Norwegian market (Damman et al., 2020). R&D investment in hydrogen technology, such as fuel cells, has also been substantial throughout the years (Suurs et al., 2009). To a certain degree, it can be argued that much of the focus previously on FCEVs has shifted towards FCETs and hydrogen combustion engines. This would entail that the focal TIS has been developing for decades, although without significant value creation as of now.

Moreover, a characteristic of the formative phase is that there are large uncertainties surrounding the technology, markets, and applications (Bergek et al., 2008). Although uncertain in terms of diffusion, I would argue that the technology of hydrogen trucks is in the pre-commercial stage. This entails that the technology is relatively developed, at least beyond the stage of R&D, but expensive because of the smaller production volumes. There are also uncertainties prevailing in terms of markets and applications. By this, I refer to uncertainty regarding the *desirability* of hydrogen trucks in Norway. This is not as apparent in the maritime sector, for instance. To a certain degree, the prevailing narrative surrounding hydrogen in the transportation sector, in general, can be summed up as a question of whether this is the best use of renewable resources. Therefore, I would argue that there are uncertainties about whether hydrogen in the heavy-duty segment is needed, i.e., market uncertainty, and whether the application of hydrogen in the heavy-duty segment should be prioritised alongside the maritime venture, i.e., application. Note that these mechanisms are not exclusive to the formative phase but can also appear in a growth phase (Markard, 2020).

The last characteristic of the formative phase considered here is the one of unarticulated demand. As established multiple times in the analysis, the demand from the end users, e.g., truck and cargo owners, is not articulated in Norway. There are various reasons why, many of which can be attributed to the infamous chicken-or-the-egg dilemma. However, another form of unarticulated demand that has not yet been considered explicitly is the articulation of demand from policymakers. The role of policy has been discussed multiple times, but not as an entity with preferences. Here, it can be relevant to compare with the maritime hydrogen TIS. In this sector, there were explicit policy ambitions to develop five maritime hydrogen hubs and several pilot projects (Meld. St. 36 (2020–2021)). This was followed up with Enova grants for maritime hubs and hydrogen-powered vessels. These grants are justified by the decarbonising potential of hydrogen in this sector. In other words, the investments made to facilitate learning are perceived as small compared to the expected future gains in terms of emission reductions (Azar & Sandén, 2011, p. 138). The same cannot be said for hydrogen trucks, despite being frequently mentioned in political strategies addressing emission reductions in the transportation sector. In contrast, the only pilot project with hydrogen trucks in Norway was driven by private actors. Therefore, I argue that the lack of articulation of demand from policymakers is a second layer to this dynamic.

To a large degree, the focal TIS is dependent on external forces to align with the system to promote growth, as is often the case in the formative phase (Markard, 2020). As mentioned earlier in the section, building a functioning innovation system takes years, even decades. Therefore, comparing TISs in different phases can result in unrealistic performance expectations. Further, new technology is often scrutinised *because* of their unfamiliarity. This can pose a serious barrier to legitimation if it is constantly compared to established technology or other new technologies. Again, this is relevant in relation to the frequent comparisons between the battery-electric truck TIS and the focal TIS. The number of battery-electric trucks in Norway is accelerating (Ministry of Transport, 2022), which is sometimes used in the disfavour of hydrogen trucks. However, there are good reasons why this acceleration is taking place. Importantly, the battery-electric TIS's political support has contributed to a stronger performance of its functional pattern. Thus, comparing the two is not necessarily fair, even though both TISs are in the heavy-duty segment. This can contribute to an either-or discourse that weakens the legitimacy of hydrogen trucks and other technologies in this segment. On the contrary, investments in and experimentation with multiple technologies are often necessary for sustainability transitions (Azar & Sandén, 2011).

6.1.2 Summary RQ1

So far, I have assessed the functions of the focal TIS. By doing this, I have also answered the main part of the first research question. Additionally, I have discussed the phase of development and drawn parallels between TISs. This has contributed to a more holistic understanding of the performance of the TIS functional pattern. It also supports that the focal TIS is relatively weak in a Norwegian context. This is reflected in the functions – all of which are either assessed as weak or intermediate. However, the analytical frame I have chosen, particularly the geographical limitation of focusing on Norway, plays a big part in why the functions are not assessed stronger. Hydrogen trucks have a stronger momentum in Europe and the EU, arguably leading to a better performance of the functional pattern. The European context is also addressed in the TIS context structures, although I do not regard them as directly increasing the focal TIS's performance. Rather, it showcases how a TIS can be differently regarded in various geographical and political contexts.

