Hydrogen technology experimentation for sustainable mobility

A case study of hydrogen fuel cell experimentation in Lower Saxony in Germany

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Abstract

We are living through a transformation in the way we see ourselves and our relationship with the environment. While scholars and politicians have focused on how to overcome this common action problem, awareness of the need to understand and develop the possibilities of a response to climate change is rapidly evolving. Sustainable mobility initiatives are increasing in cities all around the world. Climate objectives on both national and international levels call for change across sectors. The European rail network is considered a central contributor to the decarbonization of today's mobility sector. Germany is currently creating a link between its mobility system, dominated by automobility and fossil fuels, and a transition towards renewable sources. During the timespan of the thesis, Germany is experimenting with hydrogen fuel cell technology for rail applications in the area of Lower Saxony. Based on conducted interviews and qualitative content analysis, the thesis will provide new understanding of sustainable mobility initiatives in a German context. I have investigated the rationale behind the experimentation and the emergence of the initiative. Further, I have investigated the institutional barriers and enabling factors associated with the experimentation. The latter can be important for further implementation of hydrogen fuel cell technology for rail applications.

Throughout the thesis, it has become apparent that one of the most prominent barriers are non-technical. Rather, the barriers are more of a regulative nature. The thesis states that new technology within the mobility sector struggles at the start pit due to bureaucracy and the lack of new technical standards and regulations. In addition, there are clear barriers associated with both cognitive and normative institutions. To the general public, hydrogen seems to be viewed as an explosive energy carrier, representing danger and decreased safety. Despite the aforementioned barriers, I have found enabling factors for further implementation of hydrogen fuel cell technology for rail as a mode of mobility. The ongoing experimentation in Germany seems to be protected from the “normal” selection environment, and can thus accumulate knowledge important for further implementation of hydrogen technology. Moreover, ambitious climate goals on different levels function as prominent triggers for sustainability initiatives. Based on the empirical findings, I have created three institutional innovative activities that can be of importance for further implementation of hydrogen fuel cell technology for rail application.

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Finally, I would like to thank my friends and family for the support through the course of this year. I would especially like to thank Synne Boberg and Anine Erevik, who spent hours proofreading the thesis.

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List of abbreviations

CNG - Compressed natural gas

ERTMS - European Rail Traffic Management System

GHG - Greenhouse gas emission

IEEP - Institute European Environmental Policy

LNVG - Lower Saxony regional authority

MFS - The mobility and fuels strategy of the German Government

MLP - The multi-level perspective

NIP - National Innovation Programme Hydrogen and Fuel Cell Technology

NOW GmbH - National Organisation Hydrogen and Fuel Cell Technology

SNM – Strategic niche management

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1.0 Introduction

In 2016, the world's first hydrogen fuel cell train for passenger services was launched. Coradia iLint represents an alternative to diesel power, and can potentially facilitate a transition towards a low-carbon mobility system. Only two years later, in 2018, the Coradia iLint entered commercial service in Germany. The two iLints are operating in Lower Saxony, and between the cities of Cuxhaven, Bremerhaven, Bremervörde and Buxtehude (Alstom, 2018).

The hydrogen fuel cell powered trains have today been operating in commercial service for nearly two years. There has already been signed contracts for further delivery, both within Germany and across the borders (Alstom, 2020). The nature and timing of the hydrogen fuel cell powered trains are very much in line with ambitious climate objectives through the Energiewende. However, the hydrogen fuel cell powered trains are not isolated from regulations. Regulative institutions, both on EU and national level, require (among others) sustainability and competition. In addition, further implementation of hydrogen fuel cell technology for rail application face both cognitive and normative institutional barriers. The thesis aims to investigate how sustainable niche innovations can be introduced in today's mobility system, currently characterized by automobility and fossil fuels.

In the following chapter, I will present the area of research and the case at hand. I will elaborate the choice of case and its relevance, and explain why the case is appropriate for research.

1.2 Research topic and research question

The research area of the thesis is based on the research tradition of socio-technical transitions. The mobility sector is conceptualized as a “socio-technical system”, consisting of (networks of) actors, institutions, material artefacts and knowledge. Components of the socio-technical system interact, and together they provide specific societal function. However, the mobility system is currently manifesting itself in an unsustainable way. The general assumption is that such unsustainable systems need a socio-technical transition (Markard, Raven & Truffer, 2012). This type of transition may involve change in technology, institutional structures and user practices, and can thus imply a fundamental shift in socio-technical systems (Geels, 2004).

The research topic is the socio-technical system of the mobility sector. Today's mobility system can be characterized by fossil fuels and automobility, and is associated with CO2 and NOx emissions. Automobility can be associated with freedom, allowing individuals to travel where they want by themselves. However, automobility is also associated with large amounts of greenhouse gas emissions. Hence, the socio-technical system of the mobility sector can be considered unsustainable (Bakker & Konings, 2017).

Transition studies question how socio-technical systems can be brought from an unsustainable state towards a more sustainable one (Smith et al., 2005). Governance of socio-technical systems research tradition takes on questions concerning how, and if possible, socio-technical systems can be both governed and steered towards sustainability (Smith et al., 2005). Sustainability experimentation can be considered a prominent tool in relation to governance of socio-technical systems, taking on a central role within the academic field that investigate transformations towards sustainable socio-technical systems. Sustainability experimentation within a socio-technical system can be considered a testing phase of new sustainable technologies or practises, and may facilitate further transition (Bulkeley & Castán Broto, 2013). Further, literature questions who should take on responsibility for this governing. My case takes on the sustainability experimentation that is currently ongoing in Lower Saxony, Germany. Germany is experimenting with hydrogen fuel cell technology for rail application. The thesis is based on the assumption that the experimentation is both triggered and effected by prominent landscape developments on different levels. I have been highly inspired by Aagaard’s (2018) study on zero-emission bus experiment in Oslo. Aagaard (2018) attended the same masters programme as me, and had access to the same theoretical and analytical framework. Consequently, there are clear similarities between both theses. However, my findings revolve around different aspects of the sustainability experimentation due to differences in contexts, informants and mode of mobility. The purpose of the thesis is two-folded. It can function as a contribution to the socio-technical sustainability research tradition. In addition, it can provide fruitful discussions associated with experimentation with hydrogen technology in today's mobility sector. Based on the area of research and research topic, I intend to answer two research questions;

RQ1: What is the background for the hydrogen fuel cell experimentation in Lower Saxony in Germany, and how can the perceived effects influence further implementation?

The focal context within socio-technical transition studies is usually national or global. However, urban authorities appear to exert more successful sustainable initiatives (Bulkeley et al., 2015). Sustainability experimentation is considered a prominent tool for the introduction of novel sustainable technologies (Sengers et al., 2019). However, such top-down initiatives seem to have been ignored in early multi-level perspective frameworks. Rather, bottom-up transitions have been dominating in the field of transition studies (Smith et al., 2005). Based on the abovementioned analytical framework, I intend to investigate the background of the sustainability experimentation in Lower Saxony in Germany. I foremost seek to gain insights into the initiative; where it came from, how it emerged and why it was considered an appropriate way to introduce hydrogen technology in rail application. Further, I intend to investigate how the perceived effects of the experimentation can influence further implementation of hydrogen technology within rail as a mode of mobility. Note that I acknowledge that findings related to the experimentation phase may differ from one context to another. Thus, there is no intention of generalizing the findings. Rather, I seek to initiate fruitful discussions concerning sustainability experimentation and processes related to sustainable niche-innovations in an urban context.

RQ2: Which institutional barriers and enabling factors are associated with the hydrogen fuel cell technology train experiment in Germany?

Sustainable experimentation allows the discovery of early stage institutional barriers which can be dealt with beforehand further implementation. Hence, for my second research question, I intend to investigate the institutional barriers and enabling factors associated with the hydrogen fuel cell experimentation in Lower Saxony in Germany. Studying a sustainability transition within a geographically defined context allows the reveal of local institutional factors. Such factors may provide explanations of why certain niche-innovations "break through" within a specific area and not in other places (Raven et al., 2012). Formal and informal rules or institutions guide behaviour and can thus be able to influence socio-technical transitions (Geels et al., 2016). The perceived barriers associated with the experimentation phase may affect a further implementation of hydrogen technology in rail application. However, sustainable experimentation allows the discovery of early stage institutional barriers which can be dealt with before further implementation. In addition, I will investigate the institutional enabling factors associated with the hydrogen technology experimentation in Lower Saxony. The enabling factors should be maintained and focused for further implementation of hydrogen technology in rail application.

1.3 Sustainable mobility

A discussion concerning sustainable mobility inevitably takes us back to the concept of "sustainable development". The term "sustainable development" was first used in the UN report "Our Common Future" in 1987, and has since been subject for discussion concerning how the world can be steered in a more sustainable direction. The terminology is versatile and can be used in various contexts. In this thesis, I intend to use the term sustainable development in the context of initiatives and actions aimed at adapting to climate change. However, what is considered sustainable can be subject to interpretation and may change over time.

To address the sustainability of a transport system, I intend to refer to the term "mobility". Holden (2007) presents and discusses the term "mobility", and composes a transport system in three subsystems. The first one is the motorized means of transport. What is considered as sustainable in transport is not limited to specific artefacts (such as vehicles), but also to the level of mobility in the society. The second subsystem is the transport infrastructure. Sustainable mobility involves an assessment of all kinds of impacts due to the construction, use and maintenance of infrastructure for different modes. The third subsystem is the energy system. Sustainable mobility involves assessments of the impacts of improving the existing, conventional energy system and the impacts of promoting alternative energy systems. Based on the abovementioned, sustainable mobility includes assessments of the supply of transport and energy facilities (infrastructure), as well as the use of these facilities. The measure of mobility, according to Holden (2007), include all journeys that have been carried out during a period of time and that incorporate travel by people.

Today's energy and transport system are mainly based on fossil energy carriers, and can not be evaluated as sustainable. Hence, we are facing the challenge of finding the best way to rein in emission while also providing the energy required to sustain economics. Concerns regarding energy supply security, climate change, local air pollution and the increasing prices of energy services have a growing impact on policymaking throughout the world (Ball & Wietschel, 2009).

Climate governance literature questions who should be responsible for socio-technical transitions and how transitions should be steered (Bulkeley et al., 2015). Further, the research tradition of climate governance argues that transitions can be steered through a set of strategic tools. In terms of responsibility for sustainability initiatives, local authorities are recognized as important innovation platforms for promoting and creating a sustainable future (Hodson, Geels, & McMeekin, 2017). Local authorities can be considered important for the mitigation of climate change for two reasons. First, the local authority is often responsible for public services such as public transport, and may in that way be able to steer the transition. Second, among various levels of governance, the local authorities are the ones closest to the people. That enables them to influence behaviour change among society (UNCED, 1992). Additionally, local authorities are believed to exert more successful policies than national governments or global actors being both closer in proximity to specific issues and responsible for public transport, waste management and other services (Madsen & Hansen, 2018).

1.3.1 EU climate goals

In Paris in December 2015, all nations were brought together due to a common cause, aiming to undertake ambitious efforts to fight climate change and adapt to its effects. The notion of the agreement is to accelerate and intensify actions and investments that are needed for a low carbon future. Thus, the international community agreed to limit global warming to below 2°C above pre-industrial levels and, if possible, to limit it to 1,5 °C (UN, 2015). Identifying policy priorities for the European Union (EU) to achieve Sustainable Development Goals (SDG) and implement the Paris Agreement, the Institute European Environmental Policy (IEEP) published the Europe Sustainable Development Report. By the IEEP, the Paris Agreement and the SDGs are viewed as a package. However, note that the SDGs are aimed towards 2030, and the Paris Agreement oriented towards climate-neutrality by 2050, including major progress by 2030 (IEEP, 2019). As with all sectors, emission reduction is important in the mobility sector in order to reach the aforementioned climate goals. Based on 2017 numbers, the emission mitigation of the mobility sector represents 21 percent of the EU greenhouse gas in total. Only a small proportion of these are coming from railway. However, according to Thorne et al. (2019), passenger travel as a segment can expect a greater share in the future. Thus, the European rail network is central in the decarbonisation of the mobility sector.

IEEP (2019) suggests all EU members decarbonise their energy system by increasing the use of renewable energy and thus need to integrate their energy system more closely in order to manage the intermittency of power generation. The EU railway network is currently 60% electrified, carrying 80% of all traffic. The majority of electric-powered trains operate on a third rail or overhead line. The latter is the dominant form of the current railway for both long-distance passenger and freight trains on main rail networks in the EU,
and is based on an electric high voltage system. Third rail is more common in rapid transit rail systems like metro and subway systems. Third rail can also be used for light rail application (Thorne et al., 2019).

The electrification of European rail lines is expanding. Electrification of the railway is associated with a low maintenance cost, quiet operation and increased passenger comfort. Additionally, it allows the use of higher voltages, which reduce line loss. Although there are no technical barriers for electrifying (remaining) lines, electrifying rail lines may not always desirable due to economic, interoperability and visual reasons. According to Thorne et al., (2019), investment costs for new line electrification may not necessarily be cost-efficient but may be around several million EUR per km. This includes power generation, transformers and transmission lines in addition to the service disruption due to the overhead wire installation. Moreover, over-head lines on little-used sections are usually not profitable, in scenic areas often not wanted (NOW, 2016), and face difficulties to fully electrify freight lines across national borders due to interoperability issues (Thorne et al., 2019).

For passenger lines today and/or future lines not suited for electrification, there are zero-emission alternatives to diesel propulsion. At the current state, Germany is experimenting with zero-emission technology within the public mobility sector.

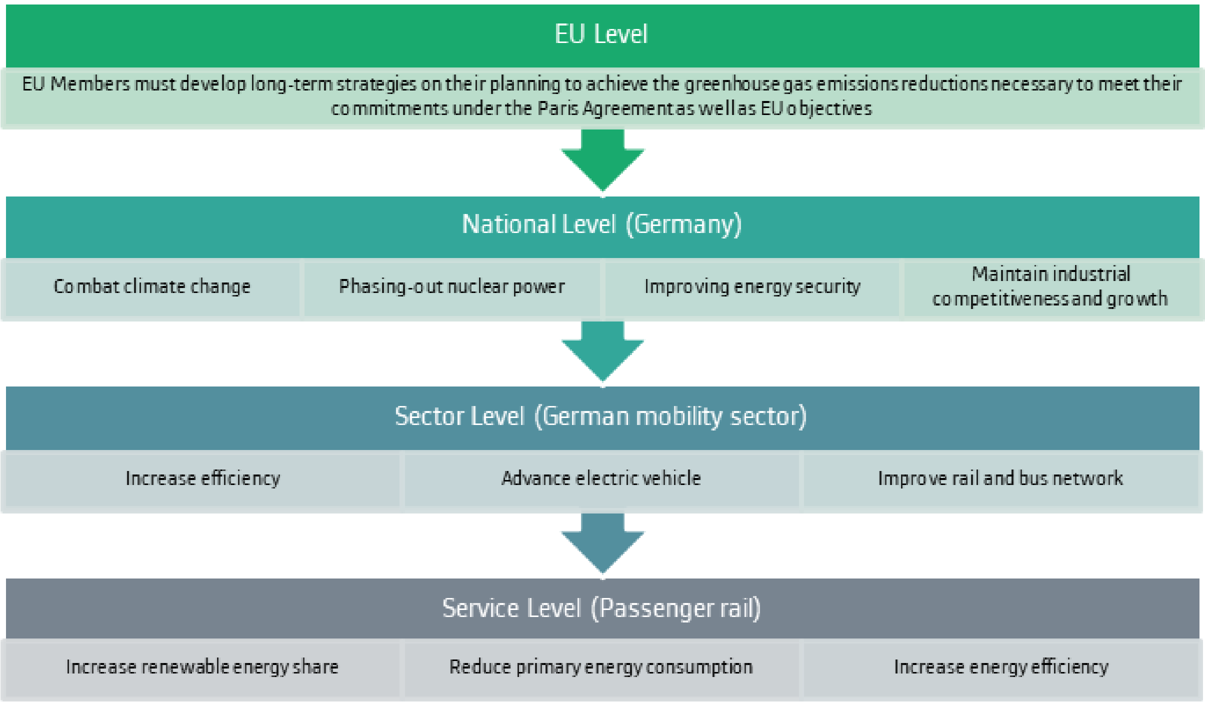
1.3.2 Energiewende and the German railway

EU Members are required to develop long-term strategies on their planning to achieve the greenhouse gas emissions reductions necessary to meet their commitments under the Paris Agreement as well as EU objectives (EU, 2018). Germany is an interesting context for the thesis due to its policy plans for a pioneering energy transition, the “Energiewende” (Leiren & Reimer, 2018). Energiewende is Germany’s planned transition towards a low-carbon, nuclear-free economy, and is driven by four political objectives; fighting climate change, phasing out nuclear power, improving energy security and maintaining industrial competitiveness and growth. The undertakings of the Energiewende is complex and will affect many parts of German society and economy (Agora Energiewende, 2013).

The German energy system can be characterized by nuclear energy, coal, petroleum and natural gas. Due to its almost complete dependence on petroleum, the German mobility sector has enjoyed a certain autonomy, which will not be possible to retain an energy system transition. Germany aims to redesign and reorganize power, heating and mobility sectors in favour of energy efficiency and renewables (Agora Energiewende, 2018). The German energy system follows a so-called “copper plate” principle, assuming a uniform domestic energy market and thus ignore regional specifics. Germany obtains new wind power in the North. Transferring new wind power requires an expanded transmission network. However, network expansion projects have encountered public resistance. Hence, only 850 kilometres of the planned 7,700 kilometres of new transmission lines have been built. Similar controversies have yet to arise for heating and gas networks. At the current state, the network is based on fossil-fired power plants and imported natural gas, and low shares of renewables (Agora Energiewende, 2018). Increasing emissions from the road, rail, ship and air traffic over the past few years has nullified Germany’s successes in climate protection in the first decade of 2000. The mobility sector is thus the only sector in the German economy to release more carbon today than it did in 1990. As a consequence, Germany has developed three further strategies for 2030; “increase efficiency, advance electric vehicle use and improve rail and bus network” (Agora Energiewende, 2018, p.32).

Zooming out, public passenger mobility is already making a contribution to environmental and climate protection within the mobility sector due to low emissions per person-kilometre. However, rail is considered a key mode of mobility in the Energiewende, whereas the aim is to extend the proportion of renewable electricity of hundred percent by 2050. At the current state, about 60 percent of all lines in Germany are electrified, albeit with regional differences. However, electrified services are and will be decarbonized by the continuous adaptation of the traction current mix, including an increase in electricity from renewable sources (The Federal Ministry of Transport, 2018). Based on the abovementioned, I have crafted an overview of the structure of the climate objectives on different levels;

Figure 1: Overview of the structure of the climate objectives on different levels



Moreover, I will underline that Germany has one of the largest railway companies in the world. Deutsche Bahn is a mobility and logistics service provider and is owned by the German state. The company offers passenger and freight rail transportation and operates the infrastructure both in Germany and globally through its subsidiaries. However, its core business is the German railway, where Deutsche Bahn is the operator of 33,300 km of modern rail (Railway Technology, 2016). In parallel with the abovementioned, the company states that due to climate change and an increase in traffic volume, rail will become a prominent area in the coming years (Deutsche Bahn, 2020). In order to meet set climate objectives, Deutsche Bahn (2020) calls on policymakers, industrial production, and the public to cooperate towards the common goal.

Although there are no technical barriers for electrifying (remaining) lines, electrifying rail lines may not always be desirable. Thus, for passenger lines today and/or future lines not suited for electrification, there are zero-emission alternatives to diesel propulsion. The operation of hydrogen and fuel cell powered trains is a suitable alternative from a present-day perspective (The Federal Ministry of Transport, 2018). Thus, in the following sections, I will present hydrogen technology, and the world's first hydrogen fuel cell powered train.

1.3.3 Hydrogen technology

IEEP (2019) suggests that all countries decarbonise their energy system by increasing the use of renewable energy. Fossil fuels such as diesel are at the current state the incumbent fuel in the mobility sector, and 50 percent of the world's oil production is provided to the sector (Qvale & Taraldsen, 2015). However, the use of fossil fuels is not considered sustainable and is associated with increasing environmental issues. As a result of the aforementioned issues, sustainable fuels are currently under exploration. These fuels can be divided into two categories; fossil-free fuels and zero-emission technology. Fossil free fuels may, for example, appear as biogas or biodiesel, and can be conducted from biological matter such as waste, forestry residues, plant residuals and various cooking oil residuals (HVO). However, its sustainability depends on its origin (Hagman et al., 2017). For example, biofuels conducted from palm oil is considered unsustainable, while biofuels conducted from forestry residues usually are considered sustainable. In addition, fossil-free fuels cannot be categorised as zero-emission technology as it is still associated with some greenhouse gas emissions (GHG) (Hagman et al., 2017). Zero-emission technology, on the other hand, have no GHG emissions at all. A zero-emission vehicle can be defined as a vehicle where all available energy from propulsion is stored as electrical energy in rechargeable batteries (Hagman et al., 2017). The thesis is focused on hydrogen fuel cell powered trains.

Hydrogen may contribute to the three most important targets with respect to transportation energy use that are favoured by policymakers around the world: GHG emissions reduction, energy security and reduction of local air pollution (Ball & Wietschel, 2009). Hydrogen is not an energy source itself, but a secondary energy carrier. Hydrogen may offer effective solutions to both emissions control and the security of energy supply. In general, is hydrogen an odourless, colourless, highly inflammable, reactive, non-toxic gas (NOW, 2016). Hydrogen is a zero-emission energy carrier at the point of final use, and thus avoids the transport-induced emissions of both air pollutants and CO2. As a secondary energy carrier, any advantage from using hydrogen as a fuel depends on how its produced. Hydrogen can be produced from any locally available primary energy source. It occurs most frequently in water and hydrocarbons, and naturally in the form of chemical compounds. Hydrogen can be produced from fossil fuels, nuclear and renewable energy sources by various processes such as water electrolysis, water splitting by high temperature heat, natural gas reforming, gasification of coal and biomass, biological processes and photoelectrolysis. However, today the production is based almost exclusively on fossil fuels and on-site for captive uses (Ball & Wietschel, 2009).

Any assessment of the effects of a transition towards hydrogen fuel cell technology within the mobility sector may involve various assumptions concerning long term future energy policy developments. In addition, a future hydrogen system may be subject to market preferences and to competition to other energy carriers (Ball & Wietschel, 2009). The approval and introduction of hydrogen technology require facilities for the generation, transport and refuelling of hydrogen (NOW, 2016). Electrolysis can be generated both on site (included in railway infrastructure) and in industrial parks outside the railway infrastructure. The hydrogen can be transported by pipeline exclusively on public or private properly. The refuelling stations must be included in the railway infrastructure (NOW, 2016). Hence, a transition from diesel to hydrogen call for change on various levels and may require an updated legal and regulative framework. However, the aforementioned variables may vary between contexts and countries. The findings related to hydrogen infrastructure for rail as a mode of mobility may thus be specific to the context of the thesis.

1.3.4 Coradia iLint

In September 2018, two prototype hydrogen fuel cell powered trains entered regular commercial service in Lower Saxony in Germany. The trains are named Coradia iLint and are the first approved passenger trains using hydrogen fuel cell for traction power (Alstom, 2018). The two trains are in operation on the Eisenbahnen und Verkehrsbetriebe Elbe-Weser network, on a 100 km line between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude (Thorne et al., 2019). One filled tank obtains a range of 1,000 km, similar to a diesel train. The maximum speed is 140 km/h, whereas the kinetic energy generated during braking and surplus fuel cell energy is stored in the lithium-ion batteries. The trains has seating for 150 passengers, including a further 150 standing (Thorne et al., 2019).

The iLint prototype project in Lower Saxony was supported by the German Ministry of Economy and Mobility, and the development of the train was thus funded by the German government as a part of the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP) (Alstom, 2018). Coradia iLint offers a combination of innovative elements, such as clean energy conversion using hydrogen fuel cells, flexible energy storage in batteries, as well as management of the traction power and available energy. The train is suited for operation in non-electrified networks and enables sustainable train operation (Alstom, 2018.).

Alstom (2020) states that whenever a green solution is introduced, the full system must be optimised, including rolling stock. Hence, there are several supplier-contracts involved. Selectron Systems provides the control and management system (TCMS), Hydrogenics provides fuel cells, storage tanks are provided by Hexagon Xperion, and Akasol provides underfloor batteries (Railway Technology, 2018). Alstom has long term plans for iLint. At the current state, Alstom has signed two contracts for hydrogen fuel cell powered trains in Germany. The first one is for 14 Coradia iLint to be delivered to Lower Saxony Regional Transport. The contract includes maintenance and energy supply service for 30 years. In addition, there will be delivered 27 Coradia iLints to the Frankfurt metropolitan area (Alstom, 2020). The contract includes the supply of hydrogen, maintenance and the provision of reserve capacities for 25 years (Alstom, 2019). Alstom's hydrogen fuel cell technology is adaptable to different countries and contexts, and the iLint appears to be expanding across the German borders. In 2019, Alstom and the Province of Groningen, local operator Arriva, the Dutch railway infrastructure manager ProRail and the energy company Engie signed plans for a pilot project with the Coradia iLint. This is the first pilot project with Coradia iLint outside Germany. According to Alstom, the UK, France, Denmark, Norway, Italy and Canada are also developing plans for Hydrogen Fuel Cell trains (Thorne et al., 2019).

