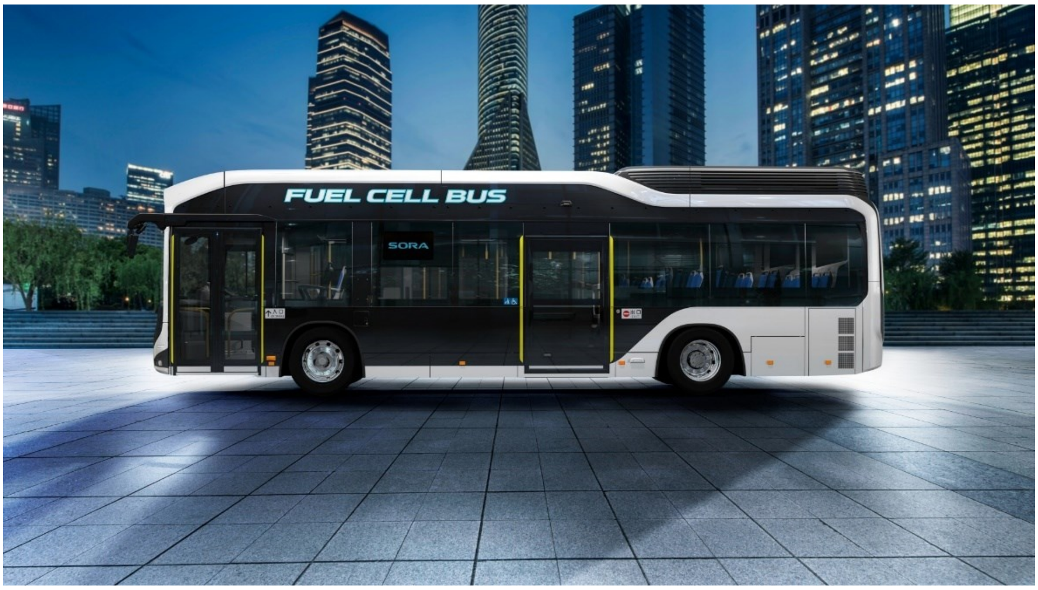
The role of hydrogen fuel cell buses in the transition towards zero-emission public transport in the Netherlands



Carmen van der Beek
Student number: 5922305
Sustainable Business and Innovation
Supervisor Utrecht University: Toon Meelen
Second reader: Christina Bidmon
Internship Company: Shell
Internship Location: The Hague, Netherlands
Internship function: Assessed Intern Commercial Hydrogen Mobility Benefrux
Date: 09-05-2023
Word Count: 18623

Utrecht University

Abstract

Sustainable solutions in public bus transport are an important element in decarbonizing the transport sector. The Netherlands is a pioneer in the implementation of electric buses, working towards a goal of zero emissions from public buses by 2030. In this thesis, the role of hydrogen buses in the transition to zero emissions is explored. Seventeen semi-structured interviews actors across the value chain were conducted next to a literature research. First, the system dynamics and developments around public transport and hydrogen buses were provided, followed by an overview of the most prevalent barriers for the implementation of hydrogen buses. These barriers include high prices of hydrogen and assets as well as institutional barriers concerning governmental policy. Additionally, the interactions with battery electric buses were analyzed using the building blocks of the multi-mode framework. These interactions go beyond the horizontal concept of competition, providing insight in the effects of external events such as COVID-19 and Ukraine as well as the overlap in benefits of digitalization and the use of telematics. The interactions give insight into the complex system dynamics and the implications of entering a market where another technology has already gained market share.