6.2 RQ2: What are the TIS's central blocking and inducement mechanisms, and how can policy address this?

In this section, I will address the second research question of this thesis. This will mainly be done by addressing the next two steps of the TIS analysis: identifying inducement and blocking mechanisms and specifying key policy issues. By discussing these aspects, it will be easier to address the role of hydrogen in the transportation sector and which policies should be considered if the uptake is to accelerate. The latter aspect will be discussed using central literature where policy measures are explicitly mentioned.

6.2.1 Identifying inducement and blocking mechanisms

As illustrated throughout this thesis, a number of factors and dynamics come into play when assessing the functional pattern of the TIS. For instance, much of the socio-technical transportation system is currently manifesting in unsustainable ways. With concrete targets of reducing emissions from several sectors by 2030 and 2050, including the transportation sector, there are growing expectations related to the potential of hydrogen. This can be described as a landscape factor affecting the entire socio-technical regime (Geels et al., 2017). Additionally, this landscape factor functions as an inducement mechanism for the focal TIS by creating significant momentum for low- and zero-carbon technologies (LoZeC). Stated differently, it also represents an external link that influences the focal TIS by creating a demand for and expectations of hydrogen as a LoZeC technology (Bergek et al., 2015).

As established in the former section, the performance of the functional pattern of the focal TIS is relatively weak. There are multiple reasons why, with the absence of supportive policies as one of several blocking mechanisms. However, I would like to address this from another angle, using terms derived from Suurs et al. (2009): that of *enactors* and *selectors*. Regarding the focal TIS, I would argue that some of the main enactors are networks such as the Norwegian Hydrogen Forum, H2 Truck, and Greater4H. In turn, these networks have a wide reach, including multiple actors throughout the TIS value chain. That being said, they do not represent a strong "entrepreneurial pack" in Norway (Bergek, Jacobsson & Sandén, 2008). Arguably, Norwegian policymakers are the most important (potential) selectors of the focal TIS at this point, as there are few actors positioned to take the risk of investing in hydrogen trucks and their value chain. However, as discussed in the previous section, the enactors have difficulty convincing this group of selectors about the necessity or desirability of the focal TIS. Amongst other things, this is due to other technologies aimed at remedying the same problem, i.e., sector complexity (Bergek et al., 2023). In other words, the enactors are not powerful enough to contribute to the legitimation process of the focal TIS. Consequently, this does not lead to an increase in supportive policy. In turn, this facilitates poor institutional alignment and represents a blocking mechanism (Bergek et al., 2008).

In this context, the institutional alignment of hydrogen trucks, or lack thereof, is interesting. The focal TIS aligns with one of today's main narratives: reducing emissions. However, the will to diversify the portfolio of emission-reducing technologies in the Norwegian transportation sector seems to end with batteries. This is not only evident in the case of hydrogen trucks; the recent decision of Enova to abandon the support for biogas trucks also speaks to this. As many informants already have argued, the technologies in the heavy-duty segment, especially batteries and hydrogen, could be complementary but are treated as competitive. This duality can be explained by different technology and sector dynamics: both technologies answer to a sectoral need for emission reductions while they compete for limited resources at a technology level, i.e., electricity, funding, infrastructure etc. In other words, they are complementary on a sector level, while on a technology level, they are competitive (Bergek et al., 2015; Markard & Hoffmann, 2016). An advantage of battery-electric trucks is their institutional alignment, which makes for a bigger impact on sectoral development. This relationship is not present with respect to hydrogen trucks, with the sector having a more exogenous and one-sided influence on the TIS (Markard, 2020).