Exploring various literature relevant to the topic, I have noticed a repetitive discussion concerning hydrogen fuel cell and battery technology. While some literature discusses the two solutions as a commercial competition, Alstom (2020) argue that the two solutions are complementary, whereas each of them answers different needs.

> Generally speaking, battery solutions are more suitable in case of short and medium length of non-electrified sections, while hydrogen solutions are best to use when

> range is key. (…) Alstom is professional in both, and we are very well prepared to support our customers in choosing which one is the most suitable green solution for them (Alstom, 2020).

The implementation of hydrogen fuel cell powered trains depends on several parameters, such as operational requirements, existing infrastructure and topography, level of electrification, the density of the traffic on the line, level of needed investments and fleet size. This will be further discussed in the discussion section (section 6.0).

1.4 Alstom

The Coradia iLint is developed by the French multinational company, Alstom. Alstom develops and markets systems, equipment and services for the mobility sector, and offers a broad range of passenger solutions, customised services, infrastructure, signalling and digital mobility solutions. Among others, Alstom offers high-speed trains, metros, tramways and e-buses. The company has 36 300 employees worldwide, working from sites in 60 different countries (Alstom, 2020). I am working for Alstom Transport Norway as a Project Assistant and will enter a new position as a Document Controller at the end of the thesis. The project I am working for is an ongoing project in Norway. Norway has committed to an implementation of the European Rail Traffic Management System (ERTMS) on its national railway network. ERTMS will renew the existing signalling system in Norway (Bane Nor, 2015). At first, I was eager for ERTMS to be the focal unit of the thesis. However, the project is still at the start phase and thus lack "results" and discussions associated with perceived effects and/or barriers. In July 2019, Alstom unveiled its new brand identity: Mobility By Nature (Alstom, 2019). With the new identity, Alstom considers themselves as *"a promoter of sustainable mobility"* (Alstom, 2020). Hence, I was eager to capture and discuss Alstom's sustainable mobility solutions.

As abovementioned, Alstom is engaged in sustainable mobility and consider it their responsibility to support the transition to sustainable mobility solutions (Alstom, 2020). I came across the hydrogen fuel cell experimentation that is ongoing in Germany and found the case to be subject for fruitful discussions concerning sustainability initiatives and potential transitions. In addition, the case corresponds well with the TIK syllabus. During the timespan of the thesis, I have been questioning how I can avoid appearing as a salesperson of the hydrogen fuel cell powered trains and Alstom in general in an unbiassed discussion. Especially in relation to the Norwegian railway (as I am both Norwegian and work for Alstom in Norway). There are ongoing discussions among key actors within the mobility sector in Norway concerning zero-emission solutions for a few lines in the north of Norway (NHF, 2020). I will come back to the content of these discussions in later sections. However, I will here note that the thesis is not meant as a contribution to favour hydrogen as a zero-emission. Rather, the thesis can contribute to discussions concerning how sustainable initiatives revolve and its perceived effects and barriers. In addition, my findings are more specific to the case of Germany, and there is no intention of generalising findings to the case in Norway (or any other country). Thus, Alstom should not be confused as the subject of the thesis. Rather, Alstom as a sustainable mobility manufacturer is considered a key actor in the sustainable initiative in Lower Saxony.

1.5 Content of the thesis

In the previous chapter, I have introduced the area of research and research topic. I have presented both research questions and described the intention of the thesis. I have presented how the current mobility sector is organized. I have discussed how the mobility sector is manifesting itself in an unsustainable way, and why there is a need for change. Last, I have presented the case of hydrogen fuel cell technology experimentation in Lower Saxony in Germany.

In the second chapter, I will present the research tradition literature of relevance to the thesis. I will also discuss the shortcomings and research gaps in the literature on socio-technical transitions.

In the third chapter, I will present the analytical framework consisting of literature on governance of socio-technical transitions, sustainability experimentation, strategic niche management, urban climate change experimentation and institutional theory. The frameworks provide me with an analytical lens through which I will analyse my empirical findings.

In the fourth chapter, I will present and explain the methodological choices that have been made throughout the thesis. I will discuss why a qualitative approach is appropriate and discuss ethical considerations.

In the fifth chapter, I will present the empirical findings. The findings are bases on conducted interviews and qualitative content analysis of relevant reports. The empirical findings will be presented as they have emerged from the data material.

In the sixth chapter, I will discuss the empirical findings based on the analytical framework. I will answer both research questions. Additionally, I have created three innovative institutional activities for further implementation of hydrogen fuel cell technology in rail application.

In the seventh chapter, I will conclude the thesis. I will provide a summary of the thesis and present the most prominent findings of both research questions.

2.0 Literature review and research gaps

In the following section, I intend to present the research field of transition studies. First, there will be an introduction to the concept of socio-technical transitions, followed by a presentation of the most relevant framework(s) in this research tradition. Second, I will present various research gaps highlighted in the literature. Finally, the chapter will be finished with an explanation regarding how these research gaps have contributed to shaping my research questions.

2.1 Sustainability transitions

Sustainability transitions of sectors such as energy and transport have become explicit goals of national policy programs in several parts of the world. Truffer, Schippl and Fleischer (2017) argue that the governance of associated innovation and transformation processes requires an integrated assessment on how new and superior technologies interact with the societal, economic, industrial and political context. Sustainability transitions studies constitute a field of research of high societal relevance, given the sustainability challenges we are facing today. However, sustainability transition is a complex field due to the large number and variety of actors and interests involved in transformation processes. Understanding the analytical and practical implications of shifts in established socio-technical systems can, therefore, be challenging (Truffer et al., 2017).

> Research on “sustainability transitions” comprises all scientific articles that are concerned with the analysis of the institutional, organizational, technical, social, and political aspects of far-reaching changes in existing socio-technical systems (e.g. transportation and energy supply), which are related to more sustainable or environmentally friendly modes of production and consumption (Markard et al., 2012, p.959).

Sustainability transitions research include empirical studies, in addition to conceptual and methodological contributions. Sustainability transitions are multi-dimensional, long-term and fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption. Moreover, guidance and governance often play a particular role in sustainability transitions (Markard et al., 2012). The transportation sector is challenged by congestion, fossil fuel depletion, local air pollution and CO2 emissions, safety risks and more. These challenges are related to environmental, social and economic issues. However, sustainability challenges are affected by strong path-dependencies and lock-ins. Markard et al. (2012) argue that established technologies are highly intertwined with user practices and lifestyles, business models, complementary technologies, value chains, regulations, organizational structures, institutional structures and even political structures. Consequently, established socio-technical systems undergo transitions that may not suffice to cope with the prevailing sustainability challenges (Markard et al., 2012).

Based on the abovementioned, I intend to present and discuss the multi-level perspective on socio-technical transitions.

2.2 Socio-technical transitions

Geels (2004) defines socio-technical systems in an abstract, but functional sense as the linkages between elements are necessary to fulfil societal functions. The societal functions are fulfilled by socio-technical systems, consisting of a cluster of elements such as technology, regulation, user practices and markets, cultural meaning, infrastructure, maintenance networks and supply networks (Geels, Elzen & Creen, 2004). Moreover, a socio-technical system encompasses production, diffusion and use of technology. The mobility sector is conceptualized as a “socio-technical system”, consisting of (networks of) actors, institutions and material artefacts and knowledge. These different elements interact, and together they provide a specific societal function (Markard et al., 2012). However, the mobility system is currently manifesting itself in an unsustainable way.

Security of supply and climate change are two major concerns regarding the future of the energy sector, and we are facing the challenge of finding the best way to rein in emission while also providing the energy required to sustain economics (Ball & Wietschel, 2009). The transition research tradition argues that these unsustainable socio-technical systems would benefit from deep, structural changes of the systems - a socio-technical transition (Smith et al., 2005). A socio-technical transition is a set of processes that lead to a fundamental shift in socio-technical systems. The term transition refers to far-reaching changes along different dimensions such as technological, material, organizational, institutional, political, economic, and socio-cultural. Transitions may involve a broad range of actors and unfold over considerable time-spans. Such a transition may partly complement and/or partly substitute existing products, services or business models. Technological and institutional structures change along with the perceptions of consumers, referring to what constitutes a particular service and/or technology (Markard et al., 2012).

> (...) socio-technical transitions do not just change the very structures of existing systems, such as transportation, but they also affect related societal domains, such as living, housing and working, production and trade, and planning and policymaking (Markard et al., 2012, p.956).

The term transition was first used by Kinsley Davis in 1945 to describe demographic changes during the industrial revolution in Europe (Davis, 1945). In later years, evolutionary economists developed a theoretical framework that enables scientific research on transitions (Dosi, 1982). The approach focuses on the development and change of specific technologies and differs from the approach that we know today as it lacks consideration of social, cultural and institutional factors. The framework is influenced by the early studies of science and technology studies, and contribute to a more complex understanding of the term transition.

Today, the socio-technical transition research tradition is based on the aforementioned assumptions. Technologies do not exist in a social vacuum. They are maintained, moulded and developed by a range of actors, institutions, user-practises and policies (Markard et al., 2012). Thus, a socio-technical transition will cause changes in all of the mentioned dimensions. The subject of this thesis is to investigate how local governance steer green transition in the mobility sector in the regional parts of Germany. In a socio-technical transition like this, it is not sufficient to change only the technology. In addition, users, practices, institutions and actors are all central mechanisms that will have to change in accordance with the technology. Moreover, researchers within the transition studies often seek to gain insights into how we can introduce, promote and govern sustainable transitions (Markard et al., 2012). Thus, the subject for my analysis is to understand the notion of sustainable change within regimes (Smith, Stirling & Berkhout, 2005).

Scholars often assume that new technology co-evolves with the predetermined function of the regime (Smith et al., 2005). In this context, co-evolution refers to the new technologies that evolve alongside the function that they serve. Thus, technology may evolve alongside the technological trajectories that the regime decides will best serve the function (Smith et al., 2005). In such technological change, socio-technical regimes and existing sectors are often path-dependent and experience lock-ins. Both path dependency and lock-ins may appear in innovating firms and refer to the phenomenon where an organization chooses one path to pursue innovation, and thus struggle to break free from that path at a later point. Such phenomena may appear as a result of the uncertain nature of innovation. Schumpeter (1942) argues that innovations often consist of large levels of uncertainty as it is rare that one organization is familiar to the best sources or most relevant options to pursue innovation. In situations of high uncertainty, it may be difficult to break out of path dependency and to alter technological trajectories (Fagerberg, 2005).

However, transition does occur. Thus, several theoretical frameworks have been developed within the socio-technical transitions tradition. Among these are the multi-level perspective and transition pathways.

2.3 The multi-level perspective

The multi-level perspective (MLP) is one of the most prominent analytical frameworks for studies on socio-technical transitions. The MLP conceptualises the link between technology and society and features an analytic distinction between three levels: niches, in which radical innovation emerges; socio-technical regimes, which comprises dominant institutions and technologies; the landscape, which represents trends and contextual drivers and barriers to change (Whitmarsh, 2012). The three levels make out the macro, meso and micro level, whereas the dynamics of change occur within and between the regime and niche levels. The MLP describes both the structure and dynamics of socio-technical systems and strives to explain how various factors interact in order to produce both stability and change. In this section, I intend to present the multi-level perspective approaching the three different levels.

Socio-technical regimes are situated at the meso level. The conceptual meaning of technological regimes was redefined by Rip and Kemp (1998) as:

> (...) the rule-set or grammar embedded in a complex of engineering practices, production process technologies, product characteristics, skills and procedures, ways

> of handling relevant artefacts and persons, ways of defining problems; all of them embedded in institutions and infrastructures” (Rip & Kemp, 1998, p. 340).

Thus, a socio-technical regime is a stable configuration of three subdimensions: (i) the socio-technical system, (ii) actors, and (iii) formal, cognitive and normative rules. The first dimension, the socio-technical system, comprises all elements/mechanisms pertaining to production, distribution, and use of technology. The second dimension, actors, can be defined as social groups and groups of organisations that are involved in the socio-technical system. Finally, rules guide the activities of the actors and can be formal, normative, or cognitive. The rules materialise in the form of technologies and processes, as well as in practices followed by engineers (Van Bree, Verbong & Kramer, 2010).

Moreover, landscape developments take place at the top level - the macro level. Landscape developments are outside the sphere of influence of regime actors and can put pressure on the current configuration of the regime. Geels (2002) describes the socio-technical landscape as a set of heterogeneous factors such as economic growth, oil prices, wars, emigration, environmental issues, emigration, political coalition, and cultural and normative values. The landscape represents an exogenous environment that may influence both regimes and niches. Thus, neither the regime nor niches could manage to affect the landscape factors to a significant degree. However, changes within the landscape may occur, but at an even slower pace than within the regime. Such changes (or pressure) can open a so-called “window of opportunity” for a new configuration to breakthrough. This configuration can involve a new technology that has been developed at the lowest MLP-level - niches. Through these niches, new technologies can develop protected from market pressures, and can thus be categorised as a transition. For example; the introduction of hydrogen as a public train fuel can represent a transition because it requires changes in multiple elements of the socio-technical regime (Van Bree, Verbong & Kramer, 2010).

The MLP can be a useful analytic framework for understanding transitions, highlighting the precursors, dynamics and complexity of incremental and radical innovations. The framework goes beyond more economic focussed models focusing on innovator characteristics and operation dynamics or industry characteristics and innovation decision-making (Whitmarsh, 2012). The MLP differentiates regime and niche actors as they may behave differently and offer different perspectives on societal problems of unsustainability (however, this distinction is not absolute, and regime actors may support niche projects). That way, the categorisation of regime and niche is not to be used to confirm the dominant status of a certain actor. The presence of niche actors within a research or policy process can ensure that alternatives to the status quo are to be considered within analysis and decision-making (Whitmarsh, 2012). Moreover, MLP offers benefits for researchers because of its broad system-wide focus and consideration of both "outsiders" and radical perspectives in order to identify recommendation for policymakers, industry and other actors or groups interested in activating social change. This is both important and relevant for mobility and transport research because of the inadequacy of incremental approaches for dealing with intractable environmental, economic and social problems with the current mobility system. A so-called techno-fix solution favoured by regime actors may at the best only address a sub-set of such issues. However, they may, in some cases, exacerbate or create other issues by failing to deal with their root/systemic causes (Whitmarsh, 2012).

> (...) fuel cell vehicles reduce air pollution, but do nothing for climate change unless energy supply systems are transformed, and biofuel vehicles put further demands on land use and threaten food supplies (e.g., Royal Society, 2008). Similarly, investment in transport infrastructure, such as light rail systems, may produce undesirable modal shift (e.g., cycle to tram; Schwanen et al., 2004; Lee and Senior, in press); while park and ride systems can actually generate more car use (Goodwin et al., 2004) (Whitmarsh, 2012, p.485).

Thus, I would argue that the MLP framework is multidisciplinary, long term and a systemic approach to the thesis. It appears to be the best analysis to identify unintended consequences and feedbacks and emphasises the diversity of processes and actors involved in social change (Whitmarsh, 2012).

2.4 Transition pathway

As mentioned previously, the MLP features an analytic distinction between three levels: *niches*, in which radical innovation emerges; *socio-technical regimes*, which comprises dominant institutions and technologies; *the landscape*, which represent trends and contextual drivers and barriers to change (Whitmarsh, 2012). Based on these three levels, Geels and Schot (2007) suggest that different kinds of alignments lead to different transition pathways, and constructed a typology based on the combination between the *timing* and *nature* of multi-level interactions. This resulted in four different transition pathways; technological substitution, transformation, reconfiguration and de-alignment and re-alignment. The kinds of alignments between MLP levels lead to different transitions pathways (Geels et al., 2016).

Geels et al. (2016) present two contributions to the sustainability transitions literature. The contributions are mainly based on Geels and Schot (2007) transition pathways typology. Geels et al. (2016) both reformulates- and differentiates the typology through the lens of endogenous enactment, identifying the main patterns for actors, formal institutions, and technologies. In addition, Geels et al. (2016) argue that transitions may shift between pathways, depending on issues concerning technology deployment and institutions.

As mentioned previously, the typology is based on the combination between the *timing* and *nature* of multi-level interactions. *The timing of multi-level interactions* focuses on how mature the niche is when the regime meets pressure. Geels and Schot (2007) argue that the timing of landscape pressure on regimes with regard to the state of niche-innovations is especially important. If landscape pressure occurs at a time when niche-innovations are not yet fully developed, it can result in the transition path being different than when they are fully developed. Further, Geels and Schot (2007) offer three criteria that imply niche maturity; learning processes have accumulated the presence of a dominant design, powerful actors in the innovation system support the technology and that the price and/or performance have improved and there are expectations of further improvement. In addition, Geels and Schot (2007) suggest that the *nature of interaction* can affect the transition outcome. This dimension involves the relationship of the niche innovation to the broader regime. Niche innovations may have a competitive relationship with the existing regime, aiming to replace it. However, niche innovations can also have a so-called symbiotic relationship if they can be adopted as a competence-enhancing add-on in the existing regime to improve the performance of solving problems.

Technological substitution pathway: This pathway is based on disruptive niche-innovations which are sufficiently developed when landscape pressure occurs. In this pathway, the niche innovation may replace the regime (Geels & Schot, 2007).

Transformation pathway: This pathway refers to a transition where landscape pressure stimulates incumbent actors to gradually adjust the regime when niche-innovations are not sufficiently developed. The moderate landscape pressure affects the regime to reorient the direction of its technological development. The landscape pressure may result from social movement groups, scientists and engineers, or other firms developing new practices (Geels & Schot, 2007).

Reconfiguration pathway; This pathway is based on symbiotic niche-innovations that are incorporated into the regime and trigger further (architectural) adjustments under landscape pressure. The niche innovations lead to adjustments within a regime, but the majority of the regime rules remain unchanged. However, the adoption of innovation may lead to experimentation with new and old elements in the regime, accelerating new learning (Geels & Schot, 2007).

Dealignment and re-alignment pathway: In this case, the landscape pressure destabilizes the regime when niche-innovations are insufficiently developed. The landscape pressure is large and divergent, resulting in challenges in the regime, such as internal conflicts and erodes. When there is no innovation fully developed, several niche innovations may compete for resources until one is sufficiently developed (Geels & Schot, 2007).

In the later years, the transition pathways framework has been renewed by Geels et al. (2016) as the former typology lacked attention to agency and institutions. Geels et al. (2016) argue that the “disruptive” and “symbiotic” relationships between niche-innovations and regime depends on how the niche-innovations are institutionally embedded and configured, in addition to the technical characteristics.

2.5 Criticism and research gaps

As mentioned previously, the MLP framework is a multidisciplinary, long term and a systemic approach to the thesis. However, there are literature gaps and room for improvements that one should be aware of. As there are several discussions that could highlight literature gaps of the MLP, I intend to focus on the most relevant in the context of the thesis.

The social aspects of the transitions perspective and MLP have been criticised of being excessively functionalistic, ignoring the agency of actors and social context at the expense of explaining technological processes (Whitmarsh, 2012; Smith et al., 2005). Shove and Walker (2007, p.768) argue that *"for all the talk of socio-technical-co-evolution, there is almost no reference to the ways of living or the patterns of demand implied in what remain largely technological templates for the future".* This may be the result of the supply-driven focus of much socio-technical transition literature. The public is neither homogeneous nor passive. Rather, the public may represent interests and activities with considerable potential for creativity. Geels (2011) argues that the MLP tends to assign the public role of technology consumers and users, rather than citizens or members of communities. This tendency has long been criticised by both sociologists and geographers (Whitmarsh, 2012), as well as by transport scholars (Schwanen et al., 2011). Understanding the tension between niche and regime actors and potential synergies, in the context of travel behaviour, can be a priority for future improvements related to the MLP research. Whitmarsh (2012) argues that individuals may alter their behaviour in more non-technological or social ways. At the individual level, one might choose to live close to the workplace to reduce the need for travel. This choice may offer significant social and health benefits such as work-life balance and social support but can also pose economic threats. As a result, regime actors may suffer from a lack of support (Whitmarsh, 2012). Hence, the public may exert an influence on mobility systems. According to Whitmarsh (2012), the public can influence mobility systems through political engagements, community or workplace action, at the household level and through social networks. Such social-behavioural niches are significant in understanding societal transitions. First, there is potential for behavioural changes to address mobility problems. Second, the engagement of several of social actors in challenging prevailing structures becomes a key locus of innovation. This forces us to consider geographical context and level at which radical innovation within mobility systems and subsystems occurs and could potentially grow. Factors such as policy regimes, opportunities and barriers to political participation, infrastructure, markets and population density can vary across regions and cultures. This can result in very differently shaped and configured landscapes, regimes and niches (Whitmarsh, 2012).

Furthermore, Whitmarsh (2012, p.486) suggests *"to enhance the MLP by integrating insights from the sizeable literatures on habits, heuristics, norms, social learning, social movements, human geography, governance, evidence-based policy, practices".* Hence, throughout the timespan of the thesis, I have paid attention to ongoing discussions concerning action to climate change, especially in relation to zero-emission technology. My intention is to gather insights into social aspects of a transition and identify prominent normative, regulative and cognitive institutions. This will be elaborated in later sections (section 3.5).

Further, a common criticism of the MLP is its lack of spatial dimensions (Bulkeley at al., 2015). The spatial space of socio-technical systems is neither conceptualised nor explicitly stated (Raven et al., 2012). Local diversity and institutions can serve explanations of why niche-innovations emerge in specific contexts and not in others. Consequently, my study especially takes on context-specifics that are of importance in relation to sustainability experimentation.

Last, the MLP has been criticised for its bottom-up focus. Throughout recent years, sustainability transitions politics have been of significant interest. It is widely accepted that strategic transitions through policy instruments do occur (Markard et al. 2012). There is no longer an exclusive focus on niche-innovations breakthrough and replacing regimes. Rather, top-down processes or steering of socio-technical transitions are becoming more important in the transition literature (Meadowcroft, 2009). Top-down initiatives and policies may, through long-term goals, steer the development of socio-technical systems in a sustainable direction (Markard et al., 2012). For example, local authorities can exert efficient policy initiatives (Madsen & Hansen, 2018). There are recent examples of locally urban top-down sustainability initiatives (Bakker & Konings, 2017; Geels et al., 2011; Raven et al., 2017).

3.0 Analytical framework

In the following section, I will present the analytical framework. The framework will function as the lens through which I view and analyse the gathered data. In the first section, I will present the notion of governance of socio-technological sustainability transitions, and the role of the governance concerning the eventual success of the reconfigurations of Germany's regional trains. In the second section, I will present and discuss how experimentation for sustainability can function as an effective tool for steering the development and diffusion of technology through the achievement of strategies and goals. In the third section, I present strategic niche management and how the early adoption of new technologies with high potential to contribute to sustainable development. In the fourth section, I will present relevant literature on urban climate change experimentation and how local authorities can both govern and steer sustainability initiatives. Last, I will present institutional theory and highlight the ways institutions may function as barriers or enabling factors in the experimentation phase.

3.1 Governance of socio-technical transition

Sustainability goals are ambivalent and complex as they are subject to controversies based on heterogeneous perceptions, values and interests of individuals and societal groups. In addition, the knowledge of the complex dynamics involving society, technology and nature is uncertain and unstable. Finally, actors and societal subsystems shape structural change in society and technology. Questions concerning if (and how) transitions can be steered at all are central in the transitions studies (Newig, Voß, & Monstadt, 2008). As in the case of this thesis, the transformation can be steered through long-term goals with the strategy made by both national and international actors. It is expected that various actors aim in the same direction to fulfil the set objectives (Markard et al., 2012). In the following section, I intend to present and explain what role the governance obtains concerning sustainability transitions and reconfigurations.

One pronounced feature of sustainability transitions is that governance often plays a somewhat profound role (Smith et al., 2005). As sustainable development as a concept calls for a debate on how and with whom it can be achieved, there are issues of governance and political steering. There are several approaches to this matter that focus on spatial scales of governance for sustainable development, such as the EU, nation-states, cities or regional governance. Others highlight particular aspects of governance, such as implementation challenges or participation. They all have in common that they assume to a certain extent that sustainability goals can be (assumed) given, as they all focus on how to put “it” in place (Newig et al., 2008).