The roles of incumbents in the implementation of hydrogen buses are explored for different types of public- and private incumbent organizations. Four theoretical dimensions of incumbency are established in the theoretical framework, which are used to explore the roles of incumbents on three different themes, based on the established barriers, interactions and relevant topics discussed in the interviews. Vested networks, changing business models and the influence of decision processes in incumbents were discussed to investigate strengths and barriers of incumbents in the implementation of hydrogen buses. The strengths of incumbents lie in scaling up through experience, financial resources and a good position in the value chain. Challenges lie in slow decision making and difficulties in changing business models against stakeholder expectations. The role of hydrogen buses is seen as an addition to battery electric buses on technical aspects such as the expected increased range and short refueling time. Moreover, hydrogen buses are perceived as a flagship for the wider implementation of hydrogen in mobility. This thesis adds to the existing body of literature by expanding the concepts of interaction and incumbency beyond traditional views, as well as providing management recommendations for the further implementation of hydrogen buses.

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1: Introduction

With growing populations and increasing environmental concerns, sustainable solutions in the transport sector are necessary. The chance of keeping global warming beneath 2 degrees Celsius is decreasing in probability and greenhouse gas emissions persist on high levels (IPCC, 2022). The transport sector, including public transport, is responsible for a quarter of the global greenhouse gas emissions (Moriarty & Honnery, 2019). Sustainable solutions in public transport are a key element in the decarbonization of transport (Too & Earl, 2010). Buses are an efficient and widely used mode of public transport (Chang et al, 2019), providing access to activities and create value on a social and individual level (Veeneman & Mulley, 2018). There is a high energy saving potential for buses (Chang et al, 2019). Most buses have a diesel engine, which makes them contributors to urban air pollution as well as the generation of greenhouse gases. Using diesel vehicles causes health problems for people exposed to the emissions, including respiratory diseases, inflammation, and an increased risk of death (Kryzanowski et al, 2005). To decrease greenhouse gas emissions and health problems, zero-emission buses are required.

The Netherlands has taken steps towards zero-emission public transport and is pioneering in the electrification of their buses. Dutch people travel an average of 386 kilometers by bus, tram and metro each year (CBS, 2021). To meet these traveling needs, a system is in place. The Dutch public transport system consists of different regions with designated public transport authorities (PTA's). These PTA's design the requirements for public transport in their regions over designated periods of time, which are laid down in a concession. Public transport operators can apply competitively to execute this concession. The offered deliverables, budget and assets operators offer are laid out in a tender (Veeneman, 2016). The Netherlands has approximately 5300 buses for public transport, of which 24 percent was zero-emission in 2020 (Zero-emissiebus, 2023). The Dutch ministry of infrastructure and environment, together with the fourteen PTA's, signed an agreement for zero-emission regional public transport. Starting in 2025, the purchase of new diesel buses is prohibited, and by 2030 all buses in operation must be emission-free (Ministerie van Infrastructuur & Waterstaat, 2019). Most of the zero-emission buses are battery electric buses, referred to as electric buses. In addition, hydrogen fuel cell electric buses, referred to as hydrogen buses, are now driving in the provinces Zuid-Holland, Groningen and Drenthe (Ministerie van Infrastructuur & Waterstaat, 2019). The number of zero-emission buses is increasing, but the role of hydrogen buses remains unclear. Literature on the implementation of hydrogen in heavy duty- or personal transport is extensive (Hardman et al, 2013; Trencher & Edianto, 2021; Ajanovic & Haas, 2021), but there is still a research gap for the implications of the implementation of hydrogen buses.

There are benefits and disadvantages to both electric and hydrogen buses. Electric buses have zero-emissions at the tailpipe and low recharging costs. However, they do have a limited driving range, which generally lies between 300 to 450 kilometers (Ebusco, 2022). This range decreases further in cold weather due to a lower effectiveness of batteries and the need for heating in the bus (Kim et al, 2019). By using only electric buses, capacity constraints of the electricity grid could emerge, especially when all vehicles charge at peak time (Bellekom et al, 2012). Moreover, recharging electric buses is time consuming (Forrest et al, 2020). Finally, the batteries used in electric buses contain lithium. The process of extracting, producing and the disposing of lithium batteries can have negative effects on the environment (Dubey et al, 2022).