It is also possible to have complementarities between sectors. As mentioned in the TIS context structures, hydrogen in the maritime sector can have positive repercussions for hydrogen in the heavy-duty segment in Norway. This is due to shared or overlapping assets, making the potential for synergies between the sectors present (Hanson, 2018). Depending on the development, this can be an inducement and or a blocking mechanism. Both can be true simultaneously, with complementary and competitive relationships co-existing (Markard & Hoffmann, 2016). Additionally, this represents a structural coupling (Bergek et al., 2015). However, this will require the ability to scale up hydrogen production in Norway, which in turn is dependent on power production. According to Mäkitie, Steen, and colleagues (2022), an increasing number of hydrogen-powered ships will necessitate more electricity production, which poses certain challenges. Mainly, this is related to the limited expansion potential of hydropower in Norway and resistance to land-based wind production. This challenge is also present in the focal TIS, even though the number of hydrogen trucks in Norway will not likely explode in the coming years as the situation is now. Nevertheless, it poses a barrier to the focal TIS.

Lastly, there is a need for *synchronisation* in the value chain of the focal TIS. This relates to something that has been mentioned many times in the analysis – i.e., the need for establishing multiple elements in the value chain simultaneously. This includes, among other things, trucks, refuelling infrastructure, and the fuel itself. Synchronisation is, in other words, translated to simultaneous and mutually supporting development in multiple parts of the value chain (Mäkitie, Hanson et al., 2022). However, this is rarely present in novel technology value chains and often represents the cause of the chicken-or-the-egg dilemma. Given its formative phase, it is neither the case for the focal TIS.

6.2.2 Key policy issues

The heavy-duty segment is facing extensive demands of reducing emissions, thereby having to implement new technology in the coming years. By 2030, 50% of all new trucks sold are set to be battery-electric or hydrogen-powered in Norway (Meld. St. 13 (2020–2021)). To many companies in this segment, this poses a challenge. This is especially true in relation to small-sized companies with limited profit margins, as illustrated throughout the analysis of the functions. This can also be observed in other sectors, such as ship-owners in the maritime sector. The bigger and well-established ship owners with multiple vessels in their fleet usually constitute early adopters. Those that struggle to adopt new technology are usually younger and smaller companies with fewer vessels, which in turn has a more “business-as-usual” attitude (Mäkitie, Steen et al., 2022).

These tendencies in both sectors can likely be attributed to many things. The financial situation of incumbents does, of course, play a part in this. However, it can also be reasonable to assume that incumbents' knowledge base and in-house resources are very useful when applying for public funding and investment support (Mäkitie, Steen et al., 2022; Steen et al., 2019). Given these tendencies, it will likely be easier to stimulate the interest of incumbents in hydrogen trucks compared to smaller companies. However, offering assistance when applying for funding from public agencies is also a low-hanging fruit regarding companies with limited administrative capacity (Steen et al., 2019). This is also supported in the data material, with many of the smaller actors in the heavy-duty segment experiencing that demands of reducing emissions are imposed on them without sufficient guidance on how this can be done cost-effectively.

Establishing a market for hydrogen trucks would require supportive (and generous) policies able to affect the entire value chain. In other words, this entails a holistic policy approach. In TIS analyses on alternative fuels in the maritime sector, where hydrogen specifically was addressed, the following was recommended: increasing *resource mobilisation*, which in turn can create opportunities for *knowledge development and diffusion* and *entrepreneurial experimentation*. Lastly, this lays the foundation of *market formation* and positively reinforces *legitimation* (Steen et al., 2019, pp. 63-64). In other words, much growth and activity depend on adequate funding schemes – especially in the formative phase. CfDs are one example of increasing resource mobilisation that several informants have highlighted. This can play a crucial role in determining a price for hydrogen that is viable for both producers and users. Once again, this is connected to operating expenses (OPEX) – an aspect that many stakeholders agree needs to be increased for implementing LoZeC technologies in the socio-technical system.