Strategies towards decarbonization or other types of sustainable development often involve reconfigurations of factors and processes within an existing socio-technical structure (Newig et al., 2008). As mentioned previously, a socio-technical system contains a large number of heterogeneous actors with different goals, values and interests. One major challenge related to sustainable reconfigurations within socio-technical systems is the coordination among activities across the actors while obtaining the sustainable objective. The literature on sustainable governance has been contested if steering of sustainable development is possible, and whether it should happen at all (Newig et al., 2008). However, there are several strategic tools that can function as steering mechanisms of sustainable development. Among these strategic tools, sustainability experimentation is mentioned as one of the most prominent policy tools for governing transitions (Kivimaa, Hildén, Huitema, Jordan, & Newig, 2017).

3.2 Sustainability experiments

The notion of “experimentation” takes on a central role within the academic field that investigates transformations towards sustainable socio-technical systems. Sengers (2019) conceptualizes the term experimentation as *“an inclusive, practice-based and challenge-led initiative designed to promote system innovation through social learning under conditions of uncertainty and ambiguity”* (Sengers et al., 2019, p.1). Socio-technical sustainability experiments differ from experimentation within natural science with its engaged and social constructivist position: society as the “laboratory”, involving a variety of real-world actors that commit to the experimental process that occurs in the introduction of alternative technologies and practices in order to purposively re-shape social and material realities (Sengers, 2019). Simply put, socio-technical sustainability experimentation is a testing phase of new sustainable technologies or practises, and often involves the overarching goal to reconfigure a socio-technical system or implement technology.

Sustainability experiments benefit from the opportunity of experimenting with new methods, institutions and practises over limited time and size (Kivimaa et al., 2017). The objectives of such experiments are often to reconfigure or re-shape socio-technical systems and may eventually lead to significant shifts concerning how societal needs are met in a sustainable way (Kivimaa et al., 2017). Sengers et al. (2019) argue that learning and demonstrating the effects of sustainability experimentation add to the momentum of emerging sustainable configurations, which can transform unsustainable socio-technical systems. Sustainability experiments are *highly novel,* meaning that they radically differ from already existing solutions and ways of meeting human needs within a specific context. They are *planned,* conscious choices and not accidental. They are *socio-technical* in nature and appear in a social context. Moreover, they are often strongly goal-oriented and are expected to lead to substantial (environmental) sustainability goals (Sengers et al., 2019).

The notion and effects of sustainability experimentation have been emphasized in various socio-technical sustainability literature, and can for example, be found in strategic niche management (SNM) (Hoogma et al., 2002) and urban experimentation (Bulkeley et al., 2015). Despite the different approaches to socio-technical sustainability experiments, there are common characteristics that appear among the various experiments. First, experimentation often involves radical innovations. These are usually innovations that require substantial changes across different dimensions, such as socio-cultural, technological, institutional and regulative. Second, the experimentation is implemented in a real-life setting and may lead to test and improve radical innovations. The experimentation usually takes place at a small scale, aiming to trigger change and/or transition at a wider scale. Third, this type of experiment includes a wide variety of actors such as users, policymakers, local administrations, NGOs, consumer groups, industrial associations and research centres. Additionally, it includes the actors more directly linked to the innovation, such as producers, partners and suppliers. Fourth, the experiment is usually implemented in a protected space, protected from the mainstream selection environment. The innovation is temporarily shielded from the selection pressure, consisting of markets and institutional factors. As the innovation is shielded, it creates an alternative selection environment. Ceschin (2014) argues that *"the crucial dilemma of protection measures is to find the right balance between the need to nurture the innovation and the need to prepare it for the selection pressures of a market environment"* (Ceschin, 2014, p.3). Fifth, these experiments aim to learn and improve the innovation of multiple dimensions. Last, socio-technical innovations may stimulate change in the socio-technical context. This may include aspects such as technology, economics, market demand, politics, regulations, environmental, culture and society (Ceschin, 2014).

To sum up, socio-technical sustainability experiments can be beneficial as they provide the opportunity of experimenting with new methods, institutions and practises over limited time and size. In addition, the experiments may reconfigure or re-shape socio-technical systems and can lead to significant shifts concerning how societal needs are met in a sustainable way (Kivimaa et al., 2017).

3.3 Strategic niche management

In relation to niche experimentation, the main interest of strategic niche management can be considered process-oriented. Rather than direct sustainability effects derived from the experiments, SNM literature argues that the success of experiments depends on the extent to which they lead to learning and/or the initiation of structural change. Reduced GHG emissions or improved biodiversity will not necessarily translate to success. Rather, SNM argues that niche experimentation can facilitate broader institutionalisation of values, practices and regulations (Madsen & Hansen, 2018).

SNM literature focuses on understanding the early adoption of new technologies with high potential to contribute to sustainable development (Schot & Geels, 2008). The strategic niche management approach suggests that sustainable innovation journeys can be facilitated by creating technological niches like protected spaces that may allow the experimentation with the co-evolution of technology, user practices and regulatory structures. The assumption was that if such niches were constructed appropriately, they could act as building blocks for broader societal changes towards more sustainable development. Various researchers have focused on the role of several niche-internal processes such as learning, networking, visioning and the relationship between local projects and global rules and policy that guide actor behaviour (Schot & Geels, 2008). Thus, Schot and Geels (2012) argue that an analysis of niche-internal dimensions needs to be complemented with attention to niche external processes.

At the beginning of the SNM, scholars investigated which processes determine successful niche development. This was based on the idea that strategies such as SNM can only work well when modulating on-going dynamics. Thus, SNM as a policy tool does not suggest creating niches in a so-called “top-down” fashion but focuses on endogenous steering. In other words, niches are not inserted by governments but are assumed to emerge through collective enactment (or steering). Such steering may appear as a specific learning process, by adding new actors and/or as a set of demonstration projects and can be enacted by various actors, users and social groups. Moreover, niches can be modulated into more sustainable directions. Thus, Schot and Geels (2008) define SNM as a form of reflexive governance.

SNM scholars argue that for many innovations with sustainability promise, market niches and user demands are not readily available. Their argument is based on innovations not being minor variations from the prevailing set of technologies but differs radically from them. Consequently, SNM was developed to serve the management of a particular type of innovations. These innovations are usually socially desirable, serving long-term goals such as sustainability. Additionally, these innovations are often radical novelties that may face a mismatch with regard to existing infrastructure, user practices, regulations and more. Thus, real-world experiments (like the hydrogen fuel cell experiment in Germany) are important projects to precede market niche development. SNM scholars argue that proto-markets can be exploited for potential alignments of technology, user demands and sustainability issues (Schot & Geels, 2012).

Sustainability transition research emphasises the role of niches as a source for path-breaking innovation. Smith and Raven (2012, p.1026) argue that a key feature of socio-technical regimes is *“the way they function as selection environments for the creation and retention of innovative variants”*. Socio-technical regime theory argues that alignments and mutual interdependencies across multiple socio-technical dimensions generate processes of lock-in and path-dependency. Path-breaking sustainable innovations are at a structural disadvantage within these contexts as they risk being too demanding in terms of their socio-technical implications for the regime. However, scholars in the field of evolutionary theories argue that path-breaking innovations tend to develop in niches that shield those innovations from mainstream selection pressure (Smith & Raven, 2012). Shielding can be defined as *“those processes that hold at bay certain selection pressures from mainstream selection environments”* (Smith & Raven, 2012, p.1027). There is an analytical distinction between passive and active niche spaces. Passive protective spaces can be defined as *“generic spaces that pre-exist deliberate mobilisation by advocates of specific innovation, but who exploit the* *shielding opportunities they provide"* (Smith & Raven, 2012, p.1027). Initial niches can function as passive spaces where the selection pressure is more concerned for content rather than strategic reasons. Such spaces could be geographical spaces, such as smaller regions outside the energy grid infrastructure. Active protective spaces, on the other hand, can be defined as *"those spaces that are the result of deliberate and strategic creation by advocates of specific path-breaking innovations to shield regime selection pressure*" (Smith & Raven, 2012, p.1027). Niches can be constructed more actively by strategic niche management interventions. Still, technology policies may play a role in such inventions and can include regulations, taxes and tariffs. In addition, it may include demand-side measures such as public purchasing, information campaigns and market segmentation. Instead of the search for the right context, active shielding encompasses approaches to create spaces that "escape" mainstream selection pressures (Smith & Raven, 2012).

Last, SNM is concerned with prominent processes related to the success of niche development and implementation (Sengers et al., 2019). However, the literature does not discuss how cities and/or local authorities exert sustainable development and how sustainable experimentation is unfolding within urban contexts. Hence, I will include a recently developed academic interest; urban climate change experimentation.

3.4 Urban climate change experimentation

Urban experimentation in the field of sustainability was developed due to the assumption that other theories on sustainability experimentations are insufficient to investigate urban experimentation in cities. Over the past decade, cities have been considered important in the mitigation of climate change, functioning as central powers for sustainable development initiatives (Bulkeley et al., 2015). Local actors such as municipalities, organizations and NGOs appear to be the initiators for sustainable action. Urban experiments can be defined according to three criteria. According to Bulkeley et al. (2015), an initiative can be considered experimental if;

- It is strategic and deliberate. There is a deliberate attempt to configure an urban socio-technical system. However, it is considered as an open-ended nature of socio-technical processes
- There is an attempt to combat climate change (mitigation)

- Adapt to its effects (adaption), and it is delivered or conducted by an existing urban community

Bulkeley and Castán Broto (2013) argue that urban experimentation should be regarded as a part of climate governance. As a result, some of the areas of importance are similar to other forms of climate governance. Further, Bulkeley and Castán Broto (2013) argue that urban experimentation is tied to how urban authority is restructured. Thus, certain differences and similarities within urban experimentation may differ between cities. Based on Bulkeley et al., (2015) threefold definition, the case of this thesis is relevant to the urban experimentation literature; it is deliberate, aiming to reduce GHG-emissions from the mobility sector, and is tied to the urban context of Lower Saxony.

However, urban experimentation can face various barriers. Madsen and Hansen (2018) present interesting challenges that are of relevance to the sustainability initiative in Germany. From a political perspective, there are often several “issues” competing for both attention and resources within the urban context. Sustainability related initiatives may first bring benefits several decades in the future. Other issues, on the other hand, may lead to more immediate and concrete consequences and may thus be easier to politically prioritize. Madsen and Hansen (2018) further state that local urban governments bureaucratic challenges in relation to political engagement with climate objectives. Often, climate action extends beyond the urban experiment boundaries. This is often the case with larger infrastructures such as mobility and electricity, and are thus relevant to the scope of this study. For example, the city’s geographical jurisdiction often influences and obtains authority over such large projects. This can also be further complicated by the privatization of infrastructures, which may result in an increase in fragmented systems (Madsen & Hansen, 2018).

In order to assess the effect of a sustainability experiment, Madsen and Hansen (2018) argue that both process-oriented and goal-oriented perspectives should be included in the analysis. An integrated approach analysing the sustainability outcomes and the processes as well as the institutional change from the experiments allows more visual effects of the experiment. Thus, to assess the effect of the hydrogen fuel cell experiment, I intend to obtain both a process-oriented and goal-oriented perspective based on literature from SNM and sustainability experimentation. As mentioned in the previous section, SNM literature focuses on the role of several niche-internal processes such as learning, networking, visioning and the relationship between local projects and global rules and policy that guide actor behaviour (Schot & Geels, 2008). SNMs process-oriented view evaluates the success of experiments based on learning outcome and institutional change rather than sustainability measures such as GHG emission reduction (Madsen & Hansen, 2018). On the other hand, sustainability experimentation is more goal-oriented and can be described as a planned initiative that embodies a novel socio-technical configuration that may lead to environmental sustainability effects (Wieczorek, Raven, & Berkhout, 2015). Thus, sustainability experimentation is more concerned with the sustainable outcomes of the experiment and focuses on whether the visions and the objectives for sustainability are obtained or not.

Cities can be important sites for climate change governance as well as for sustainability experiments for two reasons. Madsen and Hansen (2018) argue that cities have “authority advantages” in terms of climate change responses, as their local government and municipalities are often responsible for public services such as public transport. Thus, municipal agents can be more equipped to initiate GHG emission reduction measures in the system that they are responsible for. Additionally, cities inherently have an “engagement and mobilization advantage” due to an urban scale. Local actors possess first-hand knowledge of the city’s challenges and needs, gaining legitimacy and trust from a range of stakeholders (Madsen & Hansen, 2018).

Relevant elements from urban experimentation, sustainability experimentation and strategic niche management will be used as an analytical framework discussing the first research question. I intend to investigate the initiative of the hydrogen fuel cell experiment. In addition, I intend to discuss how the experiment emerged, and the experiments perceived effects can have as a mean to full-scale implementation.

3.5 Institutional theory

Institutional theory can bring insights in attempts of understanding socio-technological sustainability experiments. Thus, I intend to use elements of the institutional theory to investigate the institutional barriers and enabling factors associated with the hydrogen fuel cell technology experiment in Germany (Geels, 2004). The theoretical foundation is built upon neo-institutional theory and Scotts (2008) three-pillar model of institutions. Further, the model has been elaborated by Geels (2004) to fit transition studies.

Within a socio-technical system, the activity of the actors is constrained by the rules of the game. This activity is played out to reproduce or modify elements of a socio-technical system (Geels et al., 2016). Geels (2004) argues that in all activity that occurs by various actors, there is a consequence. By those activities, actors *"make investment decisions about R&D directions, introduce new technologies in the market, develop new regulations, propose new scientific hypotheses. These actions maintain or change aspects of ST-systems" (*Geels, 2004, p.909). Thus, actors are allowed to act within the institutional environment. New technologies do not always fit well into these rule-systems that require institutional innovation or change (Bakker & Konings, 2017). As a result, from a socio-technical perspective on transitions, institutions do matter for sustainable development (Kern, 2011).

Institutions can be defined as *"multifaced, durable social structures made up of symbolic elements, social activities, and material resources"* (Scott, 2008, p.48). They are usually tenacious, reproduce and transmit throughout generations. In addition, the concept of institutions embraces the importance of behaviour and material resources. Determined by processes connected to regulative, normative and cultural-cognitive processes, institutions may guide behaviour (or resist change). Institutions cannot provide meaning and/or reproduce themselves without being acted upon. Hence, rules, norms and cognitive elements must be legitimised. Consequences must follow if failing to comply with the conducted structures. If not, the institutions lose their meaning and will fail to guide behaviour. This is how the material resources appear in the form of monetary resource, as well as legitimate power. Those with the possession of power may have the ability to sanction those not following the institutions (Scott, 2008).

Institutions can be classified as formal/hard and informal/soft. Formal/hard institutions refer to laws, regulations and societal structures that function as sanctions of fines and lawsuits (Geels, 2004). Informal institutions, on the other hand, provide nonetheless important societal structures that consist of values, norms and beliefs. These unformalised institutions are usually shared by several individuals within the same system (Bakker & Konings, 2017). Further, Scott (2008) has provided a typology of institutions by dividing them into three different categories by adding a third category to the formal/informal institutions. The typology accounts for all institutions and can be used as an analytic framework based on neo-institutional approaches in research across various disciplines. In the thesis, the typology has been useful to analyse the transition and the transition dynamics (Geels, 2004).

As abovementioned, Scott (2008) distinguished between three dimensions; regulative, normative and cognitive institutions. The typology is based on the formal/informal institutions, which provide a biased image of each pillar. The formal/informal classifications are interrelated (Scott, 2008). However, I find it helpful to separate them into entities for theoretical purposes (Geels, 2004). I will present each pillar in the following section.
The regulative institutions refer to explicit, formal institutions, that constrain behaviour and regulative interactions such as government regulations which structure the economic process. This dimension of institutions often includes rewards and punishments that are backed up by sanctions. Institutional economists tend to highlight these institutions as they often structure economic processes at a national level, such as property rights, contracts, legal systems and more (Geels, 2004). Thus, regulative processes may steer behaviour with various sanctions. However, the seriousness of the sanction can affect the strength of the institution. In some cases, regulative institutions can constrain behaviour and human interaction. In other cases, regulative institutions can map out the exact way a process may be executed (Scott, 2008).

The normative institutions are often highlighted by traditional sociologist and refer to values, norms, role expectations, rights, responsibilities and duties. Scholars within the sociology tradition argue that such institutions are internalised through socialisation processes (Geels, 2004). While values can be conceptualised as individual or collective beliefs of preferences or desired, norms can be described as the allowable ways to obtain desired goals. Thus, normative structures can both define what has preferred as well as the legitimate ways of research certain desired (Scott, 2008). Different normative institutions exist for different actors, and a central aspect of normative institutions is how these actors in a perceive their role in the socio-technical system. That way, what is considered as appropriate goals and how to behave in specific social interactions may differ among actors (Scott, 2008). Roles can be of either formal or informal character. Formal roles are often tied to specific responsibilities and resources, while informal roles appear over time based on interactions and expectations (Scott, 2008).

The cognitive institutions constitute the nature of reality as well as the frames through which meaning or sense is made. Such institutions involve symbols, such as words, concepts, signs, gestures and myths, that effect by shaping the meanings that vi attribute to objects and activities. Social and cognitive psychologists have focused on the limited cognitive capacities of human beings and how we use frames, schemas, cognitive frameworks or belief systems to both select- and process information (Geels, 2004). Cognitive elements are often implicit and taken for granted. However, they are very much influential in people's lives as cognitive schemas and routines. Thus, if actors possess new and/or different schemas, confusion may arise (Raven et al., 2017). One challenge relevant to the subject of the thesis is system change. This may appear as a challenge as it depends on the actors to cooperate towards the same goal (Sengers et al., 2019). Even though the implications of unconformity to cognitive institutions cannot compare with the formal penalties that may come with regulative institutions, implementation of an innovation or technology can slow down or hinder the process (Raven et al., 2017).

The institutional dichotomy can function as a helpful tool for my analysis when investigating transitions and socio-technical system transition. The framework has previously proven useful in projects on urban sustainability initiatives (Bakker & Konings, 2017; Raven et al., 2017).

As mentioned previously, the institutional division is meant as the “rules of the game”. Thus, it is considered “appropriate” for actors to act and behave within the rules. Geels (2004) argue that rules are sewn together into rule systems that differ between the social groups and entities where they exist. In order to avoid sanctions, actors within the institutional system have to act within the frame of these rules. Moreover, Geels (2016) conceptualise the so-called “rules of the game” as rule-regimes. Thus, it is implied that institutions co-exist, and the impact and implications of the institutions may be difficult or even impossible to separate. That way, institutions both guide and restrict behaviour and may thus result in institutional (and/or technological) lock-ins (Geels, 2004).

3.5.1 Institutional lock-ins and path-dependence

Socio-technical systems are usually stable for long periods, which are often referred to as lock-ins or path-dependencies (Geels, 2004). As “the rules of the game” within a socio-technical system, institutions provide stability by guiding behaviour. Thus, institutions are sometimes referred to as the “deep structures” of an innovation system (Geels, 2004). Based on the typology framework, Geels (2004) describe how institutions create path-dependencies and lock-ins.

The cognitive institutional lock-ins may appear as a consequence of the cognitive frames that provide meaning to social life. As previously mentioned, cognitive frames are often apparent as routines thus may block the search for new opportunities. Such routines make you blind to developments outside your focus. Geels (2004) argue that capabilities, knowledge and skills function as "cognitive capital" with sunk investments. It requires a wide timeframe and resources to build new capabilities and acquire new knowledge. For established firms and organisations, it is often difficult to develop (or switch) to competence destroying breakthroughs. Thus, learning can be a major source to path-dependency as learning normally is a cumulative process. Cognitive frames can be shared belief systems and expectations, which orient perceptions of the future and in that way, steer actions in the present. As long the firms and/or organisations expect that certain problems can be solved within the existing regime, they will not invest break out, but continue along with existing oaths and technical trajectories. Additionally, Geels (2004) argue that the perceptions of user preferences function as central cognitive rules. As long as firms and/or organisations believe that they meet user preferences, they will continue in the same path producing similar products (Geels, 2004).

Normative institutional lock-ins (both technological and institutional) may occur as a consequence of mutual role perceptions and expectations of proper behaviour that has been established within social and organisational networks (Geels, 2004). Thus, Geels (2004) stress the importance of a mutual understanding of role expectations among actors. In some relations, it may not be seen as "proper" to raise certain issues or to act a certain way. This sort of behaviour is not regulated by law, but behaviour that has over time been associated with different actors and activities in a specific relation.

Regulative institutional lock-ins may occur within established systems that are stabilised by legally binding contracts. Long-term contracts that are legally binding can for example prevent the implementation of new technologies. Moreover, Geels (2004) argue that other stabilisation rules, such as technical standards or rules for government subsidies may favour existing technologies.

In addition, Geels (2004) mention a fourth type of stability; the alignment between rules. It may be difficult to change one rule without altering others. Thus, the three-pillar framework indicates strong relations between the institutions.

Table 1: “Rules of the game” within the German mobility sector Germany

Institution	Function	What to look into
Cognitive	Cognitive schemas and routines	Mutual visions, knowledge and competence, routines, users opinion and perspective,
Normative	Normative values and behaviour	Common perception of the organization itself (“Mobility by Nature”), policy goals
Regulative	Laws, contracts, regulations, legislations	Policies, regulative practises, governmental funding,

3.5.2 Institutional innovation

Schumpeter (1942) argue that innovation is an invention with a successful implementation. An invention can thus be defined as an innovation when the results in some way return to a market (not only financial) (Mieg, 2013). Successful implementation of innovation fit into the social and institutional context and are able to fulfil its societal function. An innovation such as the hydrogen fuel cell powered train may fail to adapt to the current rules of the system. In such cases, there are two options. One can either discharge the invention or alter the rules of the game.

By alter the rules of the game, you change the institutional setting. This is referred to as institutional innovation. Due to national guidelines and regulations, altering the rules of the game may be challenging (Mieg, 2013). However, it is possible to change the “game”. Even legislations may have loopholes. Despite its long-lived nature, both normative and cognitive institutions may be changed without legal sanctions (Foxon, 2002). However, altering existing institutions is not a straightforward process and may take a long time (Geels, 2004).

The aforementioned three-pillar institutional framework creates the analytical lens used for the analysis of the second research question. The second research question seeks to investigate the institutional barriers and institutional enabling factors associated with the hydrogen fuel cell powered train experiment in Lower Saxony.

4.0 Methodological approach

In the following section, I intend to present the methodological choices that has been made throughout the thesis.

4.1 Qualitative research

Based on the nature of the research question, I decided to conduct qualitative research. Qualitative research encompasses research that produces findings that are not of statistical procedures or other means of quantification (Strauss & Corbin, 1990). The method itself tells us how we should work to obtain or verify knowledge (Dalland, 2015). Qualitative research is concerned with elucidating human environments and human experiences within various conceptual frameworks and usually revolve around an interest in a specific phenomenon (Winchester & Rofe, 2016). Research questions dealt with by qualitative researchers are concerned either with social structures or individual experiences. This dualism can be challenging to disentangle in practice but can be of high importance in explanation. The behaviour and experiences of an individual can be determined by their position in the social structure (Winchester & Rofe, 2016).

My research is intensive by nature, and focus on why how processes work, why opinions are held or how actions are taken in the particular case (Stratford & Bradshaw, 2016). The research seeks an understanding of processes related to experimentation with hydrogen technology and will provide discussions of the background and perceived effects associated with hydrogen fuel cell experimentation. The research also aims to discuss institutional barriers and enabling factors associated with the experimentation.

4.2 Case study research

The thesis will be organized according to the case study tradition. Case study research can be recommended when the objective of the research is to understand a social phenomenon (Yin, 2014). According to Baxter (2016, p.130), case study research involves the *"study of a single instance or small number of instances of a phenomenon in order to explore in-depth nuances of the phenomenon and the contextual influences on and explanations of that phenomenon".* This type of study is often used to better understand- and sometimes directly resolve concrete issues and can create important philosophical assumptions regarding the nature of research that support the value of case research.

> The primary guiding philosophical assumption is that in-depth understanding about one manifestation of a phenomenon (a case) is valuable on its own without specific regard to how the phenomenon is manifest in cases that are not studied (Baxter, 2016, p.131).

This depth of understanding may concern solving practical and/or concrete issues associated with the case or broadening academic understanding (theory) about the phenomenon in general, or a case study may to both of these things. However, there have been various misconceptions of case study research as a method. This has been caused by several examples of researches failing to follow systematic procedures and lack of rigour (Yin, 2014). However, Yin (2014) argues that this may be a consequence of the lack of a clear step-by-step procedure when using a case study research as a method. There is therefore important to ensure rigorous research, especially for me as a researcher with little experience. I intend to present- and discuss rigour in a later section.