Hydrogen buses can offer a solution for some of these disadvantages. Using hydrogen can save up to 93 percent of emissions compared to diesel buses over their life cycle. They also have zero emissions at the tailpipe (Ajanovic & Haas, 2021). Hydrogen fuel cells have only been implemented on a small scale, and they are still expensive compared to electric- and diesel buses (Pyza et al, 2022). However, when implemented on a bigger scale, the hydrogen bus costs are expected to reduce (Moriarty & Honnery, 2019). Additionally, surplus electricity from windfarms or solar panels can be used to generate hydrogen, which can release pressure from the electricity grid (Moriarty & Honnery, 2019). Finally, hydrogen buses have a range of approximately 350 to 600 kilometers depending on the which is expected to increase (Solaris, 2020; Luxfer, 2022), and they take the same time to refuel as diesel buses. Both technologies have advantages and disadvantages, but the potential for hydrogen buses makes them a relevant topic to study.

Understanding the role of hydrogen in zero-emission public bus transport requires an understanding of the current system and the transition. Multiple actors spread over different sectors have a part to play in the implementation of low-carbon solutions (Falcone et al, 2021). These are all part of a system, which is defined in this research as "the collection of actors, institutions, infrastructure and policy involved in the transition to zero-emission public transport." The transition of the Dutch public bus transport system is defined as follows: "The gradual, systematic change of public bus transport in the Netherlands from a fossil-fuel based, unsustainable system towards a zero-emission public bus transport system where actors and their actions across the value chain are aligned towards the use of zero-emission technologies." The zero-emission technologies refer to electric-and hydrogen buses. The transition is subject to complex system structures and dynamics, influencing the potential of electric- and hydrogen buses.

A distinctive element of the introduction of hydrogen buses is that it does not happen in isolation, but in a system where electric buses already gained market share. Hydrogen buses and hydrogen refueling stations are not yet implemented on a large scale (Moriarty & Honnery, 2019). Literature on drivers and barriers for implementing hydrogen in heavy-duty transport is extensive (Hardman et al, 2013; Trencher & Edianto, 2021; Ajanovic & Haas, 2021), but there is still a research gap regarding the implications of implementing hydrogen buses in a system where electric buses are gaining market share continuously. Where previous research has focused on the competition between different technologies (Offer et al, 2010; Hardman et al, 2013; Ligen et al, 2018), there are more interactions in a system that go beyond competition. Some interactions could, for example, also be beneficial for both technologies, while competition merely focuses on gaining market share at the cost of other technologies. Interactions can be studied on a system level instead of solely on a horizontal level. More knowledge can be gained on the interactions of electric- and hydrogen buses by considering the system dynamics. This can lead to a better understanding of the role- and implementation of hydrogen buses in the public transport system.

Another distinctive element of the system is that it is dominated by incumbent actors who have, next to operating business as usual, also been dominant in introducing new technologies. In this research, incumbents are defined as "vested companies, institutions, authorities and governmental institutions, which are embedded in- or have an influence on the public bus transport system." This definition includes energy- and infrastructure companies, public transport authorities, bus manufacturers, operators, municipalities, regional- and national government. Incumbents played a significant role in the implementation of zero-emission buses. Incumbents often have power to change the workings of the system, and it is relevant to understand how they influence transitions (Sovacool et al, 2020). Specifically for hydrogen buses, there could be a necessity for incumbent action to enable market expansion (Ajanovic, 2021; Berggren et al, 2015). As opposed to traditional transition theories where niche actors and technologies enter the market and replace current actors and technologies, incumbents have a role in pilot projects (Bakker & Konings, 2018). Incumbents can help accelerate and implement innovation, challenging the idea that transition can only come from radical outsiders (Trencher & Edianto, 2021).