In policymaking, internal coherence is often assumed. However, increasing funding without considering the complexity of many hard-to-abate sectors would be a mistake. Additionally, there is much uncertainty at play before a dominant design emerges. The heavy-duty segment's LoZeCs display heterogeneity and synergies. This is also true of other hard-to-abate sectors and segments, which is the reason why there is often a call for technology-specific policies to remedy poor institutional alignment (Bach et al., 2020; Bergek et al., 2023; Steen et al., 2019). In this thesis, heterogeneity in the heavy-duty segment is related to the different infrastructure requirements of the technologies. For instance, it is likely easier to build an infrastructure for HVO100 due to its inherent similarity with diesel. Limited availability of fuel is rather a challenge, which is also the case in biogas. In the case of hydrogen and batteries, this would require more effort in terms of physically establishing the infrastructure and facilitating grid connections for either direct use of electricity or hydrogen production. As discussed earlier, this also entails facilitating the necessary power production. If these technologies are to complement each other, there is a need for policies that creates niche markets for more than one technology at a time. This complexity is something that needs to be addressed, and there is a need to make choices as to which technology is suited for which purpose (Steen et al., 2019). Additionally, establishing a value chain for hydrogen is more complicated than that of batteries. This is due to the need to produce hydrogen and transport it to designated refuelling or bunkering spots. Simplified, battery-electric vehicles and trucks of various sizes can be “plugged-in” and have gotten a flying start because of this inherent capability (Langeland et al., 2022). This aspect must also be acknowledged in relation to hydrogen, as it represents a significant need for coordination and technology-specific policies (Mäkitie et al., 2021).

Increasing carbon fees is a general policy that would increase the competitiveness of many LoZec technologies and promote emission reduction in multiple sectors (Bergek et al., 2023). Although the price of emitting CO_2 is set to increase gradually by 2030 in Norway, this is currently insufficient to stimulate the uptake of new technology among many actors in the heavy-duty segment. Therefore, it is difficult for hydrogen to compete with fossil fuels in areas where it is still “too cheap” to produce emissions. Arguably, the harmful aspect of emissions is not yet reflected in the carbon price. Therefore, increasing carbon prices sufficiently to enable LoZeC technologies to outcompete fossil fuels is an important cornerstone in reaching net-zero.

6.2.3 Summary RQ2

In this section, I have addressed the second research question of this thesis, which is mainly concerned with identifying blocking and inducement mechanisms. Throughout the analysis and discussion, it becomes apparent that there are more obstacles than drivers to the diffusion of hydrogen trucks in Norway. This is also where the second part of the RQ is relevant: policy. In relation to this, I have identified technology-specific policy interventions that can be used to overcome some of the barriers to hydrogen trucks. This is mainly related to increasing funding and considering the complexity of the segment. More general policies have also been discussed. Further, this has been addressed by employing relevant literature.

7 Conclusion

In this thesis, I have reviewed the role of hydrogen trucks in the Norwegian transportation sector by employing the TIS framework. I have especially emphasised the TIS functions, which constitute the very heart of the analysis. Further, I have employed four categories of TIS context structures. The TIS framework has sometimes been accused of not being sufficient in capturing the complex circumstances of novel technologies. The TIS context structures replies to this criticism, aiming at a more nuanced approach to TIS analyses (Bergek et al., 2015). I would argue that the thesis reflects this sentiment, with multiple context structures thoroughly analysed and discussed alongside the focal TIS. This has contributed to a richer understanding of the focal TIS and its challenges. Given the relatively weak position of hydrogen trucks in Norway, I would also argue that it has been necessary to consider other technologies, sectors, and policies. In fact, it would be futile not to do so. In addition to being one of the main implications of the thesis, this is also the way in which it contributes empirically to the literature on sustainability transitions and complexity challenges related to hydrogen.

Hydrogen trucks may not be the most energy-effective option, especially compared to battery-electric solutions. On the other hand, energy efficiency is not the only relevant parameter when comparing hydrogen solutions to that of other technologies. Hopefully, this is something this thesis underscores. While not the primary objective of the thesis, I have tried to nuance the view on batteries in Norway. To be clear, batteries will solve many of the emission reductions in the transportation sector and other sectors in the coming years – and have already gained an impressive market share in Norway. However, using this technology to disfavour other technologies is not the answer to the profound changes multiple socio-technical systems will have to undergo in the years leading up to 2030 and 2050. There is a need for deep decarbonisation, something that requires innovation on multiple fronts. If there is anything highlighted by scholars engaged in debates about technology-related policies in recent years, it is the need for experimenting with multiple technologies (Geels et al., 2017). Importantly, such an approach will also seek to avoid technological lock-ins, which have characterised so much of our current emissions-intensive practices for decades (Klitkou et al., 2015).