Case studies play two exclusive roles: to test theory and to generate or expand theory. The first may involve the search for negative or falsifying cases, while the second concerns cases that are more typical. Yin (2003) argue that theoretical propositions should be stated prior to entering the field. I have viewed the case study as a theory-generating endeavour and decided to follow Yins (2003) recommendation that formal propositions need to be stated upfront. Thus, two cautions are necessary. First, "*qualitative researchers presume that propositions are contingent or context-dependent such that concepts describing relationships are only "true" under certain conditions"* (Baxter, 2016, p. 136). However, concepts are still "true when… ", as well as accounting for the context or contingencies within which a "truth" happens falls within the realm of what many qualitative researchers do in practice. Second, *"there is a potential logical flaw in ever stating propositions upfront at the beginning of a study"* (Baxter, 2016, p. 138). Formal propositions may require well-developed theory as their basis. However, qualitative case studies may often be used to look into under-explored and thus under-theorized phenomena. Furthermore, researchers tend to borrow from related areas of inquiry. Most often, it is not necessary to re-invent the conceptual/theoretical "wheel".

Qualitative research is usually not based on a pure deductive or pure inductive endeavour. Rather, Baxter (2016) argue that both deductive and inductive research inevitably involve “multiple loops” of reasoning as the researcher tentatively develops concepts (induction) and further compares them to the details of the social world which comprise the case (deduction).

> (...) it tends to be more cyclical in the sense that theory stated initially either formally as hypotheses or loosely as budding ideas are explored (deductively) by studying the real world of the case and then that information is used to generate new concepts (theory) to explain what is observed (inductively) (Baxter, 2016, p.138).

Yin (2014) suggests three conditions (or criteria) to consider when selecting a research method: the nature of the research question, the extent of behavioural control, and whether the focus is on a contemporary or historical event. For a case study to be the most appropriate, Yin (2014) argues that the research ought to be of a contemporary event as opposed to historical events. The event that I am investigating is contemporary and is unfolding within the timespan of the thesis. Discussions concerning the ongoing experimentation and further implementation are thus based on the current socio-technical mobility system, and take on recent events. Second, the research should focus on the “how” and/or “why” components. I seek to understand the concrete and practical aspects of how hydrogen fuel cell powered trains became a priority in Germany, and how the existing socio-technical mobility system facilitate or obstruct such a transformation. The empirical findings related to the “how” and/or “why” components may be subject to discussions of further implementation of hydrogen technology in rail application. Last, a case study can be appropriate when the researcher does not have the need to or is unable to control variables. The thesis fits well with all three conditions. As socio-technical experimentation usually appears in real-life settings, there is no possibility to control variables or behaviours. I seek to enter the experiences and perspectives of my informants and generate explanatory theoretical concepts (Yin, 2014).

Case study research can offer challenges as there is a lack of step-by-step guides on how to conduct rigorous research (Yin, 2014). However, attempts to provide guidelines have drawn attention to the importance of the design of case studies. I decided to conduct a single case study, including two data collecting methods; qualitative interviews and content analysis of relevant documents. Yin (2014) argues that when a case is critical, unusual, common, revelatory or longitudinal, a single-case design is recommended. My research subject is somewhat a revelatory one as there is a lack of studies of hydrogen fuel cell experimentation.

4.3 Qualitative interviewing

A qualitative research interview is an interpersonal situation that is based on a dialogue between two parties concerning a particular phenomenon (pa, 2015). As the event that I am investigating is contemporary, there is a lack of reports discussing the matter (Patton, 2002). Thus, by conducting oral interviews, I can access perspectives and explanations that may not be included in the latest reports. Interviewing is a popular data collecting tool that enables the researcher to gain insights into people's perspective, experiences and opinions. However, interviewing can not be mistaken for a regular conversation. Conducting interviews require certain skills and techniques, and is know-how practices that need preparations and rehearsals (Patton, 2002). The main objective of an interview to gain insight into the informant's thoughts, feelings, motivations and intentions (Patton, 2002). Not only can interviewing allow the informants to describe events or a phenomenon from their own perspective, but it will also allow the researcher to discover what is relevant to the informant (Dunn, 2016).

There are several variations on how to conduct data using qualitative interviewing. Dunn (2016) suggest to separate the different approaches in three further categories; the structured interview, the unstructured interview and the semi-structured interview. Structured interviewing follows a predetermined and standardised list of questions, while unstructured interviewing is characterised as "oral histories" and is directed by the informants. Semi-structured interviewing can be found in the middle of this "continuum", and has some degree of predetermined order. This type of interviewing maintains flexibility in the way issues are addressed by the informants. However, different approaches are not mutually exclusive. It is possible to use more than one of the interview forms or even combine the approaches during one interview (Patton, 2002). Patton (2002) argues that the quality of the data relies on the quality of the researcher. Both the interview process and results may be affected by my limited experience of conducting interviews. When the researcher finds herself in a situation like mine, it is recommended to conduct *semi-structured interviews*.

Semi-structured interviews are organised around ordered but flexible questioning, whereas my role as a researcher is recognised as being more flexible than in structured interviews. Consequently, I was a researcher with the responsibility of redirecting the conversation if it had moved too far from the actual research topic (Dunn, 2016). Moreover, semi-structured interviews are characterised by the use of an interview guide, containing questions or topics for discussion (Patton, 2002). The identification of key concepts and themes functioned as a preliminary part of the research project and has been applied as a tool during the interviews. The interview guide includes a list of key topics, concepts and questions, and is based on existing literature from the socio-technical transition tradition. In addition, I focused the interviews in accordance with ongoing discussions concerning hydrogen technology within the mobility sector.

Due to the flexibility of semi-structured interviewing, I found myself in a position to explore, probe and ask questions to illuminate the subject of interest (Patton, 2002). As I interviewed informants with different competences and area of expertise, the questioning differed from each interview. At the beginning of each interview, I asked the informants to explain their experience and position in relation to the hydrogen technology in rail application. This allowed me to sort out the questions most relevant to their role and experience. That way, using semi-structured interviewing allowed me to direct the interview in accordance with their answers. In addition, I noticed that the different informants focused on different areas of the subject. For example, throughout some of the interviews, both the questioning and answering took a political turn. Informants engaged in the German government’s climate protection and energy targets were particularly eager to discuss energy policy. In other interviews, the informant focused on the more technical aspect of the subject. For example, informants from the energy sector directed the conversation towards the technical and environmental benefits of hydrogen technology within rail. However, I believe that I conducted the data needed to answer the two research questions. Additionally, the differences among the informants provided fruitful discussion and allowed me to analyse the research questions from different perspectives.

4.3.1 Sampling

When conducting interviews as a part of a case study, the selection of informants may have an impact on the findings of the study (Dunn, 2016). Even though the representativeness is not the objective of qualitative research, the selection of informants can affect the data material. All informants were selected through purposive sampling, using both snowball- and criterion sampling (Tansey, 2007).

Early in the research process, I was able to contact various actors for an exploratory interview to see what type of relevance they could bring to the research question or if they could relegate me to others that may have more relevant competences. For example, I had a meeting with a key informant from Alstom in October. He mentioned various relevant actors, both internally (in Alstom) and externally. This method is suitable when the population of interest is not fully visible and allowed me to identify the initial set of relevant informants. In addition, several of the informants suggested other potential subjects and informants who share similar characteristics or who have relevance in some way to the object of study.

Moreover, to ensure a broad variety of informants, I wanted to interview informants that were not recommended by Alstom. Hence, I searched through central reports to find actors relevant to the thesis. This form of criterion sampling leads me to actors such as climate organisations and think tanks. Moreover, I experienced great enthusiasm among the informants, and several of the informants recommended other relevant informants due to their specific knowledge. This allowed me to get in touch with well-experienced informants that I might normally struggle to reach. In addition, it saved me a lot of time and energy searching for potential informants (Dunn, 2016). This process continued until I felt that the sample was large enough for the purpose of the project. The informants were contacted by email with a short explanation of the thesis in addition to the practical information. When agreeing to participate in an interview, each informant received a letter of information and consent. This will be further elaborated in the “ethics and rigour” (4.6) section below.

Table 2: Overview of conducted interviews

Informant	Company	Date	Duration
Informant A	Agora Energiewende	09.01.2020	45 min
Informant B	Alstom (iLint Project)	16.01.2020	25 min
Informant C	Innovation Norway	17.01.2020	45 min
Informant D	Norsk Hydrogenforum (NHF)	31.01.2020	65 min
Informant E	Innovation Norway	23.01.2020	25 min
Informant F	Alstom (iLint Project)	30.01.2020	45 min
Informant G	Hydrogenics	06.02.2020	60 min
Informant H	NOW	13.02.2020	35 min

4.3.2 Elite interviews

The conducted interviews can be categorized as elite interviews. I decided to conduct elite interviews for two reasons. First, elite interview data are rarely considered in isolation and seek to confirm information that has already been collected from other sources. Tansey (2007) argues that *"when documents, memoirs, and secondary sources provide an initial overview of the events or issues under examination, interviews with key players can be used to corroborate the early findings".* Consequently, conducting elite interviews can confirm the accuracy of the information that has previously been collected from other sources. Second, as well as serving a corroborative purpose, elite interviews can additionally provide new information that can advance the research process (Davies, 2001). One such additive function is to establish people's thoughts, attitudes, values and beliefs. As mentioned previously, the interview format allowed me to probe informants at length concerning their thoughts on key issues relevant to the research topic (Tansey, 2007). When selecting relevant informants, I did background research on their previous work and competences. Based on their background and competences, I chose people who could communicate aspects of their experiences and ideas relevant to the subject. Moreover, I negotiated permission for the interview and received the consent of the informants themselves. As several of the informants were based in Germany, I decided to contact them using email (Dunn, 2016).

Smith (2006) state that identifying individuals as “elite” often relies on structural notions of power. The informants were both older and more educated than me. In addition, all informants naturally have more knowledge in regard to the subject. Due to the asymmetrical power relation, there was a risk of the informant taking control of the interview. In order to prevent this to happen, I looked into the company that each informant represent and their position within the mobility sector. I also educated myself in terms of the current situation within the mobility sector, and especially in relation to hydrogen technology. That way, I was able to adapt the questions to the competences and expertise of the informants. This will be further discussed in the section concerning positionality and reflexivity in qualitative research (4.6.1).

4.4 Transcribing interviews and analysis

Audio recording is one of the main techniques for recording Skype/Teams-interviews and allowed for a natural conversation between the informants and me. I consider audio recordings as an efficient and appropriate way to gather data as several of my informants were based in Germany. In addition, Teams allowed me to record the interview without any extra equipment.

I decided to not take notes as note-taking researchers tend to be so busy taking notes that they may find themselves unprepared to ask the next question. Without the distraction of note-taking, I had more time to organize the next question and maintain the conversational nature of the interview. However, Dunn (2016) argue that audio recordings may inhibit informant’s responses. Informants may feel vulnerable thinking in this type of situation. Opinions and thoughts are given by the informants on the “spur of the moment” have the potential to become a permanent public record of the informant’s perspectives. This may make the informant less forthcoming (Dunn, 2016). However, all the informants were comfortable with the audio recording as they were familiar with this tool from a “normal” workday. Rather, I experienced certain difficulties in terms of audio and language. During one of the meetings, there were severe difficulties with the audio. Thus, I had to interrupt the informant repeatedly in order to clear up any potential misunderstandings. I believe that this had a negative effect on the interview and thus restricted the findings. However, I captured the most prominent arguments and has been able to use some of the statements in the empirical findings. Moreover, five of the interviews were conducted in English. Some of the informants were struggling to express themselves properly with the English language. Thus, I was struggling to transcribe their interviews and capture their arguments correctly.

Records of an interview are usually written to facilitate analysis. A transcript s a reproduction of the interview including descriptions of gestures and tone in addition to the words spoken. I transcribed the interviews shortly after they were conducted. Transcribing interviews is often time-consuming, and according to Dunn (2016), it is expected to take about four hours to transcribe a one-hour-long interview. However, due to little experience transcribing interviews, it took me about five hours to transcribe a 45 minutes interview. In addition, it took me six hours to transcribe the interviews that had to be translated from Norwegian to English. Due to difficulties in terms of audio and language, the finished transcript was sent for review and approval to all informants. That way, I eliminated any sort of misunderstandings. One of the informants edited the finished transcript and added additional comments.

After transcribing the interviews, I did a latent content analysis, searching through all the transcripts in order to sort out important themes or concepts. This required me to search for the underlying meaning of what was said. This sort of search for meaning is a form of coding (Dunn, 2016).

4.5 Qualitative content analysis of relevant reports

In addition to the conducted interviews, I analysed relevant reports to complete my analysis. Qualitative content analysis is a much used research tool that aims to make sense of written material such as interview transcripts and other documents (Dunn, 2016). Dunn (2016) stress the importance of being aware of what the researcher is looking for when conducting a qualitative content analysis. As a result of the current energy crisis due to depletion of resources and increased environmental issues, hydrogen fuel cell technology is a popular topic among the public. That has provided me with relevant reports that have been published within the timeframe of the thesis. Thus, I have searched for information concerning zero-emission technology, sustainable mobility goals and initiatives through various relevant reports.

At the beginning of the content analysis, I did a manifest analysis. I searched for surface information concerning sustainable mobility goals- and strategies. I then marked the relevant parts of the reports. Finally, the latent content analysis started. This involves making sense of the written material, aiming to gain an understanding of what is stated (Dunn, 2016). I searched for specific sustainable mobility goals within railway and strategies concerning hydrogen fuel cell technology.

4.6 Ethics and rigour in qualitative research

There are several ethical considerations that are of importance to any research project. In advance of the interviews, I reported the research to The Norwegian Centre for Research Data (NSD). When conducting qualitative research, one has certain obligations to the individuals involved. Especially the informants and organizations that are subject to the research (Dowling, 2016). As previously mentioned, the main objective of an interview is to take on the informant’s perspective and gain knowledge concerning their thoughts, feelings, motivations and intentions (Patton, 2002).

Based on the privacy regulations by NSD, I created an informed consent that every informant received in advance of the interviews. The objective of this letter was to communicate the topic of the interview, the manner in which the interview will be conducted, and rules and regulations in terms of confidentiality (Dunn, 2016). The letter stated that the interviews would be recorded and the information stored afterwards. The recordings and transcripts of the interviews have been stored on my personal computer, which has been password protected. The informants were also informed that they will be anonymous. Neither their name nor characteristics have been used in the thesis. However, I will refer to the organization/company that they represent. Thus, their citations will not be directly traceable to any individual informant. Additionally, I informed that the recordings would be deleted 01.05.2020. Last, the informants were aware that participation in the project is voluntary. Even though you choose to participate, they may withdraw their consent at any time without giving any reason. All the information will then be anonymous, and there will not be any negative consequences if they do not want to participate or later choose to withdraw (Dunn, 2016).

There was no intention of addressing sensitive personal information. However, some of the informants mentioned a few things that could disclose their identity. Thus, I will leave out any revealing information as it is not important for my findings.

4.6.1 Positionality and reflexivity in qualitative research

Subjectivity is an important part of qualitative research and involves the intention of personal opinions and characteristics in research practice. Subjectivity involves your everyday understanding of the world, and the researcher gives emphasis to subjectivity as the method involves social interactions (Dowling, 2016). Furthermore, intersubjectivity refers to the meanings and interpretations of the world created, confirmed and/or disconfirmed due to interactions (action and language) with other people within a context. During the conducted interviews, my personal characteristics and social (and educational) position cannot be controlled or changed. How I was perceived by my informants, the way I perceived them, and the way we interacted are partially determined by societal norms (Dowling, 2016). All of the informants were both older and more educated than me, resulting in an asymmetrical balance. However, this was never an issue during the interviews. The informants were all positive and engaged and welcomed me into their worlds. This resulted in a less apparent power relation.

I found that critical reflexivity was an appropriate strategy for dealing with issues of both subjectivity and intersubjectivity. As a researcher, I brought my own assumptions and views of the world, and especially concerning the subject of the thesis. This does not affect the findings in a negative way. However, as a researcher, I need to be aware of my own position in the project (Dowling, 2016). There are several ways both my social and cultural position may have affected the process and outcome of the research. I am interested in and positive towards an emission-free and (more) centralised mobility system. In addition, I am working as a project assistant for Alstom Transport Norway. Thus, my daily life revolves around mobility-related issues. All of my informants were either connected to the mobility sector, climate organisations or energy companies. In common, they all had a positive mindset towards finding the best energy solution within the mobility sector. Considering the informant's position in the mobility sector, there was no situation of conflict interest or opinions between the informants and me. In addition, one of my goals was to communicate with different parts of the mobility sector. Hence, I contacted actors that were connected to the mobility sector in different ways. Some obtained more commercial interests, while others were more committed to sustainability and the achievement of various climate goals. However, I missed a governmental actor. I was planning on a trip to Lower Saxony. However, the trip was cancelled due to the Corona pandemic. A governmental perspective on the transition could be a fruitful addition to the other informants. I would also like to gain insights into their future projects concerning zero-emission technology within the mobility sector. Last, a trip to Lower Saxony could allow me to interview iLint passengers. I contacted one of my colleagues in Alstom and requested a passenger survey. However, there has not yet been conducted a passenger survey, not by Alstom at least.

5.0 Empirical findings

In the following section I will present my empirical findings. The findings are based on interviews with relevant actors in the mobility sector and content analysis. Based on the two different research questions, the findings will be presented in two parts.

5.1 Background and perceived effects

This section will present the empirical findings related to the first research question; *What is the background for the hydrogen fuel cell experimentation in Lower Saxony in Germany, and how can the perceived effects influence further implementation?* As the informants represent different levels of expertise and experience in addition to different areas of interest, the transcribed material obtains a more general nature. Thus, the empirical findings have relevance to a European context rather than exclusively the German case, and can thus be adapted to other countries in Europe. However, certain findings were specifically relevant to the current situation and case in Lower Saxony in Germany. This will be further discussed in the section concerning Limitations of the thesis (section 6.2).

Socio-technical sustainability experimentation can function as an "*inclusive, practice-based and challenge-led initiative designed to promote system innovation through social learning under conditions of uncertainty and ambiguity"* (Sengers et al., 2019, p.1). Sustainability experimentation and its learning and demonstration effects can add to the momentum of emerging sustainable configurations, which can (or may) transform unsustainable socio-technical systems (Sengers et al., 2019). I have investigated what my informants believe to be the background and perceived effects of the hydrogen fuel cell technology train experiment in Lower Saxony. I start by presenting how hydrogen fuel cell technology became a priority in the regional parts of Germany, where the initiative came from, in what way it promotes green technology and its opportunities to expand beyond Germany's borders. Last, I will present an overview of the findings related to the first research question.

5.1.1 Context

The iLint trial trains were located in the area of Lower Saxony in Germany in 2018, and have since then been operating in commercial service. In order to investigate the background and perceived effects of the experiment, I foremost seek to create an overview of the context and landscape through which the experimentation is located. During the analysis of the transcribed material, I noted in particular three repetitive discussions within context dependence for introducing hydrogen fuel cell technology in a rail application; local conditions in terms of geographical factors, energy availability and governmental support. Due to its 40 percent non-electrified railway, the informants argued that both Germany and Lower Saxony were a fitting context for a hydrogen fuel cell experiment for passenger rail. Hydrogen vehicle traction systems are configured and optimized to fit operation and conditions under which the vehicle is to be operated. The iLints are configured for operation as local trains in a completely flat and relatively rural area with moderate winter conditions. In addition, the tracks provide a relatively low average speed. For operation under significantly different conditions, the vehicle's configuration must respect traction effect, battery size, fuel cell capacity and storage tank size (Sintef, 2019). Based on a decision by Alstom and the Lower Saxony regional authority (LNVG), the prototype trains were deployed on a route that were identified and planned to be the subsequent deployment of a full fleet. The trial trains were located in Lower Saxony due to its major non-electrified line that were previously operating on diesel (informant F, Alstom).

In addition to geographical factors, energy availability was repetitively mentioned as a central factor related to the location of the trial. The environmental impact of hydrogen fuel cell powered trains are depending on both production and distribution of the hydrogen (Sintef, 2019). At the current stat, 90 percent of the hydrogen produced is produced from fossil energy sources. However, Sintef (2019) argues that due to strong guidelines in Europe to increase the proportion of renewable sources, there are growing requirements for the guarantee of origin for hydrogen production (Sintef, 2019). The current refuelling is based on a small transportable fuelling station (informant F, Alstom). This is a temporary solution that will be used for the trial trains in Lower Saxony.

> (...) we had a study that gave us three good lines where we have a big part of non-electrified trains and potential available hydrogen for refuelling. Where we are now is near the North Sea. Thus, we have a lot of regenerated electrical energy where we in the future could produce regenerated hydrogen by electrolysis. At the moment, it's not done like this, but it could be done in the future (Informant F, Alstom).

Further, the informant argues that from a technical point of view, the only opportunity to make the hydrogen transportable was to supply the fuelling station with liquefied hydrogen. Thus, the trial trains are currently operating on gas hydrogen. However, the station is supplied with compressed liquified hydrogen that vaporizes into gas. This allows the trial trains to refuel on the small transportable fuelling station. For the further operation of the complete fleet, there will be used hydrogen produced by specific electrolysis as well as hydrogen produced partly from by-product electrolysis (Informant F, Alstom).

In addition to local conditions in terms of geographical factors and energy availability, the informants argue that the iLint project were located in Lower Saxony due to governmental support. Alstom have obtained a close relationship with the local government and the public transport authority of Lower Saxony, which have functioned as a cooperation partner in the development of the prototypes. NOW (2016) stress the importance of public participation in the form of a transparent and discursive introduction process with an exemplifying campaign. This affects the public understanding of the technology, which may result in support for the concept.

> The government of Lower Saxony and the public transport authority of Lower Saxony, which are responsible for the regional train operation in this area, are our partners and strong supporters of us. Thus, it was clear that the trial of these trains were to be placed in Lower Saxony.(...) Finally, the railway operator is partly owned by the state. Thus, it was easier to apply this trial operation with a local state-owned railway operator compared to full private railway operator or a railway operator which is owned by a big company of another country.(...) Now we have an operator that is a local one and which is partly owned by the State of Lower Saxony (Informant F, Alstom).

Informant D puts it this way;

> They have been lucky to use existing expertise within the railway sector through Alstom. In addition, they have decided at an early stage to create a new important project for hydrogen technology in Germany. (...) It seems like they have succeeded to communicate across public authorities, and have engaged the (equivalent to the Norwegian Jernbane Direktoratet) railway directorate who has been positive towards

> regulations, frameworks, financial support etc. In addition, the project is well fitted into the Energiewende (Informant D, Norsk Hydrogenforum).

Informant A (Agora Energiewende) agrees with the abovementioned informants and argues that overall, the location of the iLint project were based on industrial politics whereas the sustainability experimentation can create value to the area of Lower Saxony. This will be further discussed in the next section.

5.1.2 Experiment initiative

There are challenges related to sustainable reconfigurations within socio-technical systems in terms of initiative and governance. Literature on sustainable governance focuses on coordination among activities across the actors while obtaining the sustainable objective, and questions if steering of sustainable development is possible, and whether it should happen at all (Newig et al., 2008). Sustainability experimentation is mentioned as one of the most prominent policy tools for governing transitions (Kivimaa et al., 2017). As previously mentioned, there are several of literature discussing who should be responsible for socio-technical transitions and how transitions should be steered (Bulkeley, Castán Broto, & Edwards, 2015). The iLint project started out as an initiative from Alstom. According to the conducted interviews, I found that the project was pushed by two strategic factors; keeping market position and answering to climate goals. Thus, this section will be presented in two parts.

Due to growing competition coming from both eastern Europe and Asia, Alstom had to act in order to strengthen their market position. Informant F argues that this was one of the initial goals at the early phase of the project.

> Alstom have been, and still are, the market leader for diesel vehicles in Germany. Currently, we have the market share of 70% percent or more. Some years we had a market share of nearly 100%. Nevertheless, we have seen a strong competition coming from eastern Europe. In addition, we had the idea that there was coming some strong competition from far east, from China, Japan Korea and so on. Thus, we had to think about how we could strengthen our market position (Informant F, Alstom).

Further, informant F elaborates that Alstom lost a big contract in 2012 with Deutsche Bahn, the biggest railway company in Germany. The contract was given to a company in Poland. Alstom first tried to strengthen their position by adjusting the cost structure. However, the trains were manufactured in Poland and the cost were thus much lower than what Alstom would be able to develop. Due to difficulties competing on a cost level, Alstom decided to challenge the technology.

> Thus, we did several studies to check what could be possible and what could be required by our customers. The studies showed us that we had to provide new technology on energy supply system, especially towards green technology. At the same time, we found out that there was available public funding for green technology for example for fuel cells (informant F, Alstom).