The focus of this thesis is the role of hydrogen buses in the transition to a zero-emission public bus transport system in the Netherlands. The interaction with the electric buses is explored to further investigate the system dynamics and the consequences for hydrogen buses. Moreover, the roles of incumbents in this transition are explored to understand the drivers and challenges regarding hydrogen buses for incumbent actors in the system. This leads to the following research questions:

Research Question: How do hydrogen buses fit in the transition towards zero-emission public bus transport in the Netherlands?

Sub question 1: What does the current system of public bus transport in the Netherlands look like?

Sub question 2: What are current system barriers in the implementation of hydrogen buses?

Sub question 3: How do the interactions between battery electric buses and hydrogen fuel cell buses influence the implementation of hydrogen?

Sub question 4: What are the roles of incumbents in the implementation of hydrogen buses?

Sub question 5: What are management recommendations for incumbents to accelerate the implementation of hydrogen buses?

This thesis contributes to the existing body of literature on sustainable public transport and hydrogen and creates possible societal benefits. It can be useful for incumbents in integrating hydrogen in the transition to zero-emission public transport by giving an overview of the roles that different types of incumbents have. This helps incumbents on an individual level as well as to make an informed collaboration strategy. These collaborations could improve the speed of the transition, the competitiveness of companies and the feasibility and affordability of hydrogen as a fuel. Moreover, this research can be used as an input for new subsidy schemes, for example for the new Rijksoverheid hydrogen scheme announced in 2023. This scheme provides 22 million euroes in subsidy, but the money is not yet allocated for specific purposes. The current Spuk-ZEbus scheme provides subsidy for buying zero-emission buses, but this scheme ends in 2023 (RVO, 2021). New schemes could benefit from the insights provided in this thesis regarding the barriers for hydrogen buses and the needs of incumbents. Finally, the implications of the interactions between hydrogen- and electric buses can be used by incumbents as a foundation to understand the wider implications of including hydrogen in public transport. This can help strengthen their strategies by understanding the role the technologies have.

For this research, semi-structured interviews are conducted with relevant incumbents and start-ups as well as experts on public transport or hydrogen. With the analysis of the results, implications for the implementation of hydrogen buses are provided, accompanied by management recommendations.

2: Theoretical Framework and case background

The theoretical framework consists of three elements: sociotechnical system transition, the role of incumbents in transition and the multi-mode interaction framework, which is used to analyze different types of interactions between hydrogen- and electric buses. The theories are explained, accompanied by a brief analysis of the current state of the sociotechnical system. The theoretical framework is a starting point for understanding the role of hydrogen in the transition to zero-emission public bus transport. It provides categories to classify barriers, building blocks to describe different types of interaction between electric-and hydrogen buses and categories to define incumbency as a foundation for investigating the role of incumbents in the transition. The framework offers a basis for investigating the role of hydrogen buses in the transition to zero-emission public bus transport.

2.1: A Sociotechnical system in transition

When researching transitions, taking a system approach can be useful in displaying the change processes through the complex interactions between different actors and factors. The system of public transport can be described as a sociotechnical system consisting of intertwined social and technical elements (Geels, 2002). It comprises social and technical elements related to the production, distribution and use of technology. In a sociotechnical system, certain technologies can be supported by actors and institutions, in line with the norms and rules that are in place (Geels, 2002; van Bree et al, 2010). New technologies are developed over time, which can be promising but are not yet fully integrated in the system. These technologies are called niche technologies. For system transitions to occur, external pressure as well as willingness to change are necessary (van Bree et al, 2010). These transitions are often complex and slow. For example, due to high pressure from science and society regarding climate change and the issues of fossil fuels, the energy transition started. It takes time to fully transition to renewable energy due to vested interests, high costs, infrastructure changes and the unclarity of responsibility to take action. These factors can also reinforce each other, increasing the resistance to transition and maintaining a state of lock-in. The notion of complex system interactions in the transition also applies to the public transport system, which is why a sociotechnical system approach is useful in this research.