Considering the European strategy of exploring multiple options to decarbonise the heavy-duty segment and following this up with concrete ambitions to establish a subsequent infrastructure, dismissing this development in Norway can be unfortunate. This is perhaps one of the main implications of this thesis. Given the many informants referring to complementarity between technologies, there should be room for exploring hydrogen where appropriate. Mainly, this includes long-haul freight transport, where some of the benefits of hydrogen are logistical. Again, this relates to sector complexity, and different user needs (Bergek et al., 2023). Regardless of which technology will have the biggest market share, this should not be synonymous with dismissing other technologies.

7.1 Limitations and further research

Hydrogen is a complex technology due to its numerous potential uses. In this thesis, I have explored the role of hydrogen trucks because of an identified research gap, combined with a select few actors' interest in hydrogen trucks in Norway. As illustrated throughout this thesis, significant complexity is at play in this segment. Much of the literature mentioned in this thesis that explores hydrogen in the maritime sector takes a more holistic approach, considering multiple technologies simultaneously (Bach et al., 2020; Mäkitie, Steen, et al., 2022; Steen et al., 2019). In the heavy-duty segment, this could be done by doing a multi-case study of hydrogen, batteries, biodiesel, and biogas in which the TIS framework is applied. These technologies have all been considered throughout this thesis. However, a more explicit focus on the three latter technologies could prove fruitful in understanding central dynamics in the segment and future developments. Consequently, this constitutes a limitation of the thesis and an area of future research. A whole system analysis of the ongoing sustainability transitions in the Norwegian transportation sector using MLP could also be an interesting research case (Geels & Schot, 2007).

Heavy-duty transport also includes other technologies, mainly trains and buses. These have not been considered in this thesis, although they, too, represent segments in which hydrogen could answer to a growing need for decarbonisation and flexibility. This could also be interesting in terms of hydrogen hubs that serve a multitude of technologies. There are many synergies between different hydrogen applications, mainly because increased production and use can ultimately reduce costs. Therefore, thinking in terms of hubs is something that is often considered when discussing the emission-reducing potential of hydrogen (Mäkitie et al., 2021). This aspect has been mentioned in the thesis, particularly in relation to hydrogen in the maritime sector, although it could have been highlighted further, even as a separate analysis. Hydrogen in heavy industry is something that could have been included in such an analysis. Additionally, there are also many industrial actors who currently use grey hydrogen as a feedstock, where the need for eventually transitioning to either blue or green hydrogen will become more pressing. In sum, all of the abovementioned technologies constitute areas of future research – much of which could also be done in a Norwegian context.

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9 Appendix

Representative interview guide

This interview guide is translated from Norwegian to English. Note that this is a representative interview guide. As mentioned in Chapter 4, this was adjusted according to the informants positions.

Background

- Can you tell me about your professional background?
- In what contexts have you worked with hydrogen during your career?
- What is the background for your employer's/company's interest in hydrogen?

Viewpoints

- Do you believe hydrogen can be an emissions-reducing solution in the heavy-duty segment? Why/why not?
- Where do you see the greatest potential for hydrogen?
- How can we drive the development of a hydrogen value chain in Norway with production, infrastructure, and end-users?
- What are your thoughts on terms like "hydrogen economy"?
- How do you think the development of hydrogen has progressed by 2030? 2050?
- What expertise do you think is needed to realise the increased use of hydrogen in transportation beyond what we see today?
    - Where can this expertise come from? Education, existing industries?
- Which actors have been most active in driving pilot projects in Norway?

Barriers

- What do you consider the biggest challenges associated with the use of hydrogen in transportation?
    - Socially?
    - Economically?
    - Technically?
- What impact do you think the explosion in Sandvika in 2019 had on the use of hydrogen in transportation in Norway?

- Why do you think there are relatively few actors investing in hydrogen to reduce emissions in the transportation sector?
- What are your thoughts on the frequent comparison between batteries and hydrogen?

Policy

- What are your thoughts on the current policies regarding hydrogen?
- What do you think should be the Norwegian government's role in a hydrogen initiative?
- How do you view the role of the EU in relation to hydrogen?
- Which policy instruments do you believe are suitable for promoting the more widespread use of hydrogen in transportation?

General

- Do you think Norway will reach its emissions reduction goals by 2030?
- Is there anything else you would like to add?