Alstom's goal was to develop a train with hydrogen technology that would be able to operate in the same service as a diesel train. Moreover, the purpose for the trial operation was to gain experience (informant B, Alstom). In addition to strengthen their market position, both Alstom informants argue that the iLint project was affected by the 2015 Paris Agreement. As previously mentioned, the Paris Agreement aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise well below 2 degrees Celsius above pre-industrial levels.

> In the UN Climate Change Conference 2015 in Paris (COP21) clear targets were set to reduce CO2 emission. Despite a lot of electrification was done in the past a considerable part of the railway network is not electrified, there is the need for alternative propulsion technology. Thus, Alstom decided to develop a technology that contributes to the goal (Informant B, Alstom).

Alstom expected a significant change of requests of alternative solutions to non-electrified lines in the future, and thus explored green technology. According to informant F (Alstom), from about 2020 to 2025, there will be a significant rise of request for alternative solutions for non-electrified lines. However, the development of such technology may take about five to ten years. Alstom started the project in 2012. That way they would be able to answer the expected demand for hydrogen fuel cell technology (informant F, Alstom). Hence, the project was not a direct consequence of the Paris Agreement. Rather, climate objectives such as the

Paris agreement may have functioned as a triggering effects pushing the sustainability experimentation. This will be further discussed in the discussion section (6.1.2 Experiment initiative).

Even though the initial idea came from Alstom, the project was also supported by the German Ministry of Economy and Mobility. Additionally, the development of the train was funded by the German government as a part of the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP) (Alstom, 2018.). That means that local authorities signal to obtain an emission-free public rail. Informant A argues that such transition is based on industrial politics. *"It is interesting for politicians to push something that will lead to more stable jobs in the area and will add value to the area. That is a major aspect"* (Informant A, Agora Energiewende). Thus, the hydrogen fuel cell train experiment in Lower Saxony can be considered a top-down initiative as it derives from the local authorities. However, this will be further discussed in later sections (section 6.0).

5.1.3 Knowledge accumulation for hydrogen fuel cell technology promotion

The Coradia iLint was presented by Alstom for the first time in Berlin in 2016, and was the first approved passenger train using hydrogen fuel cell for traction power (Alstom, 2018). According to the conducted interviews, various climate goals are perceived as triggering effect in relation to the hydrogen fuel cell experimentation as well as pushing an energy transition within the mobility sector in general. Informant A (Agora Energiewende) argues that due to climate change, an energy transition needs to happen as quickly as possible.

> We see that climate protection really means that we need to go from oil and gas to renewable energies, and the only existing renewable energy that can be scaled up quickly and worldwide is green electricity. Most of this comes from sun and wind power. Climate change is really threatening. Thus, this energy transition needs to happen as quickly as possible. Consequently, electricity from renewable energies will be for the next decade, not necessarily because there is limited space available in general (Informant A, Agora Energiewende).

S*ustainability experimentation* is of the most highlighted tools to help bring a system from an unsustainable state to a more sustainable state, and often takes the form of demonstration projects such as the iLint project in Germany (Bulkeley et al., 2015). The iLint project is, according to the conducted interviews, well suited for technological development and demonstrates the opportunities for hydrogen to the general public. The operation of hydrogen fuel cell trains is still at a prototype-level. The existing systems have been built in a small number with high cost and low standardisation. The smaller systems have matured more than the bigger systems used for trains, as there are only a few experiments with this technology for train application (Sintef, 2019). However, Thorne et al. (2019) argue that the fuel cell technology for rail application may have the potential to be technologically mature between 2020 and 2025. Informant G (Hydrogenics) argues that the iLint projects demonstrated that fuel cell technology can properly function in passenger-rail applications.

> In the last year since the two Alstom trains have seen to be successful and reliable, a significant number of very large companies in conventional technologies like engines and trucks have stepped in with investments and acquisitions to gain footholds to fuel cell vehicles or similar products in a very big way (Informant G, Hydrogenics).

Alstom is currently finding themselves in a “push-market”. In a push-market, the *“invention is the mother of necessity”* (Garud, Tuertscher & Van de Ven, 2013, p. 779). With the iLints, Alstom aims to create a market demand for hydrogen technology for rail application. As a result, they are expecting to enter a “pull-market” in the future. A pull-market is consistent with the commonly used adage *“necessity is the mother of invention”* (Garud et al., 2013, p.779). Alstom expects an increase of hydrogen demand throughout the upcoming years, affecting the market dynamics.

> Currently, it’s more Alstom saying we have the technology, and we are going to our potential customers asking whether they want to change their request. Thus, we are currently in a sort of “push-market”. However, we see that throughout these years it will change form push to pull (informant F, Alstom).

According to the conducted interviews, various climate goals functioned as contributing factors for pushing the iLint project. Additionally, various climate goals push an energy transition within the mobility sector in general. Sustainability experimentation such as the iLint project is well suited for technological development and demonstrate the opportunities for hydrogen to the general public.

5.1.4 Overview of findings for RQ1

The following table presents an overview of the findings related to RQ1.

Table 3: Overview of the findings related to the first research question.

Findings	Summary
Context	Findings emphasize local conditions in terms of geographical factors, energy availability and governmental support as prominent factors related to the context of hydrogen fuel cell experimentation for rail application.
Experiment initiative	The iLint project started out as an initiative from Alstom, and was pushed by two strategic factors; keeping market position and answering to climate goals. The project was supported by the German Ministry of Economy and Mobility. Additionally, the development of the train was funded by the German government as a part of the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP).
Knowledge accumulation for hydrogen fuel cell technology promotion	The iLint project is well suited for technological development and demonstrates the opportunities for hydrogen to the general public. The overall finings state that the trials provide knowledge accumulation, and can thus lead to further implementation.

5.2 Barriers associated with the hydrogen fuel cell powered train experiment

In addition to the conducted interviews, I have analysed an ongoing discussion concerning alternative solutions for non-electrified lines. In September 2019, Sintef published an analysis presenting and discussing hydrogen and battery technology for rail application. Sintefs (2019) analysis has been further discussed; first by the Norwegian Railway Directorate (2019) and then by Norsk Hydrogenforum (NHF) (2020). The Norwegian Railway Directorate’s take on the Sintef report was highly criticised by NHF, providing me with fruitful discussions concerning hydrogen technology barriers. The discussion concerns hydrogen technology barriers in general terms, and appear more frequently in sections concerning hydrogen infrastructure and safety. I will further discuss certain arguments in the next section (section 6.0).

The aforementioned discussion was a central topic in all interviews, and has provided me with empirical findings related to the second research question; *which institutional barriers and enabling factors are associated with the hydrogen fuel cell technology train experiment in Germany?* This section is separated into two parts. First, in section 5.2, I will present the findings concerning the institutional barriers associated with the hydrogen fuel cell experiment in Lower Saxony. Second, in section 5.3, I will present the findings related to the institutional enabling factors of hydrogen technology within rail application. The informants were asked what they perceived as the most dominating barriers related to the hydrogen technology experiment in Germany as well as what barriers they expect that a transition towards hydrogen technology within rail application may meet in the future. Thus, this section will be presented with two focus areas; barriers associated with the recent iLint project and future barriers associated with hydrogen fuel cell technology for rail application.

5.2.1 Infrastructure

New technology often demands new infrastructure. The hydrogen production, the transport of hydrogen to the refuelling facility and the refuelling facility itself all count among the components of a comprehensive hydrogen and refuelling infrastructure (NOW, 2016). Several of the informants highlighted infrastructure as one of the main barriers associated with the introduction of hydrogen fuel cell technology. The associated barriers are non-technical. Rather, there are challenges related to societal surroundings. During the analysis of the transcribed material, I noted in particular two repetitive discussions related to barriers associated with the infrastructure; infrastructure built up and hydrogen fuelling system.

Infrastructure built up

In addition to the infrastructure itself, infrastructure built up was argued to be a significant barrier to overcome when introducing a complete fleet. The development of the hydrogen infrastructure depends on country-specific conditions such as available feedstock (like renewable energies), geographic factors, population density and policy support, and must thus be assessed on a country-by-country basis. However, when addressing this topic I will highlight the repetitive arguments from the conducted interviews. Informant D (NHF) argues that the infrastructure built can be considered a barrier due to system change. Hydrogen technology involves a different technological regime. Thus, there is a need to introduce and redesign the part of the energy system, reshaping energy to gas, and creating a fitting distribution concept (informant D, NHF).

To ensure further implementation of hydrogen technology in a rail application as well as increasing competitiveness within the mobility sector, there is a need of technical standards. For the German mobility sector, the Federal Ministry of Transport (2018) stress the need of *"functioning, stable and efficient stipulations and processes for the production and approval of new and converted railway vehicles, from tendering through to commissioning"* (The Federal Ministry of Transport, 2018). Informant F (Alstom) argues that there are bureaucratic barriers when introducing a hydrogen infrastructure as it suffers from lack of standard procedures related to infrastructure built up. Building a hydrogen infrastructure faces a greater barrier than building a diesel fuelling station as it is not a "day-to-day" business, and thus lack of technical standards (informant F, Alstom).

> There is no easy way to build up hydrogen fuelling stations, production sites and hydrogen transport etc. We have all the regulations. However, it is more difficult to build up a hydrogen fuelling station than a fossil fuel fuelling station. The reason for this is that we build up a fossil fuel station, more or less, every day. Thus, it's a day to day business (Informant F, Alstom).

There are already standard procedures and a clear legal situation when developing a diesel fuelling station. Thus, the diesel infrastructure built seem to obtain a more familiar nature. In addition to the lack of standard procedures in relation to hydrogen infrastructure built up, my findings state that there are apparent barriers related to the technology's conformity to the current system.

Hydrogen fuelling system

Hydrogen can be stored and transported as compressed gas or as liquid. The iLint operate on compressed hydrogen, distributed as liquid and vaporised into gas at the fuelling station. As with battery and electrical-powered trains, the hydrogen fuel cell powered train operates on an electrical powerline. However, the hydrogen fuel cell powered train differs from the other options as the energy is carried by hydrogen (Sintef, 2019). The iLint is equipped with a battery pack to provide power. Hence, the trains are currently operating as battery-electric trains. The inserted battery has limited capacity and thus needs charging on the way (Thorne et al., 2019). Hence, the operation of a hydrogen fuel cell powered train requires a functional fuelling system appropriate for hydrogen application. Informant F (Hydrogenics) criticises the current hydrogen fuelling system, and argues that the hydrogen fuelling technology is nearly identical to the CNG (compressed natural gas) technology, only based on different materials. In addition, the hydrogen fuelling system suffers from lack of efficiency due to its technology being limited to road mobility.

> Currently, governments are building many fuelling stations across Europe. Unfortunately, they are mostly for cars and not heavy mobility fleets. In addition, almost all of them are delivered hydrogen coming from natural gas. What needs to happen, is that it needs to be more of hydrogen delivery chain coming from renewable hydrogen (informant G, Hydrogenics).

Moreover, informant G (Hydrogenics) suggest developing larger fleets applicable for both public mobility fleets (rail and bus) as well as personal vehicles. This matches NOW’s (2016) argument saying that a growing demand for hydrogen technology may lead to fuelling plans being optimised. Thus, based on the conducted interviews, it seems like there is a common belief that a growing demand for hydrogen technology may increase the fuelling system efficiency. In addition, informant H (NOW) argues that the current hydrogen infrastructure in Lower Saxony seems to be well-functioning.

> The regions that have decided on hydrogen trains have tracks that are very long and has thus the built-up infrastructure needed for the iLints. There are currently several of these ongoing projects in Germany, and they are usually going very well (informant H, NOW).

The presented barriers associated with hydrogen infrastructure are non-technical. Rather, the presented barriers are more of a regulative nature, and focus on the lack of bureaucratic regulations and standards. On the other hand, barriers associated with hydrogen fuelling, seem to be a result of its prototype level. This will be further discussed in the next section (6.0).

5.2.3 Safety

When asked about barriers associated with the safety of hydrogen fuel cell powered trains, I mentioned the ongoing discussion in Norway concerning alternative solutions for non-electrified lines and questioned their take on the topic of safety. At the current state, there is high market pressure finding alternatives to diesel trains among transport manufacturers. In this context, the technology contributes to maintaining the level of safety in the railways. This is a prerequisite for all choice of technology in this sector (Jernbane Direktoratet, 2019). My empirical findings highlight issues concerning hydrogen safety both under operation and in relation to hydrogen storage.

The Norwegian Railway Directorate presents hydrogen fuel cells technology with high security risks in "ordinary" operation, especially related to longer tunnels (Jernbane Direktoratet, 2019). However, NHF (2020) criticises the report and argues that all management of energy carriers pose a risk during operation, including battery technology. Despite a certain amount of risk, the iLint has been approved for commercial service and is allowed to operate in tunnels that are up to 5000 meters long. Informant F (Alstom) state that *"there is no limitation of operating hydrogen trains in tunnels. This is fully assessed, and we have this report by our independent assessor".* Further, the informants argue that a gasoline or diesel leak may be more dangerous compared to hydrogen. During a diesel or gasoline leak, the time-window of danger is long-lasting. In addition, diesel and gasoline is highly inflammable.

> If gasoline or diesel spills in an accident and/or on the road and you get it on your clothing or on your skin, it is just waiting for a flame and then it burns and burns. Natural gas is heavier than air. Thus, if it's a leak, it just waits for a spark to catch the fire. (...) If there is a leak of hydrogen, and it's not in an enclosed space, the hydrogen goes simply upwards and into the atmosphere and gone due to its low-density. The window of opportunity of that being ignited is tiny. There is the pressure energy as the tanks are usually containing compressed gas. You have that in other fuels as well (informant G, Hydrogenics).

The hydrogen tanks are especially designed and tested. If the case of a rupture or leak, the gas will be released without sending pieces of the tanks in all directions. There are safety relief valves and excess flow valves that will either shut off the gas and/or relieve it to the safety vent. Thus, the pressure is relieved safely (informant G, Hydrogenics). However, the Norwegian Railway Directorate (2019) highlights that a case of hydrogen leak enables a risk of fire and explosion. As a result, the location of a filling facility should include safety zones, and will thus have to be placed somewhat remote in relation to buildings and other activity (Jernbane Direktoratet, 2019).

Related to the barriers associated with the infrastructure, hydrogen requires large storage spaces. Although space can technically be reduced by compression, this can convey safety issues (Thorne et al.,2019). The report by the Norwegian Railway Directorate (2019) argues that storage of a larger amount of hydrogen represents a collection of a large amount of energy, which has the potential to be released and converted in the form of fire or explosion. My informants disagree with the report, and argue that regardless of energy carrier, risk assessments and measures must be carried out when storing a high amount of energy.

> There are differences between hydrogen and battery safety assessments. You have to do different safety measures. If you store energy, in any way, when there is a high amount of energy, you must analyse the risk and that specific measure to cope with those risks. Today, we are used to go for fossil fuels. Thus, nobody is afraid to drive on the motorway alongside with a big tank of fossil fuels. Even this is a severe safety issue (informant F, Alstom).

Sintef (2019) argues that the experimentation in Lower Saxony demonstrates that there is no need for an explicit new regulation for hydrogen fuel cell powered trains as hydrogen supply does not conflict with the existing European regulation. A Common Safety Method for Risk Assessment of the iLint was carried out by TÜV SÜD, and includes risk factors of new technology. The assessment states that there is a particular risk related to the source of operation (hydrogen), and highlights collision and tunnel safety. These risks differ from the assessment of “regular” electrical motor vehicle. However, Sintef (2019) states that these risks were not found significant.

Furthermore, several of the informants argue that the real issue is not the safety of the technology itself, but how its viewed by the public. These discussions obtained a more social nature, and embraced the society’s perception and understanding of hydrogen as an energy carrier, highlighting the lack of knowledge among the general public. In addition, several of the informants argue that the public's perception of hydrogen technology has been affected by the Hindenburg disaster. On May 6 in 1937, the German passenger zeppelin Hindenburg, held aloft by seven million cubic feet of hydrogen gas 300 feet in the air and, bursting into flames while preparing to dock at the Naval Air Station in Lakehurst, NJ (DiLisi, 2017). As a result of the accident, the general public holds a sceptical attitude towards hydrogen technology.

> People think of the Hindenburg. However, it was not the hydrogen burning which was visible, but the magnesium frame and the paint coating of the Zeppelin. There are already thousands of hydrogen cars and hundreds of hydrogen buses, and now starting trucks and trains. There have been nearly zero accidents and deaths (informant G, Hydrogenics).

Informant C (Innovation Norway) put it this way;

> We are so used to gasoline and diesel and remember hydrogen from chemistry lectures at school and know it to be explosive. We need to overcome this thought and make the public aware of the risk and that is can be managed. Thus, this "danger" is not "real". In addition, gasoline and diesel is also explosive. It is important to show the public what the technology can manage. I think that this will affect people's view of hydrogen (informant C, Innovation Norway).

To sum up, I noticed a two-folded discussion among the informants when asked about barriers associated with the safety of hydrogen fuel cell powered trains. However, I see a connection between the two discussions. There is a continuous comparison of hydrogen to other solutions in terms of safety, and several of the informants argue that safety barriers are new rather than more challenging. Some barriers are thus considered as effects of the lack of knowledge among the general public. As a result, discussions were directed towards the general public's perception and understanding of hydrogen as an energy carrier. Enabling factors related to safety barriers will be further discussed in the following section.

5.2.4 Single supplier

As the first company introducing hydrogen technology for rail application in the EU mobility sector, Alstom can be considered a pioneer in the field of green technology. However, Alstom being in a “monopoly position” in an EU-regulated mobility sector can also challenge market share and competition. European public transport policy aims to provide safe, efficient and high-quality passenger transport service in EU through regulated competition (EU, 2011). At the current state, Alstom is the only manufacturer of hydrogen fuel cell technology for rail application in commercial service. In addition, Alstom is currently offering both hydrogen and battery solutions, providing them with a central role on the emission-free mobility market. Sustainability experimentation such as the iLint project in Lower Saxony may affect the competitiveness of the railway. According to the Norwegian Railway Directorate (2019), the manufacturers that has not invested in zero-emission technology experience high market pressure finding alternatives to diesel trains. Compared to other transport companies, Alstom is at the current state ideally positioned, being able to offer a range of green technology solutions to the mobility sector.

Despite Alstom being in a current ideal position, several of the informants, including Alstom, argue that increased competition is key when introducing new technology. Alstom being a single supplier (in Europe), is thus considered a barrier for further hydrogen technology within the mobility sector. According to the conducted interviews, as there is only one company offering hydrogen fuel cell powered trains, the product is not considered trustworthy enough. In addition, the majority of the mobility sector is still in demand for diesel vehicles (informant G, Alstom). Thus, the informants stress the importance of trust and acceptance of hydrogen technology among potential customers in order to introduce a full fleet of hydrogen fuel cell powered trains. Informant G (Hydrogenics) argues that increased competition is crucial.

> Competition is of critical importance. Not only will the customers get better service, but they will feel more comfortable. If there is only one supplier, it is too risky for them to change to a completely new technology (informant G, Hydrogenics).

Informant F (Alstom) puts it this way;

> People see that they only can buy hydrogen trains from Alstom, and do not want to commit to the dependency of only being able to buy from one supplier. Thus, one of

> our targets is to have more offers on the hydrogen market. Even if is a competition. They need to see that this is not just a strange idea from Alstom, but that everyone else will also follow this idea (informant F, Alstom).

Zooming out, several of the informants addressed the issue of competition at another level. Alongside hydrogen as niche option within rail application, my findings state that there is an increase of sustainable offers within rail mobility. I noticed in particular a repetitive discussion concerning hydrogen fuel cell and battery technology. The focus of the discussions was two-folded; hydrogen and battery technology as a commercial competition and/or as complementary unit answering to different needs. Alstom (2020), offering both options, states that battery solutions are more suitable in case of short and medium length of non-electrified sections, while hydrogen solutions are best to use when range is key.

> There should not be a discussion concerning hydrogen vs battery. Both hydrogen and battery are needed, and we will have only battery solutions, combined battery and hydrogen solutions and only hydrogen solutions. We need both solutions. We need to see hydrogen and battery together against the fossil fuels (informant F, Alstom).

At the current state, companies such as Stadler, Bombardier or Siemens are offering a battery solution (informant F, Alstom). In relation to the discussion concerning hydrogen and battery technology competition, informant H (NOW) agrees with the abovementioned and states that the “real” aim is and should be zero-emission. Zooming back to hydrogen technology in particular, Alstom being in a “monopoly position” in an EU-regulated mobility sector is argued among the informants to be a challenge concerning market share and competition. However, according to Thorne et al. (2019), there are several of hydrogen fuel cell projects for rail applications in Europe. The projects are currently at a prototype level, and have not yet entered passenger service. This will be further discussed in the next section.

5.2.4 Overview of findings for RQ2

The following table presents an overview of the findings related to RQ2.

Table 4: Overview of the institutional barriers associated with the hydrogen technology experiment in Lower Saxony, Germany.

Barrier	Summary
Infrastructure built up	A hydrogen infrastructure built up disrupts the existing infrastructure. There is a need to introduce and redesign the part of the energy system, reshaping energy to gas, and creating a fitting distribution concept.
Hydrogen fuelling system	The trials are currently operating on a temporary refuelling solution. This solution is not a solution appropriate for a full fleet. In addition, the hydrogen fuelling system suffers from a current small demand.
Safety	Safety seem to be a central topic when hydrogen is being considered in other countries and contexts. Some reports focus on safety related to tunnels. However, there has been carried out risk assessments that clarify the risks. Questions concerning safety related to hydrogen fuel cell technology raise focus on how previous accidents have influences how people view hydrogen in general.
Single supplier	Alstom being in a “monopoly position” in an EU-regulated mobility sector can challenge market share and competition. Competition is stated to be key when introducing new technology. In addition, it appears to be a two-folded discussion concerning hydrogen and battery technology; hydrogen and battery technology as a commercial competition and/or as complementary unit answering to different needs

5.3 Enabling factors

Throughout the conducted interviews I noticed certain beneficial conditions to the implementation of hydrogen fuel cell technology in a rail application. Thus, I will in the following section present the findings related to the institutional enabling factors of hydrogen technology within rail application. During the analysis of the transcribed material, I noted in particular five repetitive enabling factors; social acceptance, funding, market competition, political incentives and sector coupling.

5.3.1 Social acceptance

As a socio-technical system, the societal functions of the mobility sector consist of technology, regulations, user practices and markets, cultural meaning, infrastructure, maintenance networks and supply networks and more (Geels et al., 2004). The societal functions of the public society and its interest were one of the main topics in the interviews. The informants identify the public as a central actor in iLint project and for further projects related to hydrogen fuel cell technology. All informants, across organisations and level of expertise appeared to be positive and welcoming towards hydrogen fuel cell technology in a rail application. In addition, several of the informants stated that they have experienced exclusively positive feedbacks from iLint passengers. Several of the informants have even travelled with the prototype themselves. The informant from NOW put it this way;

> (...) the iLint project has shown that this technology works and that it has been working for over a year. Nothing happened and people seem happy with it. In addition, I believe that the iLint project in Germany helped raise awareness of this technology. Also, when you first talk to people, you see that a lot of them are actually quite interested in hydrogen technology (informant H, NOW).

NOW (2016) stresses the importance of ensuring stability and acceptance for the sake of all involved in order to positively influence the introduction of innovative technology. This includes the general public. Further, informant E (Innovation Norway) highlights knowledge acceleration, and argues that due to increasing global knowledge production, we struggle to keep track with new technology.

> The level of knowledge production has accelerated enormously. It has never had such high pace, but will neither never go slower. It will never be as slow as it is today. The challenge is to keep track and make decisions concerning technology that are important to maintain a functional society (informant E, Innovation Norway).

By keeping ourselves updated on new technology, we gain an understanding of the interactions between the choice of technology, infrastructure and solutions related to mobility (informant E, Innovation Norway). That way, we can be more prepared for future transitions.

5.3.2 Political incentives

The automotive industry, the fossil fuel industry, the combustion industry and the manufacturing industry are seen as huge job-drivers in Germany. Germany obtains a huge industrial railway-sector that produces tracks, trains and other railway-related products (informant D, NHF). Due to the major railway industry in Germany, the informants consider it as an important political task to secure innovation within a railway sector. At the current state, Germany is hesitant to make any dramatic decisions due to lobbying of the engine manufacturers, or motor companies (informant G, Hydrogenics). Several of the informants argue that for this reason, Germany is moving at a slow pace.

> For this reason, I do understand why Germany is focused on hydrogen fuel cell trains. They gain both a local market and experience that makes them able to sell this kind of technology worldwide (informant D, NHF).

Related to the abovementioned statements, all informants highlight the importance of political incentives in order to push the early adoption of hydrogen technology within the mobility sector. My findings suggest that in terms of subsidies such as taxes and grid-fees, action must be taken in order to be able to push the adoption of hydrogen vehicles.