A brief overview of relevant actors in the sociotechnical system is given to provide a foundation for understanding the complex interactions at play. The Dutch public transport system consists of all actors, objects, interactions, institutions, policies and developments that have a connection to public bus transport in the provinces of the Netherlands. This encompasses the city buses, regional transport and the long-distance lines. The industrial actors provide infrastructure, technology, energy and fuel, while bus operators compete with each other for concessions. The operators are influenced by conditions stated by public transport authorities as well as by industrial developments (Veeneman, 2016). National and local government as well as the European Union provide policy and subsidy schemes, which can have impact on all actors in the system. (Simons & Nijhof, 2020). These actors all have a role in the sociotechnical system around public bus transport and the implementation of hydrogen buses.

When systems are in transition, they can encounter several types of barriers that influence the speed and direction of the transition. In this thesis the main focus is on barriers to the implementation of hydrogen buses. Four types of barriers are established, based on literature on barriers for hydrogen in transport: supply side-, infrastructure-, demand side-, institutional barriers. These categories are based on the categories Trencher et al (2020) use in their study on the development and diffusion of hydrogen vehicles in Japan, and enhanced by Dolci et al (2019) and Kovac et al (2021). For example, creating demand and acceptance among potential users and choosing which markets to target as well as providing a network of infrastructure are challenges in hydrogen mobility. High costs for hydrogen and vehicles are also often mentioned in the literature. The categories and examples of barriers can be found in Table 1. This categorization helps in structuring interviews and identifying where barriers might be the most pressing.

Barrier category	Examples of barriers
Supply	Production issues of materials and fuels, high initial costs.
Demand	Market segmentation. creating societal demand, public acceptance.
Institutions	Barriers to collaboration, cost reduction, difficulties in stimulating investment
Infrastructure	High energy costs, establishing a refueling network, grid congestion.

Table 1 (sources: Trencher et al, 2020; Dolci et al, 2019; Kovac et al, 2021)

Understanding the barriers to the implementation of hydrogen buses in the transition towards zero-emission public bus transport is useful in facilitating a successful transition. However, the barriers do not fully consider the context of multiple emerging technologies that are competing for market share. In the next section, a framework for analyzing the interaction between hydrogen- and battery buses is therefore explained.

2.2: Multi-mode interaction framework

Interaction between hydrogen- and battery buses can go beyond competition and influence the implementation of hydrogen buses in various ways. In previous research (Bellekom et al, 2012; Moriarty & Honnery, 2019), only one emerging technology was considered for research purposes. However, two emerging technologies play a role in public bus transport. Previous interaction research in general assumes a stable environment, but the dynamic system developments in the world are described as influential by Wang et al (2023). According to Blondeel et al (2021), taking a system approach is useful in analyzing interactions. Interactions in a system can take on more forms than merely competition. Hydrogen- and electric buses are often viewed as being in competition with each other for market share (Coppitters et al, 2022; Kim et al, 2021). However, the interaction between technologies can take on other forms as well. For example, system dynamics can create situations where two technologies can positively reinforce each other.

Verbong et al (2008) add nuance to the relation between technologies through the multi-mode interaction framework, which was initially described by Pistorius and Utterback (1995). This framework states that in transitions, emerging technologies find a way to add to- or replace current technologies, going beyond the concept of competition. Sandén and Hillman (2011) have also added to the multi-mode interaction framework, stating that technologies can interact in multiple ways and on multiple dimensions throughout the value chain. This addition is important when analyzing interactions in sociotechnical systems, because they consist of multiple dimensions and value chains. The theory is based on five building blocks (Lin & Sovacool, 2020; Sandén & Hillman, 2011), which are used to describe different types of interaction and the effect on the implementation of hydrogen buses. The building blocks and the way they are used in this research are described.