> The taxes and grid-fees on renewable energy should be cut. A way to get around it, without changing the taxes or grid-fees, is simply for renewable energy to go off-grid. We have some customers that are doing that and are not connected to the grid. The other way is to increase taxes on dirty technologies and increase the emission limitations. (...) Maybe the next step should further decrease the allowable CO2 and amount of emissions (Informant G, Hydrogenics).

Moreover, the informants stress the importance of public funding, and argue that governmental authorities need financial help such as federal funds or European funds to be able to support sustainability experimentation. Informant G (Hydrogenics) argues that transport and logistics companies are under financial pressure. Governments suffer from limited budgets, and are often forced by legislation to buy the lowest cost bid. Thus, increased funding is a matter of governmental policy (informant G, Hydrogenics).

As previously mentioned, the iLint project in Lower Saxony was supported by the German Ministry of Economy and Mobility. The development of the train was funded by the German government as a part of the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP) (Alstom, 2018). The NIP funding for the iLints in Lower Saxony covered 25 percent of the budget. The remaining cost were covered by the internal Alstom R&D budget (informant F, Alstom). The aim of the NIP was to develop and establish competitive mobility using fuel cells and hydrogen on the market for the next ten years (The Federal Ministry of Transport, 2016). For example, in the phase of 2006 to 2016, the NIP funded 1,4 billion euros supporting the development of hydrogen and fuel cell technology products until reached commercial maturity. The funding was divided between the Federal Government and industry stakeholders. In the next phase (from 2016), the NIP has (and will) support the introduction of technologically mature products in competition with one another. The funding is further provided in two pillars. One pillar will support research, development and innovation. The other one for support of direct market activation, by providing capital grants, such as for fuel cell powered trains or electrolysis systems for the generation of green hydrogen (The Federal Ministry of Transport, 2016). Furthermore, according to informant H (NOW), NOW is currently increasing their support of zero-emission technology.

> We have new funding programmes, especially for zero-emission trains. We are currently working on the funding guidelines in order to make the first official call for people to send applications for funding. However, it will be a dedicated funding programme for zero-emission trains and zero-emission infrastructure. In addition, we have recently made a study on the market potential for hydrogen trains (informant H, NOW).

The informants argue that due to the social acceptance of the iLints in Lower Saxony, increased funding is expected, which may grant Alstom and other transport companies to expand the public transport service as well. In addition, it facilitates experimentation with hydrogen technology, and allows companies like Alstom to accompany their customers in phasing out diesel.

5.3.3 Sector coupling

At the current state, there is an ongoing energy transition towards renewable energy in Germany. As a result, there is an expected increase of demand and consumption of renewable sources. The main sources of renewable energy in Germany are wind and solar. However, due to the weather-dependent nature of the underlying technologies, electricity storage is a major concern. The new energy world can be characterised by its need for flexibility. Hence, strategies such as sector coupling can be beneficial (Agora Energiewende, 2018). Sector coupling was barely mentioned in two of the conducted interviews. However, the idea was mentioned in several of central reports discussing the German mobility sector. I will not go into details of the German energy system, as I considered it be beyond the scope of this thesis. However, I will present the relevant findings discussing sector coupling as an institutional factor and innovative factor associated with hydrogen fuel cell technology. Note that there exist various approaches to realise sector coupling (Robinius et al., 2017). However, I will focus on mobility and energy sectors.

The term “sector coupling” refers to the idea of interconnection across energy-consuming sectors, and can allow for broader usage of gathered power (Robinius et al., 2017). In Germany, the main sources of renewable energy are wind and solar. However, its availability is limited. Thus, electricity storage is a major issue. Clean Energy Wire (2018) explains the concept for the general public’s understanding.

> The interconnection of sectors could help here: part of the power could be used to heat large amounts of water (power-to-heat) for heating houses, thus indirectly electrifying the heating sector. At peak power production times, electricity could be used to produce hydrogen or synthetic gas (power-to-gas). The gas that stores the energy can either be used to fuel vehicles or it could be turned back into electricity or heat in times of little sun and wind (Clean Energy Wire, 2018).

Sector coupling can be considered a tool to ““electrify’” the German economy based on renewable sources, and can be implemented differently. Both Alstom (2020) and NOW (2016) argue that sector coupling may be a key enabling factor for introducing hydrogen technology in a rail application. Technologies such as batteries and hydrogen could be a part of an interconnection with the power system (Clean Energy Wire, 2018). To increase the investment efficiency related to the fuelling infrastructure, Alstom (2020) suggests that it can be shared with other form of transport using hydrogen. Hydrogen and fuel cell technology is a modular technology. This allows fuel cells and hydrogen storage systems created for cars, buses and trucks to function for rail as well. The coupling may include railway, buses, trucks and cars. Such synergies with the transport sector can be exploited through the use of a common refuelling infrastructure with public transport fuel cell buses. NOW (2016) suggests that hydrogen technology can benefit from sector coupling due to several reasons. First, electrolysis can be considered a flexible load, allowing efficient transportation. Efficient transport increases hydrogen availability among sectors, and can thus provide lower costs and high efficiency (Sintef, 2019). Additionally, sector coupling can allow for shared hydrogen storage. Increased and efficient hydrogen storage can act in favour of renewable energy facility operators due to optimised revenue from both market and operation (NOW, 2016).

5.3.4 Overview of enabling factors

The following table presents an overview of the findings related to RQ2.

Table 5: Overview of the institutional enabling factors associated with the hydrogen technology experiment in Lower Saxony, Germany.

Enabling Factors	Summary
Social acceptance	Social acceptance appears as an important part of the socio-technical mobility system, and despite the aforementioned barriers, the iLint trials seem to have been accepted by the public.
Political incentives	The iLint project in Lower Saxony was supported by the German Ministry of Economy and Mobility. The development of the train was funded by the German government as a part of the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP). In terms of incentives related to the introduction of hydrogen technology, my findings suggest implementing subsides such as taxes and grid-fees.
Sector coupling	Sector coupling refers to the idea of interconnection across energy consuming. Sector coupling can be considered a tool to “electrify” the German economy based on renewable sources, and can be implemented differently. Hydrogen technology for rail application can benefit from sector coupling in various ways. My findings highlight hydrogen increased availability, lower cost and higher efficiency.

6.0 Discussion

Based on relevant literature and the analytical framework, I will in the following section discuss the empirical findings. The discussion has been sorted into six parts. In section 6.1 I will present the findings related to the first research question; *"What is the background for the hydrogen fuel cell experimentation in Lower Saxony in Germany, and how can the perceived effects influence further implementation?*". These findings will be discussed in the light of analytical elements from sustainability experimentation, urban experimentation and strategic niche management. In the second section, 6.2, I will elucidate the second research question; *which institutional barriers and enabling factors are associated with the zero-emission train experiments in Germany?* This section will be discussed in two parts; institutional barriers in section 6.3 and institutional enabling factors in section 6.4. The discussion concerning the institutional barriers will be based on Geels' (2004) institutional theory. Moreover, for the discussion concerning enabling factors, I will discuss how the enabling factors can affect further implementation of hydrogen fuel cell powered trains.

In section 6.6, I will discuss the empirical findings and discussions as a part of today's socio-technical mobility system. Based on the analysis, I have highlighted three institutional innovative activities for future hydrogen fuel cell powered train implementation. The three factors will be presented in section 6.7 as a result of the barriers evident in the thesis, as well as the enabling factors. Further, based on the transition studies literature, I will discuss how hydrogen-technology can fit into a mobility transition. In this section, the discussion will in particular draw on literature from the multi-level perspective and transitions pathways. In section 6.7 I will present and discuss the limitation of the thesis. Last, in section 6.8 I will present suggestions for further research related thesis.

6.1 Background and perceived effects

RQ1: What is the background for the hydrogen fuel cell experimentation in Lower Saxony in Germany, and how can the perceived effects influence further implementation?

The research question will be discussed by the use of elements from sustainability experiments, urban experimentation and strategic niche management as the analytical framework. I will discuss how hydrogen fuel cell technology became a priority in Lower Saxony, who initiated the experiment and what the perceived effects of them are.

6.1.1 Context

Investigating context dependencies has provided me with an increased understanding of the exogenous environment related to the hydrogen fuel cell experimentation (Van Bree et al., 2010). The iLints have operated in commercial service in Lower Saxony in Germany since 2018. The context (or landscape) through which the experimentation occurs can provide fruitful narratives that may be of relevance for further implementation. I view the hydrogen technology experiment as a learning processes due to its unknown outcome (Hoogma et al., 2002), and argue that the experimentation can be further exploited for potential alignments of technology, user demands and sustainability issues (Schot & Geels, 2012). Note that Alstom is a multinational company, and their interests are not limited to Germany. Alstom's hydrogen fuel cell technology is adaptable to different countries and has already expanded across the German borders. Alstom signed a contact in the Netherlands in 2019, becoming the first pilot project with Coradia iLint outside Germany (Alstom, 2020). Thus, I will not discuss whether or not the iLint is adaptable to other countries. Rather, from a process-oriented perspective, I seek to create an overview of context and landscape through which the experimentation is located. As presented in the empirical findings, I noted in particular three repetitive discussions within context dependence for introducing hydrogen fuel cell technology in a rail application; local conditions in terms of geographical factors, energy availability and governmental support.

Germany can benefit from hydrogen fuel cell technology for rail as a mode of mobility of several reasons, whereas the common argument is that hydrogen technology may potentially serve long-term sustainability goals. However, the sustainability of the hydrogen fuel cell powered trains is depending on both production and distribution of the hydrogen (Sintef, 2019). Based on the conducted research, I have found that the hydrogen fuel cell technology experiment is currently operating in a protected space, protected from the mainstream selection environment. I have not been able to create a complete view of the current selection environment of the German mobility sector. However, due to Germany's ambitious climate targets, I will argue that sustainability can be considered a main selection criterion when introducing new technology within today's mobility sector. Based on the conducted research, it appears as the iLints trials fail to meet market demand in terms of sustainable achievement. The iLints are configured and optimized to fit operation and conditions under which the vehicle is to be operated and was located in the area of Lower Saxony due to its major non-electrified line that was previously diesel operative (informant F, Alstom). The trials are currently operating with a temporarily refuelling solution and not a solution appropriate for a full fleet. The project is located nearby the North Sea and can benefit from available regenerated electrical energy that can produce regenerated hydrogen by electrolysis in the future. However, due to the trials being at a prototype-level, this is not the current practice (Informant F, Alstom). The trials are currently operating on gas hydrogen, not representing a sustainable option. The hydrogen is produced as a by-product of the industrial processes (chlor-alkali electrolysis). However, the H2 must usually be purified (NOW, 2016). As a result, the prototypes fail to meet market demand in terms of sustainable achievement. My findings suggest that even though the hydrogen fuel cell technology can be considered immature and at a prototype-level, the location of the trial was identified and planned to be the subsequent deployment of a full fleet. A full fleet will, according to the Alstom informants, operate on electrolysis in combination with hydrogen partly produced from by-product electrolysis. Hence, the iLints have the potential to meet sustainability criteria in the future in the case of further implementation.

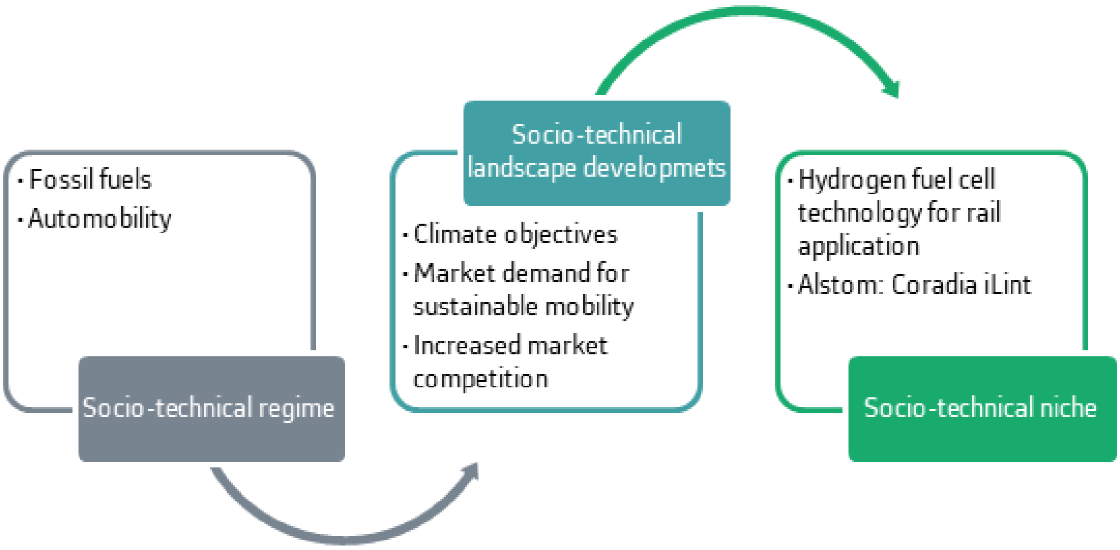
The dilemma of protection measures is finding the right balance between the need to nurture the innovation and the need to prepare it for the selection pressures of a market environment (Ceschin, 2014). As discussed in this section, the iLint trials are currently at the prototype-level and are protected from the mainstream selection environment. Even though a future full-scale implementation may be able to operate in the area of Lower Saxony, Germany may face barriers in other regions. As presented in previous sections, the German power system follows a so-called “copper plate” principle. Hydrogen production can in the future benefit from new wind power in the North. However, a further implementation to other regions may require an expanded transmission network. The problem is that the expansion projects have encountered public resistance, whereas only 850 kilometres of the planned 7,700 kilometres of new transmission lines have been built (Agora Energiewende, 2018). Consequently, a future implementation of hydrogen technology in other regions of Germany requires a system change involving several actors and areas of the mobility sector. Hence, at the current state, a further implementation of hydrogen fuel cell technology in other regions of Germany may not be prepared for selection pressure of a market environment.

I argue that the aforementioned selection pressure is connected to the last point; governmental support. As presented in the empirical findings, the experiment location was affected by governmental support. Alstom’s close relationship with the local government and the public transport authority of Lower Saxony has functioned as a top-down initiative in terms in introducing hydrogen technology within rail application in Germany. In addition to meeting set climate goals (see next section), the informants argue that due to successful communication across public authorities, the project has managed to engage German railway authorities which has acted positive in terms of regulations, frameworks, financial support and more. A discussion concerning energy efficiency and emission levels will differ between prototype-level and a full-scale implementation and should thus be subject for further research.

6.1.2 Experiment initiative

Sustainability transitions can be steered through long-term goals with strategies made by both national and international actors, and it is usually expected that various actors aim in the same direction to fulfil the set objectives (Markard et al., 2012). According to the conducted interviews, the hydrogen fuel cell experiment in Germany was pushed by two strategic factors; *keeping market position and answering to climate goals.* Even though the informants (both Alstom internal and external) state that the experiment was initiated due to and in a climate-related context, it is clear that Alstom initially obtained commercial interest. Due to increased competition from eastern Europe and Asia, Alstom acted in order to strengthen their market position by challenge the technology. My findings suggest that Alstom were initially motivated to do research and develop new technology due to landscape developments within the mobility market. Due to set climate targets, Alstom expected a change of market demand. Based on the MLP and empirical findings, I have created a figure presenting the main dynamics of change that occur within and between the regime and niche level (Whitmarsh, 2012).

Figure 2: Dynamics of change



As a lost contract in 2012 was argued to be a trigger for new technology development, I interpret the 2015 Paris Agreement as a helpful "push" in the direction of experimentation within sustainable mobility. Van Bree et al. (2010) describe this as a "window of opportunity" for a new configuration to breakthrough. Based on the conducted research, I was able to map landscape pressure from various levels within the mobility sector. I consider these factors to be prominent triggers for hydrogen technology experimentation within rail application.

The hydrogen fuel cell experiment in Lower Saxony can be considered a top-down initiative as it derives from the local authorities. From an urban perspective, local actors possess first-hand knowledge of the city's challenges and needs, gaining legitimacy and trust from a range of stakeholders (Madsen & Hansen, 2018). Thus, local authority often exceeds national (and international) governments in terms of emission reduction initiatives, as well as climate change mitigation and adaptation initiatives (Bulkeley et al., 2015). According to the conducted research, the local government and the public transport authority of Lower Saxony have functioned as a cooperation partner in the development of the prototypes. In addition, experimentation was supported by the German Ministry of Economy and Mobility, and thus funded by the German government as a part of the NIP (Alstom, 2018.). By supporting hydrogen fuel cell experimentation, the local authorities of Lower Saxony signal to obtain an emission-free public rail.

However, zooming out, the initiative can (also) be considered as bottom-up. The experiment was clearly triggered by landscape pressure from national and international climate agreements. According to the conducted interviews, one of the most prominent pressures within the mobility sector is international climate agreements such as the Paris Agreement and Sustainable Development Goals (SDG). The notion of these agreements requires EU members to develop national long-term strategies in order to achieve the greenhouse gas emissions reductions necessary to meet their commitments under the Paris Agreement as well as EU objectives (EU, 2018). Based on the aforementioned climate agreements, IEEP (2019) suggests all countries to decarbonise their energy system and thus act independently in accordance to the set climate goals. Germany's "Energiewende" aims to transform the entire power sector, going from nuclear and coal to renewables within the next four decades. Adapting Germany's policy plans for a pioneering energy transition, the mobility and fuels strategies (MFS) created by the Federal Ministry of Transport function as a "learning strategy", identifying ways in which the Energiewende can be implemented for transport (Federal Ministry of Transport, 2018). In order to meet climate targets, the Federal Ministry of Transport developed cross-industry collaboration between industry and government, characterised by the NIP (among others). Supporting innovation and research in the field of hydrogen technology, through NIP, the German government provided support and funding for the hydrogen fuel cell experiment in Lower Saxony.

There are several factors that I consider to be prominent triggers for hydrogen technology experimentation within rail application. In this specific case, I see a correspondence between top-down and bottom-up initiative. From a wider perspective, I would argue that national and international climate agreements are dominating triggers for emission reduction initiatives at a general scale. However, due to first-hand knowledge of the city's challenges and needs, local authorities may be better equipped in terms of answering the national and international climate goals. The correspondence between top-down and bottom-up initiative can illustrate the functionality of the socio-technical system of the mobility sector. The set climate goals can be argued to be a reaction to social mobilisation concerning the specific topic. This illustrates how the socio-technical mobility system, consisting of (networks of) actors, institutions and material artefacts and knowledge, interact and together provide specific societal function (Markard et al., 2012). Thus, I argue that initiatives in terms of sustainability experimentation are neither exclusively top-down nor bottom-up. Rather, experimentation with sustainable mobility can be considered a result of interaction at different levels and between several actors and institutions. In the case of Lower Saxony, I highlight social mobilisation concerning climate-related issues, market (demand and competition) and national and international climate agreements.

6.1.3 Knowledge accumulation for hydrogen fuel cell technology promotion

NOW (2016) argues that because of its pilot introduction, the first project of the hydrogen technology in Lower Saxony will directly affect the introduction of the technology in other regions. As presented in the empirical findings, according to the conducted interviews, various climate goals perceived a triggering effect in relation to the hydrogen fuel cell experimentation as well as pushing an energy transition within the mobility sector in general.

The timing of landscape pressure with regard to the state of niche-innovations is argued to be of importance in relation to transition pathway. Geels and Schot (2007) argue that if landscape pressure occurs at a time when niche-innovations are not yet fully developed, it can result in the transition path being different than when they are fully developed. The existing systems for the trials have been built in a small number with high cost and low standardisation. Due to few experiments with this technology for train application, the smaller systems have matured more than the bigger systems used for trains (Jernbane Direktoratet, 2019). Hence, the niche technology cannot be considered as fully mature. However, the hydrogen fuel cell experiment has demonstrated that fuel cell technology can properly function in passenger-rail applications (Thorne et al., 2019), and has thus provided a learning outcome prominent for further implementation. According to the conducted research, fuel cell technology for rail application may have the potential to be technologically mature between 2020 and 2025.

Sustainability experiments can function as an *"inclusive, practice-based and challenge-led initiative designed to promote system innovation through social learning under conditions of uncertainty and ambiguity"* (Sengers et al., 2019, p.1). The learning outcome from the hydrogen fuel cell experiment seems to have promoting effects within the mobility sector. The empirical findings state that the experimentation phase has been a success and has thus lead to a significant number of large companies in conventional technologies to increase investments and acquisitions to gain footholds to fuel cell vehicles or similar products (informant G, Hydrogenics). In addition, Alstom expects to move from push-market towards a pull-market in the future as the market seeks to meet energy and climate policy objectives (informant F, Alstom). The abovementioned illustrate the advantages of sustainability experimentation in terms of learning outcome across the entire system. The adaption of hydrogen fuel cell technology may lead to further experimentation with new and old elements in the regime, accelerating new learning. Alstom delivering a successful hydrogen fuel cell experiment allows learning both in terms of technical aspects as well as the general public's perception of the technology. Promotion effects can also be found in increased governmental support such as various funding programmes. The NIP are for example supporting future sustainable activities within the German mobility sector.

6.2 Institutional barriers and enabling factors associated with the hydrogen fuel cell powered train experiment

RQ2: Which institutional barriers and enabling factors are associated with the hydrogen fuel cell technology train experiment in Germany?

As the second research question is two-folded, this section will be presented in two parts. I will investigate and discuss both the institutional barriers and the enabling factors associated with hydrogen fuel cell technology in rail application.

In order to cover the dominant elements of the experiment, I intend to use Geels (2004) institutional dichotomy. Institutions affect sustainable development (Kern, 2011), and according to the three-pillar model, different configurations of regulative, normative and cognitive institutions shape the institutional configuration surrounding a social phenomenon (Geels, 2004). Within the socio-technical mobility system, the activity of the actors is constrained by the "rules of the game". Actors are allowed to act within the institutional environment, enabling them to reproduce or modify elements of the socio-technical system (Geels et al., 2016). New technologies do not always fit well into these rule-systems that require institutional innovation or change (Bakker & Konings, 2017).

All new technology does not necessarily fit into the existing "rules of the game". In some cases, institutions function as barriers to the implementation of new technology. Foxon (2002) refers to this as "lock-ins". Thus, to implement a successfully radical innovation, institutional change or institutional innovation may sometimes be necessary. At the current state, even though the iLint is in commercial service, the hydrogen fuel cell technology is considered immature and at a prototype-level. Thus, I intend to investigate the institutional barriers in order to identify both recent and potential future institutional change that could be of meaning for a full fleet. By institutional barriers, I refer to challenges that have affected the experimentation and may affect the future implementation of a full fleet. In the previous section concerning empirical findings, I have highlighted several barriers that can be categorized and discussed as institutional barriers.

However, institutional lock-ins are not static and unchangeable. Based on the empirical findings, it seems to me like various of actors in the mobility sector are very much aware of the challenges that hydrogen technology is facing. However, they are still positive to hydrogen technology experimentation, and despite the institutional barriers, I have noticed a motivation among the informants to change the institutional settings.

As presented in the analytical framework, Geels (2004) and Scott (2008) divides institutions into three pillars; regulative, normative and cognitive. The functionality of the framework is, in my opinion, more helpful in theory than in a real-life setting. The empirical findings can relate to the concept of regulative, normative and cognitive institutions. However, I consider some of the findings to be at the intersection of the analytical framework. Thus, the institutional barriers will be presented sequentially, and divided as the three-pillar model.

6.3 Institutional barriers associated with the hydrogen fuel cell powered train experiment

Smith and Raven (2012) argue that path-breaking sustainable innovations are at a structural disadvantage within these contexts as they may be too demanding in terms of their socio-technical implications for the regime. As previously mentioned, institutional barriers may occur in relation to sustainable innovation, and are referred to as “rules of the game” (Foxon, 2002). Different configurations of regulative, normative and cognitive institutions shape the institutional configuration of hydrogen fuel cell technology in rail application. Based on the conducted interviews, I have highlighted several barriers that can be categorized and discussed as institutional barriers. Thus, based on Geels (2004) institutional framework, I will in the following section detect and discuss the institutional barriers associated with hydrogen fuel cell technology for rail application.

6.3.1 Infrastructure

The operational planning of a comprehensive hydrogen infrastructure may represent a challenge. The empirical findings point to infrastructure as the most prominent barrier associated with the hydrogen technology experimentation. Hoogma et al. (2002) argue that infrastructure is a major reason for why novel mobility technology fails to develop beyond experiment. While Hoogma et al. (2002) highlight more technical aspects of infrastructure, my findings suggest that the apparent barriers are related to the technology's conformity to the current system. Such regulative institutional lock-ins can occur within established systems and can hinder the implementation of new technologies. Geels (2004) argues that other stabilisation rules such as technical standards or rules for government subsidies may favour existing technologies. Based on the empirical findings, I will in the following discuss ways in which existing institutions may hinder hydrogen technology experimentation and implementation due to infrastructure barriers.

Infrastructure built up

Due to the lack of hydrogen fuel cell experimentation, barriers concerning hydrogen infrastructure built up were discussed at a more general level. Infrastructure built up may vary between locations and context. Hence, the mentioned issues will have different impact depending on the current system. Hydrogen fuel cell initiatives are not isolated from national legislation and rules. Despite Germany's ambitious GHG-emission reduction targets, there are rules and procedures that must be complied to. Due to hydrogen technology involving different technological regimes, there is a need to introduce and redesign the part of the energy system and develop a fitting distribution concept (informant D, NHF).

My empirical findings suggest that hydrogen infrastructure suffers from the lack of standard procedures in relation to infrastructure built up, and state that there are bureaucratic barriers associated with introducing a hydrogen infrastructure. Note that "bureaucratic" here does not refer to bureaucracy in the sense that there are state bureaucrats and rules that slow down a potential transition. Rather, the informants point out the lack of and failure to establish bureaucratic procedures. Geels (2004) states that the (technical) standards present an important institution concerning sustainable innovations. The lack of such institution is argued to create a barrier for a hydrogen fuel cell implementation within rail mobility. The lack of bureaucracy and thus technical standards lead to high development cost, and can hinder transport companies to invest in the development of hydrogen fuel cell powered trains. This can have a clear negative market effect, and can be considered a regulative institutional lock-in within the established systems of the mobility sector. Government subsidies may thus favour existing technologies, hindering further implementation (Geels, 2004).

Building a hydrogen infrastructure faces a greater barrier than building a diesel fuelling station as it is not a "day-to-day" business (informant F, Alstom). Based on the empirical findings, I argue that lack of standards concerning hydrogen infrastructure built up also illustrates what Geels (2004) refers to as cognitive institutional lock-in. Such lock-ins are argued to appear as a consequence of the cognitive frames that provide meaning to social life. Cognitive frames are often apparent as routines, thus may block the search for new opportunities (Geels, 2004). Thus, establishing new routines and procedures demand a change of behaviour.

Hydrogen fuelling system

In terms of site planning or refuelling facilities within rail infrastructure, there are several of barriers that has to be overcome (NOW, 2016). Hydrogen fuelling system appears to be one of the most dominating barriers associated with the (further) introduction of hydrogen technology within rail application. Due to few hydrogen fuel cell experimentations for rail application, there is a lack of commercial and/or technical standardisation (Jernbane Direktoratet, 2019). According to the empirical findings, the hydrogen fuelling system suffers from lack of efficiency due its technology being limited to road mobility. At the current state, governments are building fuelling stations across Europe. However, they are mostly for cars and not heavy mobility fleets. My findings suggest developing larger fleets applicable for both public mobility fleets (rail and bus) as well as personal vehicles. A growing demand for hydrogen technology may lead to fuelling plans being optimised (NOW, 2016). Increased technical standardisation may also allow reduced cost and higher quality.

Another barrier associated with hydrogen fuelling system is associated with the fuel itself. My findings state that the hydrogen fuelling technology is nearly identical to the CNG (compressed natural gas) technology, but based on different materials. However, this barrier is associated with the experimentation phase rather than a full fleet. As discussed in the section concerning context, the trials are currently operating on a temporarily refuelling solution and not a solution appropriate for a full fleet. As a result, the trials are currently operating on gas hydrogen, not representing a sustainable option. However, a full fleet will operate on electrolysis in combination with hydrogen partly produced from by-product electrolysis. This solution allows for sustainable production and operation, and are thus desirable as a sustainable alternative to fossil fuels.

Hydrogen fuel cell powered trains can be considered a radical novelty and can face barriers in terms of existing infrastructure, user practices, regulations and more (Schot & Geels, 2012). Introducing new systems for hydrogen infrastructure built up and fuelling facilities may represent barriers due to the need for change. However, zooming out, I have found that new infrastructure built up and fuelling facilities call for system change. While the introduction of hydrogen technology requires new infrastructure built up and new fuelling systems, we may face more prominent barriers on a system level. As previously mentioned in this section, the lack of bureaucracy and technical standards lead to high development cost and thus low competition. Hence, the barriers related to infrastructure may not necessarily be found in the fuelling facilities itself (for example). The experimentation in Lower Saxony appear to have managed this. However, the systems established for the experimentation are affected by its prototype-level. Rather, the aforementioned barriers appear as most prominent for further implementation in specific. Due to low standardisation, low hydrogen demand and the lack of bureaucracy, it is not desirable (enough) to implement hydrogen technology for rail application. Due to a correspondence among the found barriers, I will discuss this matter in the later sections.

6.3.2 Safety

There are interesting discussions concerning hydrogen safety across the sector. I have investigated an ongoing discussion concerning alternative solutions for non-electrified lines. The discussion takes on the Norwegian railway and obtains a particular focus on hydrogen safety. Even though the focal location is the Norwegian railway, I have found that the discussions concern hydrogen safety at a general level and can thus generalise to the Lower Saxony case. In addition, the analysis and discussions present the iLint experimentation as a demonstration of hydrogen fuel cell technology in rail application. Based on analysis of the aforementioned reports and conducted interviews, my findings discuss hydrogen safety both under operation and in relation to hydrogen storage.

Different configurations of regulative institutions shape the institutional configuration of hydrogen safety in rail application. Sintef (2019) presents and discusses hydrogen and battery technology for non-electrified lines, and argues that the experimentation in Lower Saxony demonstrates that there is no need for an explicit new regulation for hydrogen fuel cell powered trains as hydrogen supply does not conflict with the existing European regulation. Alstom, with support from TÜV SÜD, thus identified relevant regulations (including road vehicles) and demonstrated "safe operations"/ cross regulations. Sintef (2019) stresses the importance of keeping track of what is being developed within other transport sectors. Components such as fuel cells and support systems will have to meet relatively similar requirements. The main differences between rolling stock and other means of transport lie in the support components and in the structural constructions that follow the system (Sintef, 2019).

The ongoing discussion in Norway concerns hydrogen safety with particular focus on tunnels. The Norwegian Railway Directorate (2019) states that there are high security risks in "ordinary" operation, especially related to longer tunnels. However, my findings disagree and argue that there has been carried out safety measures and risk assessments stating that the risks were not found significant. The iLint has been approved for commercial service and is allowed to operate in tunnels that are up to 5000 meters long (NHF, 2020). However, the iLint is currently operating on a line without tunnels. Thus, it is not unlikely that a general approval in other countries and contexts may result in further experimentation with focus on tunnel security.

Beyond the regulative institutions of safe operations and cross regulations, I argue that new technology demands new procedures and processes in relation to safety. The perceptions of user preferences can function as central cognitive rules (Geels, 2004). Due to previous accidents concerning hydrogen technology, there are regulatory and security issues around filling stations that need to be further investigated. Sintef (2019) suggests developing cognitive institutions such as routines and necessary training with particular focus on accidents. In addition, new technology demands investments in new knowledge and competences. Learning outcome can be a major source to path-dependency as learning normally is a cumulative process. Developing new procedures and routines may change the perceptions of the future and can thus steer the present actions (Geels, 2004).

My empirical findings suggest that historical accidents have affected the public's perception of hydrogen technology, where several informants refer to the Hindenburg accident in 1937. The public's perception of hydrogen safety illustrates a normative institutional lock-in and can be considered as a result of expectations that has been established within social and organisational networks. Geels (2004) argues that this sort of behaviour is not regulated by law, but has over time been associated with different actors and activities in a specific relation. Geels' (2004) literature of institutional lock-ins mainly focuses on role perceptions and expectations of proper behaviour, and is limited to mutual understanding of role expectations among actors. However, I argue that the public's perception and understanding of hydrogen safety has been shaped by normative institutions in terms of common expectations of safety issues. The "lock-in" in the case of hydrogen safety appears as a result of the lack of knowledge and a continuous comparison of hydrogen to other energy carrier solutions. Thus, my argument suggests discussing normative institutional lock-ins not only within social and organisational networks, but also as a correspondence between social actors and new technology. As presented in the empirical findings, the informants state that safety barriers are new rather than more challenging.

6.3.3 Single supplier

Based on timing and the nature of the multi-level interactions of focal case, hydrogen fuel cell technology takes on a reconfiguration pathway (Geels & Schot, 2007). As previously discussed, the niche is incorporated into the regime rather than replacing it, and may trigger further (architectural) adjustments under landscape pressure. Hence, hydrogen fuel cell technology within rail application can lead to adjustments within a regime while the majority of the regime rules remain unchanged. Informant G (Alstom) states that the majority of the mobility sector is still asking for diesel vehicles. However, the adoption of innovation may lead to experimentation within the regime, accelerating new learning within sustainable mobility (Geels & Schot, 2007).

According to the empirical findings, Alstom being in a "monopoly position" in an EU-regulated mobility sector is considered a challenge concerning market share and competition. Hydrogen technology experimentation is not isolated from EU regulations. Explicit, formal institutions like the EU are able to constrain behaviour and regulative interactions such as government regulations which structure the economic process. The European public transport policy aims to provide safe, efficient and high-quality passenger transport service in EU through regulated competition (EU, 2011). Thus, my findings state that Alstom being in a “monopoly position” in an EU-regulated mobility sector can be considered a challenge concerning market share and competition. Meanwhile, the railway manufacturers that have not invested in zero-emission technology are currently experiencing high market pressure finding alternatives to diesel trains (Jernbane Direktoratet, 2019).

Even though Alstom is the first company introducing hydrogen technology for rail application (that are already in commercial service) in the EU mobility sector, there is an apparent increase of hydrogen fuel cell prototype projects in Europe (Thorne et al., 2019). The projects are currently at a prototype level, and have not yet entered passenger service. Inspired by Thorne et al. (2019), I created an overview of hydrogen fuel cell vehicles at different stages of development.

Table 6: Overview of hydrogen fuel cell powered trains in commercial service and as prototypes.

Year	Manufacturer	Operator	Series/Model	Stage of development	Location	Segment
2018	Alstom	LNVG	Coradia iLint	Commercial service	Germany	Passenger
2017	N/A	JR-Group	N/A	Prototype	N/A	Passenger
2018	BORRE/ Porterbrook	N/A	HydroFLEX	Prototype	UK	Passenger
2018	Vivarail	N/A	Modified Class 230	Prototype	UK	Passenger
2018	Siemens Mobility	N/A	Mireo Plus H	Prototype	Germany	Passenger

Due to an increase of hydrogen technology experimentation within rail application, the future nature of MLP interactions can potentially be affected by disruptive relationships through pressure and competition. As previously mentioned, the timing of landscape pressure with regard to the state of niche-innovations is argued to be of importance in relation to transition pathway (Geels & Schot, 2007). Due to increasing competition (landscape pressure) in terms of sustainable options within rail mobility, hydrogen fuel cell technology may in the next years take on a technological substitution pathway. Geels and Schot (2007) argue that niche innovations may obtain a competitive relationship with the existing regime, aiming to replace it. However, my findings suggest that there is no intention, from either Alstom or other governmental powers, to replace the (entire) existing regime. The current mobility system consists of an energy mix. In the case of the German mobility sector, 42 percent of the mix of traction is already from renewable energy sources (The Federal Ministry of Transport, 2018). For rail as a mode of mobility, the use of electricity, increasingly from renewable resources means independence (mostly for the part) from oil and high specific energy efficiency as a result of the used technology (Federal Ministry of Transport, 2018). Alongside hydrogen as niche option within rail application, there is an increase of sustainable offers within rail mobility. I noticed in particular a repetitive discussion concerning hydrogen fuel cell and battery technology. My findings state that hydrogen and battery technology should be considered a complementary unit answering to different needs rather than competitors in the landscape of sustainable mobility (informant F, Alstom). Hence, hydrogen technology does not seek to replace the entire existing regime. However, alongside with sustainable options such as battery technology, hydrogen technology can contribute to a reduction in greenhouse gases within the German mobility sector.

6.4 Enabling factors

Despite the various institutional barriers, I have found institutional enabling factors associated with the hydrogen fuel cell experimentation.

6.4.1 Social acceptance

A cognitive institution related to the hydrogen fuel cell experimentation is social acceptance and support by the general public. The acceptance of infrastructure and technological projects by the society can be of high importance and may depend on a well-conceived and professionally public consultation (NOW, 2016). The two prototypes hydrogen fuel cell powered trains entered regular commercial service in Lower Saxony in Germany in 2018, and has since then been available for travel to the general public. The two trains are in operation on the Eisenbahnen und Verkehrsbetriebe Elbe-Weser network, on a 100 km line between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude (Thorne et al., 2019).

Introducing new technology or service into people’s daily lives may affect schemas and/or routines, and thus create confusion (Raven et al., 2017). Sengers et al. (2019) argue that system change may appear as a challenge as it depends on the actors to cooperate towards the same goal. Implications of unconformity to cognitive institutions can slow down or hinder the process (Raven et al., 2017). My findings are positive by nature and state that the technology has been accepted by the general public and adapted into their daily lives. In the previous section I have discussed safety barriers and the public’s perception of hydrogen safety.

Hydrogen safety has been discussed in general terms, whereas the informants state that the public's perception of hydrogen technology is affected by previous accidents and lack of knowledge. Despite such barriers, my findings state that the iLint prototypes have so far demonstrated a safe application of hydrogen fuel cell technology. A final safety assessment should be concluded at a later stage. However, the findings related to social acceptance can be considered vague as I have not been able to interview iLint passengers. In addition, the perceived societal effects may differ from one context to another. Hence, the findings related to social acceptance are limited to the experimentation phase and thus not transferable to a full-scale implementation. Rather, my perception of the empirical findings is the emphasis of increased knowledge for social acceptance.

As discussed in previous sections (section 6.1.3), sustainability experimentation can provide important knowledge accumulation. According to the empirical findings, due to increasing global knowledge production, we seem to struggle to keep track with new technology. As previously mentioned, the adoption of innovation may lead to experimentation within the regime, accelerating new learning within sustainable mobility (Geels & Schot, 2007). Based on the conducted research, I see a correspondence between the abovementioned barriers and knowledge accumulation. Despite the negative perceptions of hydrogen safety in general terms, the hydrogen fuel cell experimentation has successfully demonstrated safe application for passenger service. Due to the learning outcome and knowledge accumulation in relation to the experimentation, there is a change of perceptions among the general public. As argued by one of the informants; *"By keeping ourselves updated on new technology, we gain understanding of the interactions between the choice of technology, infrastructure and solutions related to mobility"* (informant E, Innovation Norway). Due to increased knowledge and understanding of the technology, hydrogen fuel cell technology for rail application seems to have been adopted by the public and may lead to long-lasting acceptance. Further, a safe application of sustainable hydrogen can be considered a crucial basic prerequisite for long-lasting acceptance. NOW (2016) argues that these and other aspects identified through issues, sensitivity and stakeholder analyses *"must be communicated in a transparent and comprehensive way tailored to each specific target group and in addition the corresponding dialogue formats offered in a timely manner"* (NOW, 2016, p.15). In order for hydrogen fuel cell technology to be a market success within the mobility sector, they must be accepted and adopted by users.

6.4.2 Political incentives

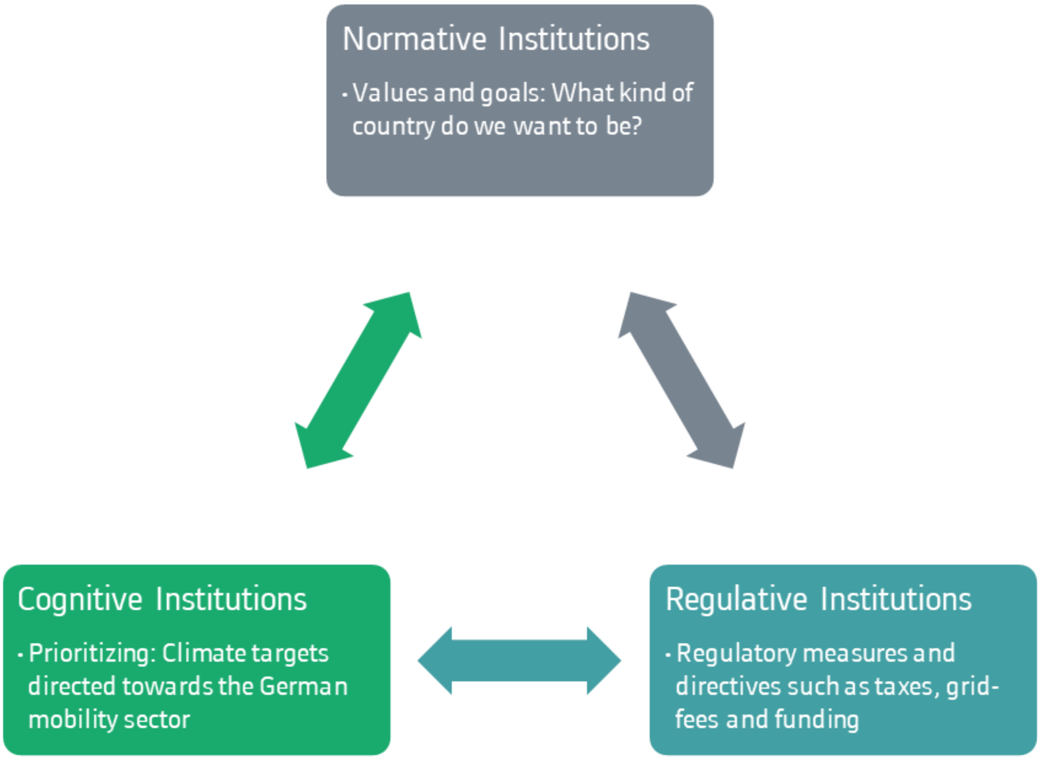
Literature on urban experimentation states that sustainability initiatives may “suffer” from lack of political support as measures may first bring benefits several decades in the future. Madsen and Hansen (2018) further state that local urban governments experience bureaucratic challenges in relation to political engagement with climate objectives. State-owned Deutsche Bahn is the operator of 33,300 km of modern rail in Germany and operates the infrastructure both in Germany and globally through its subsidiaries (Railway Technology, 2016). The company appears to be engaged in terms of climate-issues within the German mobility sector due to climate change and an expected increase of traffic volume (Deutsche Bahn, 2020). In order to meet set climate objectives, Deutsche Bahn (2020) calls on policymakers, industrial production and the public to cooperate towards the common goal. My empirical findings highlight political support and incentives for hydrogen technology as an enabling factor associated with further implementation. According to the institutional dichotomy, political engagement in new technology comprises both cognitive and normative institutional processes (Geels, 2004). Due to Germany’s planned transition towards a low-carbon, nuclear-free economy (Energiewende), I will discuss political support and incentives on a national level.

Political support and incentives can be tied up to the institutional values of Lower Saxony and Germany (Geels, 2004). Due to the major rail industry in Germany, the informants consider it as an important political task to secure innovation within a railway sector. As discussed in previous sections, the hydrogen fuel cell experiment in Germany was triggered by landscape pressure from national and international climate agreements. Germany aims to transform the entire power sector, going from nuclear and coal to renewables within the next four decades (Federal Ministry of Transport, 2018). My empirical findings state that political support and incentives can push the early adoption of hydrogen technology within the mobility sector, and suggest implementing taxes and grid-fees. That way hydrogen technology as a niche within rail application can be constructed more actively (Smith and Raven, 2012). Aiming to eliminate emissions within rail mobility, regulatory measures and directives may have an accelerating effect on the introduction of associated technology. Through a public sector directive to reduce emissions of commercial fleet(s), an increase in sustainable vehicles fleets may transpire (NOW, 2016). Hence, public regulations at a local level can provide positive effects on the future introduction process in local rail public mobility. Political support and incentives can in that way both control and direct innovations in the public sector, and thus influence and stimulate the introduction of innovative technology.

In terms of cognitive institution, Geels (2004) argues that how system actors prioritize affects system change. The undertakings of the Energiewende are complex and have an effect on many parts of the German society. However, one focal unit of the transition is the mobility sector (Agora Energiewende, 2013). Funding is a key indicator of political support. The hydrogen fuel cell experimentation in Lower Saxony was supported by the German Ministry of Economy and Mobility, and the development of the train was thus funded by the German government as a part of the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP) (Alstom, 2018). A network has already been established through the NIP, involving alliance based on partnership across politics, industry and science on both national and international levels. The aim of the NIP is to develop and establish competitive mobility using fuel cells and hydrogen on the market (The Federal Ministry of Transport, 2016). Increased funding can support the development of hydrogen and fuel cell technology products in terms of research, development and innovation. Funding can also support the introduction of new technology by direct market activation. For example, as presented in the empirical findings, the NIP has supported hydrogen technology by providing capital grants, such as for fuel cell powered trains or electrolysis systems for the generation of green hydrogen (The Federal Ministry of Transport, 2016).

My empirical findings state that increased funding is expected and may grant companies such as Alstom to expand the public transport service by developing and establishing competitive mobility solutions. That way, increased funding can also be considered as a clear political signal of both the technological and environmental direction of the public rail service. Based on the aforementioned discussion concerning political support and incentives, I have crafted an overview of both normative and cognitive enabling institutions.

Figure 3: Enabling institutions tied up to political incentives



6.4.3 Sector coupling

Sector coupling can function as an interconnection across energy-consuming sectors, but also within the mobility sector (among other vehicles and services). Sector coupling allows for altering the “rules of the game” of the current mobility and energy system, and can change the institutional setting. This can be referred to as institutional innovation (Geels, 2004). However, due to national guidelines and regulations of the German energy system, altering the rules of the game may be challenging (Mieg, 2013). From an MLP, the current mobility system in Germany can be considered the regime level, and can be characterized by fossil fuels and automobility (Van Bree at al., 2010). A change towards renewable sources may thus involve new technology, actors, institutions and new user practices and/or standards (Markard et al., 2012). However, it is possible to change the “game”.

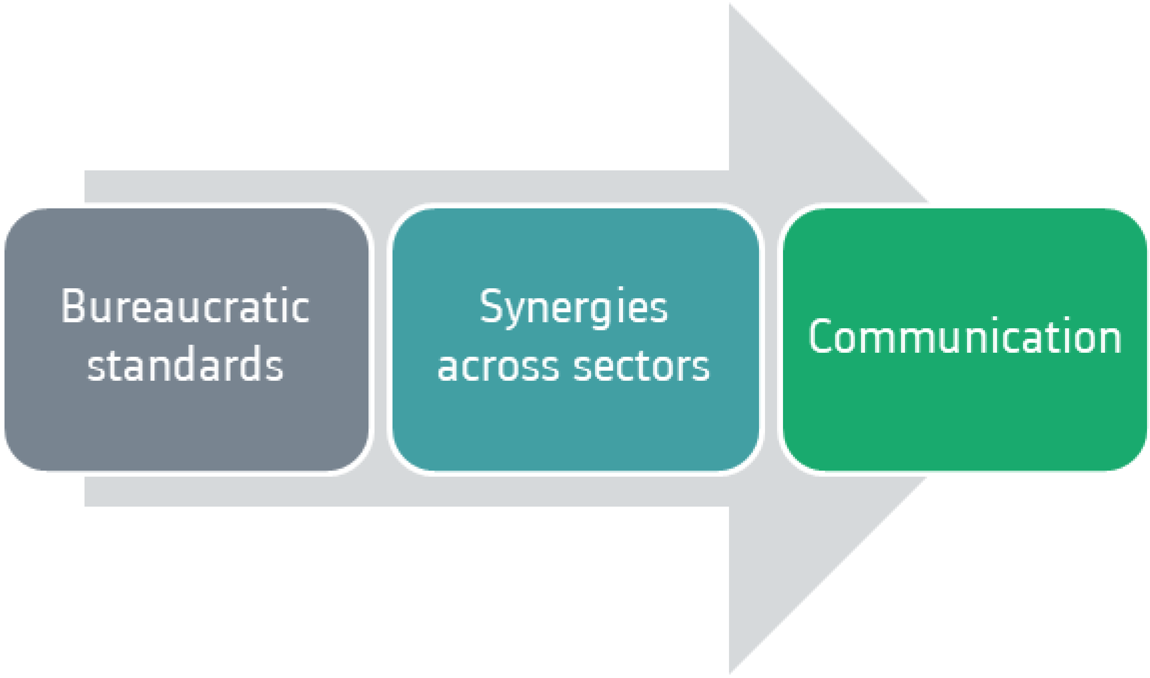
Landscape developments, such as Germany's ambitious climate objectives, challenge the current institutional setting and can thus allow for change across sectors. For example, I argue in previous sections that the hydrogen fuel cell technology experiment is currently operating in a protected space, protected from the mainstream selection environment. Despite barriers in terms of existing infrastructure, user practices, regulations and more, the hydrogen fuel cell experimentation was rolled out in the area of Lower Saxony (Schot & Geels, 2012). The iLint has even expanded both within the German railway, but also across national borders. Note that I do not categorize the protected space as a “game changer”. Rather, I use this example to illustrate how local authorities initiate and govern sustainability experimentation and initiatives despite regulative institutions. Altering existing institutions is not a straightforward process, and may take a long time (Geels, 2004). As sector coupling involves several sectors (or modes of mobility), changing the institutional setting of the German energy and mobility system depends on several variables across different institutional levels. I will not discuss how and if sector coupling can be implemented in the German mobility and energy system. However, such institutional change/activity can benefit from the current energy transition in Germany and can contribute to a potential system change. Note that I do not refer to sector coupling as an innovation. Rather, it can be considered an innovative activity operating on a system level. Such synergies across sectors will be further discusses in the next section (section 6.5.2).