1. *Directionality:* The direction of the interaction can have different effects on both technologies. Technologies can both experience negative effects from an interaction (competition), one of them can experience a negative effect and the other one is affected positively or not at all (parasitism and amensalism respectively). When one technology experiences a positive effect and the other technology is either unaffected or also affected in a positive way, this is called commensalism and symbiosis respectively. When the technologies do not affect eachother, this is called neutralism. In table 2, the different interaction directions are summarized. The directions are used to establish the possible effects of the interaction between hydrogen- and electric buses.
2. *Intensity:* the intensity and the stability of the relationship between two technologies refers to how difficult it is to change the existing interaction. This concept is used to describe the possibilities that interactions might change over time.
3. *Overlap in value chains:* technologies can be defined as a combination of value chains ranging from upstream, downstream, products and processes. These are called 'bundles of value chains'. For this thesis, this concept is used to describe where the overlapping value chains are relevant in interactions and how this influences the outcome of the interaction.
4. *Multidimensionality:* the interaction can occur on organizational-, material- and conceptual dimensions simultaneously. These dimensions can be taken into account when analyzing interactions to explain how interactions manifest in the system and how this affects both technologies.
5. *Dynamism:* the concept of dynamism entails that interactions between technologies can exist simultaneously in different dimensions and sectors. Moreover, it means that interactions are not static, but develop over time under influence of sociotechnical developments. This overarching concept gives insight in the nature of directions and creates an opportunity to analyze interactions as they develop over time.

Direction of the interaction	**Explanation**
Competition	The two technologies have a negative effect on eachother
Symbiosis	The two technologies have a posivite effect on eachother
Neutralism	The technologies don't affect eachother
Parasitism	One technology is benefited, but the other experiences a negative effect
Commensalism	One of the technologies benefits, but the other is not affected
Amensalism	One technology experiences a negative effect, but the other is not affected

Table 2: Directions of interaction (based on Sandén & Hillman, 2011)

The building blocks can be used as a conceptual foundation to establish different interactions in relation to their context. The direction is the most relevant building block in this thesis. The other four are used to describe the system dynamics and their influence on the interactions throughout the value chain. Understanding the interactions between battery- and hydrogen buses creates insight into the synergies and barriers in the transition. The sociotechnical system is reiterative: each development is a result of previous developments. It is therefore useful to take a dynamic approach to the niche interactions, which means analyzing the developments over time and not in a static manner (Hiver et al, 2017). The framework is used as a theoretical starting point to analyze the dynamic interactions across the value chains of hydrogen- and electric buses. This framework can help identify opportunities for actors in the system who are involved in implementing hydrogen buses. To understand these opportunities, the roles of incumbents are analyzed.

2.3: Incumbents in the transition

The energy transition can be an incumbent oriented transition, and according to Turnheim & Sovacool (2020), incumbents need to be engaged in low carbon transitions in general. Where incumbents were traditionally seen as blocking factors in transition, this stance is now revised and the role of incumbents is evolving and becoming more diverse than just maintaining a status-quo (van Mossel et al, 2018; Sovacool et al, 2020). It can comprise defending current technologies and promoting new technologies simultaneously (Berggren et al, 2015; Mossel et al, 2018). Incumbents can be both an active part of a regime and work on niche technologies (Steen & Weaver, 2017). Incumbents tend to be powerful, materially resourceful and politically influential. They can have influence on- and even be leading actors in the energy transition (Späth et al, 2016). Acknowledging the evolving role of incumbents is relevant for the successful implementation of hydrogen buses.

Since the implementation of zero-emission buses so far has been led by incumbents, the further implementation of hydrogen buses calls for a better understanding of the roles of incumbents. In the transport sector, incumbent actors have an ability to influence the sustainable mobility transition (Späth et al, 2016; Berggren et al, 2015). Hydrogen is a technology that requires accumulated capabilities and expertise on technological and societal issues, which are usually characteristics of incumbents (Berggren et al, 2015; Mossel et al, 2018). To explore the roles for incumbents in implementing hydrogen buses, incumbency is categorized into four dimensions. These dimensions serve as a basis for exploring the strengths, barriers and possible roles for different types of incumbents. The dimensions are not used as mutually exclusive categories, but as a starting point in exploring the different expressions of incumbency in the public transport system, and how certain elements of incumbency can strengthen- or hamper incumbents in the implementation of hydrogen buses.