6.5 Institutional innovative activities

Various literature on transition studies call for institutional innovations (Bakker & Konings, 2017; Madsen & Hansen, 2018) in relation to sustainable innovation. However, I agree with Aagaard (2018) and argue that there is a lack of institutional innovation activities for implementation of sustainable initiatives. Inspired by Aagaard (2018), I have thus developed three prominent institutional innovative activities related to a future implementation hydrogen fuel cell technology in rail application.

Based on the conducted research and its empirical findings, I will present three activities that may obtain positive effect on future implementation. Aagaard (2018) states that her tripartite model describes mechanisms that can overcome (or lower) many of the barriers found in her research. Due to context-specific findings and superior discussions concerning the perceived barriers associated with hydrogen technology in rail application, I will not state that my innovative activities can overcome or even lower the presented barriers. The perceived barriers may differ from one context (and/or country) to another, and appear as dependent on both current regime and landscape developments of each mobility system. For example, the sustainability experimentation in Germany was located in the area of Lower Saxony due to several of reasons. One of these reasons is the major non-electrified line that was previously diesel operative (informant F, Alstom). If the experimentation were to be located in an area with a lack of non-electrified lines, there might be a prominent change of barriers. In addition, the experimentation is clearly affected by the prototype-nature of the trials. Hence, I will not state or even assume that the perceived effects and barriers associated with the experimentation will appear the same as for a full implementation. The purpose of this study has not been generalizability. Rather, the innovative activities may be applicable for mobility systems that are similarly organized as in Germany. Thus, I intend to present and discuss three institutional innovative activities in general terms. I argue that the three factors may have positive effect on a future implementation of hydrogen fuel cell technology in rail application.

Figure 4: Institutional innovative activities



6.5.1 Bureaucratic standards

To maintain and increase competition within an EU regulated mobility system, bureaucratic technical standards should be required. Often, bureaucracy can be considered a hinder to innovation. However, in an EU context, its functionality changes. EU requires competition related to sizeable public procurement. A prerequisite of such acquisition is thus EU competition. Hence, the lack of bureaucracy can be considered a hinder to innovation within the EU regulated mobility sector and appears as a prominent barrier associated with further implementation of hydrogen fuel cell technology in rail application. However, even though this barrier is concerned with regulative institutions, it is neither exclusive nor independent from other barriers. Rather, I see a clear correspondence between the various barriers, demonstrating an interesting case of the functionality of a socio-technical mobility system. Each variable appears to be co-dependent and provides a specific societal function (Markard et al., 2012). The lack of and failure to establish bureaucratic procedures represent an important institutional concern within sustainable innovations (Geels, 2004), and may lead to higher development cost. Higher cost leads to higher risk of investments, making it less desirable for actors to develop hydrogen fuel cell powered trains. Further, the lack of and/or decreased market for hydrogen fuel cell powered trains limit market competition. That way, according to the presented barriers, hydrogen fuel cell technology can potentially find itself in a regulative institutional lock-in within the established systems of the mobility sector. Due to such potential lock-ins, government subsidies may thus favour existing technologies, hindering further implementation of a full fleet (Geels, 2004).

However, sustainable experimentation allows the discovery of early stage institutional barriers which can be dealt with before further implementation. The existing systems of the trials have been built in a small number with high cost and low standardisation (Sintef, 2019). However, based on the empirical findings and aforementioned discussions, I view bureaucratic standards as a key enabling factor affecting several of variables (and barriers) associated with the introduction of hydrogen technology. As described above, introducing technical standards may function as an institutional innovative activity leading to increased competition and lower the cost of future development of hydrogen fuel cell powered trains. There are several of objectives being (potentially) fulfilled by increased standardisation. On one side, it is clear that Alstom has self-interest in introducing regulations and technical standards. Bureaucratic standards will allow further actors within the mobility system to enter the hydrogen technology market for passenger rail. As previously discussed, Alstom being in a “monopoly position” in an EU-regulated mobility sector is considered a challenge concerning market share and competition. Even though there is not yet developed bureaucratic standardisation, hydrogen technology experimentation is not isolated from EU regulations. My empirical findings state that Alstom being a single supplier disrupts the trustworthiness of the technology, hindering market competition. In addition, it may have a direct effect on further sales of the iLint. On the other side, bureaucratic standards correspond with climate objectives on both a national and local level, and signal both the technological and environmental direction of the public rail service. This aspect may have indirect effects on cognitive institutions and will thus be further discussed in the section concerning communication as an institutional innovative activity (section 6.5.3).

6.5.2 Synergies across sectors

The second innovative institutional activity corresponds with climate objectives on a national level, and revolves beyond sector change. As presented in the introduction, Energiewende is driven by four political objectives; fighting climate change, phase-out nuclear power, improving energy security and maintaining industrial competitiveness and growth. Hence, the undertakings of the Energiewende are complex and affect many parts of the German society and economy (Agora Energiewende, 2013). Today's electricity sectors have been influenced by feedstock availability, technological development, market structure and political preferences. In further evolution of these actors, the total electricity demands will most likely increase. Despite efficiency gains of technologies related to the traditional electricity provision, usage of electricity applications arises (Robinius et al., 2017). In previous sections of the thesis, I argue that synergies across sectors may allow increased efficiency in terms of cost, storage and refuelling. In this section, I will present the synergies across sectors as an institutional innovative activity and its potential effects on the further introduction of hydrogen technology for rail application.

Developing synergies across sectors, such as sector coupling, may allow more efficient transition on several levels affecting cognitive, normative and regulative institutions. A cognitive institution related to new technology is learning accumulation and social acceptance of both the general public and sector actors. During the timespan of the thesis I have found that cooperation between different sectors and/or modes of mobility can create space for shared knowledge and experience among sector actors. As discussed in the previous sections, knowledge accumulation is a key factor for technology promotion, whereas shared knowledge and experience can facilitate hydrogen technology promotion across sectors. Creating a collaborative space may facilitate sustainability experimentation across sectors, and allow for new technology exploitation. Further, a prominent cognitive institution in a transition towards renewable sources is social acceptance. Collaborative spaces for various sectors signal acceptance and action related to set climate objectives on both national and sector level. Communication as an institutional innovative activity will be further discussed in the next section (section 6.5.3).

Last, synergies across sectors challenge the existing regulative institutions within the sectors involved. As mentioned in the introduction of the thesis (section 1.3.3), Germany obtains new wind power in the North. However, only 850 kilometres of the planned 7,700 kilometres of new transmission lines have been built thus far. As a result, renewable energy gathered from wind power in the north suffers from limited availability (Agora Energiewende, 2018). A sector coupling approach interconnecting the transport and energy sector may force transmission efficiency due to increased energy demand. Hence, I do not argue that such synergies directly change the current regulative institutions. Rather, an increased (renewable) energy demand may indirectly force a “change of game” in terms of energy distribution, storage and usage (Geels, 2004). That way, the sectors involved may adapt its regulative settings in accordance to increased energy demand. Within a socio-technical system, such change may involve and affect several aspects of the system. One regulative institution is not necessarily isolated from another. Thus, institutional innovative activities rarely affect one exclusively regulative institution within an existing system. Rather, such change requires change across various institutions. For example, an increased energy demand leads to increased competition. As a result, it can change the regulative institutions in terms of competition. As presented in the empirical findings, European public transport policy aims to provide safe, efficient and high-quality passenger transport service in EU through regulated competition (EU, 2011). Synergies such as sector coupling can for example affect market competition due to increased energy demand and possibilities for shared hydrogen storage and refuelling facilities (NOW, 2016).

6.5.3 Communication

A cognitive institution related to the hydrogen fuel cell experimentation is social acceptance and support from the general public. As previously discussed, the acceptance of infrastructure and technological projects by the society can be of high importance and may depend on a well-conceived and professionally public consultation (NOW, 2016). Knowledge accumulation appears to be a prominent enabling factor associated with the introduction of hydrogen technology for rail application. Consequently, I will argue that communication is an appropriate opportunity to draw on knowledge and expertise of others within the system of the mobility sector. For example, Alstom’s results and experience of the sustainability experimentation in Lower Saxony could be communicated through dialogue conferences with central actors within the German mobility system. Obtaining the competences and capabilities needed in relation to a novel innovation is crucial, and can steer the acceptance and beliefs of what is achievable (Geels, 2004). Creating spaces for system interaction among mobility actors (suppliers, operators, governmental forces, policy-makers, manufactures etc.) allows for exchange of knowledge and experience.

Moreover, literature on urban experimentation argue that organizing experimentation on a local scale may generate trust and legitimacy (Bulkeley et al., 2015). Inspired by Madsen and Hansen's (2018) study on Danish urban climate change experimentation, I will highlight local authority as a prominent actor for communicating new technology to the general public. Climate governance and initiatives at a local scale are believed to offer more effective policies. Local authorities are often responsible for public services such as public transport, and can thus steer transition (Madsen & Hansen, 2018).

6.6 A socio-technical mobility transition

The thesis contributes to the socio-technical transitions research tradition. The transition at hand takes on a decarbonisation and centralisation of our mobility system. The multi-level perspective is one of the most prominent analytical frameworks for studies on socio-technical transitions. Conceptualising the link between technology and society, the MLP creates an analytic distinction between three levels: the socio-technical regime, the socio-technical landscape and socio-technical niches (Whitmarsh, 2012). The view of socio-technical transitions is systemic, whereas the main assumption is that for substantial change to occur within a socio-technical system, alignments of development among the different elements are crucial (Markard, et al., 2012). In the case of the thesis, our current mobility system can be considered the regime level. Today's mobility system can be characterised by fossil fuels and automobility. A change may thus involve new technology, actors, institutions and new user practices and/or standards (Markard et al., 2012).

I find transitions within the mobility sector to be interesting due to their effects on the general public (users). Automobility, for example, can be associated with freedom, allowing individuals to travel where they want by themselves. In the modern age, self-determined mobility can be considered as a prominent value (Canzler & Wittowsky, 2016). Sustainability transitions within the mobility sector can involve both decarbonisation and centralising, whereas rail as a key mode of mobility can expect a greater share in the future within passenger service (Thorne et al., 2019). An increased use of public transport can be recognised as a key step towards a sustainable mobility transition, both on a national (Germany) and international level (Europe). In addition, implementing zero-emission technology improves the rail as a mode of public transport. Replacing the current regime (fossil fuels) with zero-emission technology (niche) can be a prominent step towards sustainable mobility. Local initiatives towards sustainable mobility can thus be considered a political signal of both the technological and environmental direction of the public rail service.

My empirical findings state that a further implementation of hydrogen fuel cell technology in rail application may face prominent institutional barriers, both within the social context (in terms of technology acceptance by the general public in relation to safety) and within the railway market. Hence, my findings revolve around non-technical barriers. However, sustainable experimentation allows the discovery of early stage institutional barriers which can be dealt with prior to further implementation. Despite the abovementioned institutional barriers, I have found institutional enabling factors associated with the hydrogen fuel cell experimentation.

6.7 Limitations of the thesis

I will in the following underline some of the limitations of the thesis. First, the study is geographically limited to the context of Germany, whereas some findings are specifically limited to Lower Saxony (existing lines, energy availability, support by local authorities). Hence, the findings cannot be generalized to other contexts and countries. Further, there is an apparent lack of studies and research on the field of experimentation and implementation within zero-emission technology within today’s mobility sector. Hence, there is a need of studies to map both intercity and regional similarities and differences.

Last, I have found a few weaknesses related my methodological approach. First, I wanted to interview political actors that were engaged in the experimentation. This could allow me to gain an understanding of how and why the German mobility sector prioritizes sustainability initiatives, and discuss the aforementioned findings from a political perspective. Second, in hindsight of the research, I see that the study would benefit from more interviews. As I conducted the interviews all in approximately one month, it took some time to “process” all the conducted data. During the analysis of the conducted data, I noticed that some topics were barely discussed throughout the interviews. These were topics that could provide me with interesting narratives. For example, some of the informants mentioned how a transition towards renewable sources would affect people daily lives. However, I was not able to grasp the statements at the time. Their comments were too superior, and I were thus not able to use them in the thesis.

6.8 Further research

Experimentation with sustainable technology demonstrates the society's attempt to understand and develop the possibilities of a response to climate change (Bulkeley et a., 2015). Due to the lack of hydrogen fuel cell powered trains in commercial service, there is an apparent lack of research on the subject. Besides research on technical performance, there is little research on hydrogen fuel cell technology experimentation and discussions concerning further implementation in today's mobility sector. A socio-technical transition within the mobility sector is highly complex, whereas its effects are not necessarily limited to sector level. Thus, there are several of ways to approach the subject. I hope to find both research and discussions related to sustainability experimentation from various perspectives in the future.

Due to the complexity of the German mobility system, there are many variables and areas of interest that can provide fruitful discussions concerning processes revolving hydrogen experimentation and implementation. I would in particular find it interesting to investigate the hydrogen fuel cell experimentation in Lower Saxony from a political view. As presented in previous sections, the government and the local authorities of Lower Saxony, have engaged in the iLint prototypes. I believe that a sustainable transition within the mobility sector calls for system change, steered by regulative institutions from a political force. Gaining understanding of the political processes leading up to the sustainability experimentation from a transition study perspective can provide interesting findings of how today's politicians act upon climate change. As barely mentioned in previous sections, a transition towards renewable sources threaten employment within prominent industries in Germany. How can politicians undertake ambitious efforts to combat climate change and adapt to its effects, and simultaneously avoid unemployment? How can a political party promote sustainable technology such as hydrogen if it is not in (direct) favour of the general public? I fear that politicians are hesitant to push sustainable technology development due to the fear of losing a selection. Further, my findings state that a further implementation of hydrogen technology in rail application may suffer from a lack of knowledge. Investigating the knowledge accumulation within the political forces in Germany can provide emphasis on prominent processes related to human resource development. I liked one of the statements of the informant from Innovation Norway (informant E), saying that today's knowledge has never had such high pace. However, it will neither never go slower. In a world where we are finding ourselves in constant change, it is of high importance that we keep ourselves updated on new technology to maintain a functional society. Hence, gaining insights into the process of introducing hydrogen technology in rail application can and should be considered an area for further research. Enhancing a knowledge-base on sustainable initiatives within the mobility sector can be important as it may lead to a socio-technical transition (Bulkeley et al., 2015).

As presented in the thesis, a socio-technical transition within the German mobility sector are not limited to one sector. Rather, a transition towards renewable sources engage action from the German energy system. The sustainability experimentation in Lower Saxony may be a small project. However, further implementation can provide large scale effects in terms of energy demand and supply, and can thus affect how the German energy system is organised. Hence, it could be interesting to investigate how Germanys energy system is organised and the specific preconditions related to the introduction of hydrogen technology within the mobility sector. Questioning action across the entire energy and mobility system can provide information related to the process towards (and during) socio-technical transition within the mobility system, as well as the German energy sector.

7.0 Conclusion

The thesis has aimed to answer the following research questions;

> **RQ1: What is the background for the hydrogen fuel cell experimentation in Lower Saxony in Germany, and how can the perceived effects influence further implementation?**
> **RQ2: Which institutional barriers and enabling factors are associated with the hydrogen fuel cell technology train experiment in Germany?**

We are living through a transformation in the way we see ourselves and our relationship with the environment. While scholars and politicians have focused on how to overcome this common action problem, there has evolved awareness of the need to understand and develop the possibilities of a response to climate change (Bulkeley et al., 2015). Our current mobility system is manifesting itself in an unsustainable way, and is characterised by automobility and fossil fuels (Bakker & Konings, 2017). There are several of potential paths towards sustainable mobility, and there is currently an increase of sustainable initiatives all over the world. Cities and local authorities appear to be able to efficiently exceed sustainable initiatives and thus signal transition towards renewable sources (Madsen & Hansen, 2018).

Germany is an interesting case due to its policy plans for a pioneering energy transition, the "Energiewende" (Leiren & Reimer, 2018). During the timespan of the thesis, the first approved passenger train using hydrogen fuel cell technology has been in operation on the Eisenbahnen und Verkehrsbetriebe Elbe-Weser network, on a 100 km line between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude (Thorne et al., 2019). The experimentation appears to be protected from the "normal" selection environment, and can thus accumulate knowledge important for further implementation of hydrogen technology. By experimenting with hydrogen technology, Lower Saxony respond to both national and international climate objectives. However, the experiment initiative is not exclusively climate-related. Alstom obtain self-interests, and aim to strengthen their market position by creating a market space for hydrogen technology for rail as a mode of mobility. Lower Saxony appear to be a well-fitted context for the experimentation due to several factors; existing rail operating on diesel, location nearby the North Sea and governmental support. Further, my findings state that hydrogen technology can potentially serve long-term sustainability goals. However, at the current state, the iLints fails to meet market demand in terms of sustainable achievement. The trials are still at a prototype-level due to small-scale production and the lack of hydrogen market. Thus, it would not be fair to reject the iLints at this point. Rather, it would be interesting to do another study on its progress and position in the mobility sector in five to ten years.

There are prominent barriers associated with a further implementation of hydrogen fuel cell technology in rail applications. The presented barriers are highly interactive and demonstrate a regulative weakness of the socio-technical system of the mobility sector. New technology within the mobility sector appear to struggle at the start pit due to bureaucracy and the lack of new technical standards and regulations. Simply put, it appears as the socio-technical mobility system is not responsive in terms of introducing new technology. The lack of bureaucratic technical standards cause prominent barriers associated with infrastructure and fuelling system and hinder full-scale implementation. Further, low standardisation is associated with high development cost. Hence, it may not be desirable for transport companies to invest in the development of hydrogen fuel cell powered trains. In addition, Alstom’s current monopoly position in an EU regulated mobility system leave the company as a single supplier, challenging market share and competition.

Despite prominent barriers, I have found institutional enabling factors associated with the hydrogen technology experimentation. The enabling factors should be maintained and focused for further implementation of hydrogen technology in rail application. The thesis state that an important cognitive institution related to the hydrogen fuel cell experimentation, is social acceptance and support of the general public. The iLints appear to have been adopted by the public and may lead to long-lasting acceptance. However, my findings related to social acceptance can be considered vague as I have not been able to interview any passengers. The effects of social acceptance can correspond with the second enabling factor; political incentives. Political engagement in new technology comprises both cognitive and normative institutional processes. However, local urban governments can experience bureaucratic challenges in relation to political engagement with climate objectives. The experimentation in Lower Saxony has benefitted from support and engagement of local authorities and funding by the German government as a part of the National Innovation Program for Hydrogen and Fuel Cell Technology (NIP). Political incentives can be tied up to both normative and cognitive institutions, and signal institutional values and response to climate objectives. Last, I argue that interconnections across sectors through sector coupling can open new possibilities for hydrogen technology. By altering the “rules of the game” of the current mobility and energy system, we can change institutional setting related to energy distribution and storage. Creating a collaborate space may facility sustainability experimentation across sectors and allow for new technology exploitation.

Based on aforementioned findings and discussions, I have presented three institutional innovative activities for further implementation of hydrogen fuel cell technology in rail application; bureaucratic standards, synergies across sectors and communication. For large-scale implementations, the novelty of the iLints and other hydrogen fuel cell powered trains is in the need of new institutions, practices and procedures. We may be at the start phase of a comprehensive energy transition towards renewable sources. With this pace, it will be interesting to see where we find ourselves in only a couple of years.

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Appendices

Appendix 1 – Interview Guide

RQ1: What is the background for the hydrogen fuel cell experimentation in Lower Saxony in Germany, and how can the perceived effects influence further implementation?

- And where did the initiative come from? Who paid for the project?
- Entering the project, what expectations did you have in terms of effects on marked, climate economic gain and such?
- What would you identify as the main benefits to hydrogen fuel cell technology on trains?
    - Environmental?
    - Economic?
    - Transition phase?
- Was the experiment geographically targeted?
    - Identify the existing socio-technical systems
- What are the further opportunities for hydrogen fuel cell technology on trains?
- How the hydrogen supply infrastructure would develop often depend on feedstock (like renewable energies), geographic factors, population density and policy support. Can you elaborate? Why were the test train rolled out in that exact area?
- Can you please explain how the transport- and distribution for the hydrogen has developed throughout the project? And are there conditions that are specific for Germany, and not necessarily to other countries?
- We talk about an energy transition - who would you identify as central actors in a such transition?

RQ2: Which institutional barriers and enabling factors are associated with the hydrogen fuel cell technology train experiment in Germany?

- What challenges or barriers have you met so far?
- What challenges or barriers do you expect to meet in the future?
    - Political?
    - Technological?
    - Social?

- How can you deal with these barriers?
- Some literature argues that strong policy measures, such as zero-emission mandates or tax incentives are essential to encourage the early adoption of hydrogen vehicles. What are your thoughts on this?
- There is a resent report from the Norwegian railway directorate on zero-emission technology within the mobility sector. According to the report, Norway will choose battery and not hydrogen. What are your thoughts on this?

Appendix 2 – Informed Consent Form

Would you like to participate in the research project?

”Hydrogen Fuel Cell Technology in Railway”

Purpose

This is a master’s thesis concerning zero-emission technology within the public mobility sector. I intend to focus on benefits, risks and opportunities for hydrogen fuel cell technology in a German context from a socio-technical (transition) perspective. More specific, the study is based on the Coradia iLint that has entered into passenger service in Lower Saxony, Germany. The intention of the thesis is to highlight the how- and why components concerning hydrogen fuel cell technology in rail application.

Based on your relevant experience, I would be grateful to have about 30-60 minutes of time to talk about your perspective of the transition. In addition, I would like to gain insights into your engagement in sustainable mobility in a German context and your thoughts on benefits, risks and opportunities concerning hydrogen fuel cell technology.

Who is responsible for the research project?

Technology, Innovation and Culture Centre at the University of Oslo is responsible for the project.

What does it mean for you to participate?

By signing this paper, you agree to participate in a 30-60 min interview. I intend to ask about your perspective of the transition. In addition, I would like to gain insights into your engagement in sustainable mobility in a German context and your thoughts on benefits, risks and opportunities concerning hydrogen fuel cell technology. I will both take notes and do a sound record of the interview.

Participation is voluntary

Participation in the project is voluntary. If you choose to participate, you may withdraw your consent at any time without giving any reason. All your information will then be anonymous, and there will not be any negative consequences for you if you do not want to participate or later choose to withdraw.

Your privacy - how we store and use your information

I will only use the information for purposes that I have stated previously in this letter. The information will be managed confidentially and in accordance with the privacy policy. Those who will have access to these are me, Ida Kristine Gjerdingen, and my supervisor, Helge Ryggvik. I do not intend to use your name or contact information in the thesis. However, I will use the name of the organisation/company that you represent.

What happens to your information when we finish the research project?

The project will end 01.05.20. At this time, all your information will be deleted.

Your Rights

As long as you can be identified in the data material, you are entitled to;
- insight into what personal data is registered about you,
- to have your personal information corrected,
- have personal information deleted
- receive copy of your personal data (data portability), and
- to submit a complaint to the Data Protection Privacy (Personvernombudet) or the Data Inspectorate regarding the processing of your personal data.

What gives us the right to process personal information about you?
We process information about you based on your consent.

On behalf of the Center for Technology, Innovation and Culture (TIK) at the University of Oslo, NSD - Norwegian Center for Research Data AS has considered the processing of personal data in this project in accordance with the privacy regulations.

Any questions?
If you have any further questions about the study, or wish to exercise your rights, please contact:

- Center for Technoology, Innovation and Culture (TIK) at the University of Oslo,
    - by project supervisor: Helge Ryggvik,email: helge.ryggvik@tik.uio.no
    - or student, Ida Kristine Gjerdingen, email: idakgj@student.sv.uio.no
- Our privacy policy contact: Maren Magnus Voll, email: personvernombud@uio.no
- NSD - Norwegian Center for Research Data AS, email (personverntjenester@nsd.no) or by phone: +47 55 58 21 17.

Best regards,

Ida Kristine Gjerdingen

Consent Statement

I have received and understood information about the project "Hydrogen Fuel Cell Technology in Railway”, and have had the opportunity to ask questions. I agree to:

☐ Participate in an interview

Agree that my information will be processed until the project is completed, approx. May 01, 2020.

Signed by: Informant, date