Based on literature about, for example, incumbent resources (Turnheim & Sovacool, 2020), incumbent strategies and business models (Mossel et al, 2018; Magnusson & Werner, 2022) and ways of doing business (Steen & Weaver, 2017; Berggren et al, 2015), the following dimensions have been identified for incumbent actors:

Resources: Incumbents often possess accumulated resources, as well as the ability to acquire new resources necessary when moving into new directions. Accumulated resources include physical assets, financial resources, capabilities and political influence (Turnheim & Sovacool, 2020). Moreover, in transition, incumbents have the ability to acquire and develop new resources, such as skills, new employees and technological assets. They also have the ability to acquire companies that have desired innovation or information (Turnheim & Sovacool, 2020). The required level of skills and investments are often more achievable for incumbents, giving them the possibility to participate in- or lead transitions. For example, the ability to manage complex projects with accumulated experience and knowledge is an advantage. Incumbents can have political influence (Trencher & Edianto, 2021), which can help their business case and reduce uncertainty when working with new technologies.

Strategies: Incumbents often have long-term strategies based on their experience with- and perception of the system around them, as opposed to start-ups, who may have less experience with long-term strategy. The strategic goal of incumbent firms relates to the survival of the firm (Mossel et al, 2018). Strategies comprise ambitions, investment patters and choosing goals that are in line with policy and regulation, as well as aligning with the resources and capabilities that a firm or organization has. Strategies are transient in nature, which means they change over time. Changes occur due to a changing context around the form, internal dynamics or a combination of both (Turnheim & Sovacool, 2020). Core dimensions to strategies according to Berggren et al (2015) are the following: sourcing of knowledge and resources, the selection of new technologies and the scope of development and application of these technologies. The experience of incumbents with successful strategies aligned with their stakeholders can put incumbents in a good position for a transition towards more sustainable ways of doing business.

At the core of the strategy lies the business model, describing the value proposition of the incumbent. Sustainable business models integrate not only monetary-, but also social and environmental value (Magnusson & Werner, 2022). Creating sustainable business models is attractive for incumbents because it allows them to generate profits while using resources more efficiently, but it can also be challenging for incumbents to rethink their operations, organizational culture and their stakeholder relationships (Kaipanen & Aarikka-Stenroos, 2021). The business model is a crucial factor for some incumbents in staying relevant in the transition to zero-emission public bus transport, but it could be helpful for incumbents as well as a hampering factor.

Routines: Incumbents are known to have an established way of doing business, which is expressed in routines (Steen & Weaver, 2017). This is caused by the vested interests and cognitive routines of the company (Steen & Weaver, 2017), as well as the regulatory landscape that they are in, with which they must align (Mossel et al, 2018). These routines can make incumbents less flexible, depending on the nature of the routines, but they can also provide efficiency in establishing new ways of doing business. As argued by Sovacool et al (2020) and Berggren et al (2015), it is important to align new activities with the existing routines and the environment of the firm. Certain lessons and skills acquired by incumbents that evolved into routines are necessary for implementing innovative technologies. The presence of established routines may make it difficult for incumbents to quickly adapt to the changes that come with the transition to zero-emission bus transport, but the skills and lessons learned through these routines may prove to be valuable in implementing hydrogen into their business. Understanding the role of routines for different incumbents can be valuable in understanding the possible role for incumbents in implementing hydrogen buses.

Networks: Incumbents are embedded in different networks, which they have to navigate to maintain their position (Mossel et al, 2018). Their networks impose certain expectations on them, while incumbents simultaneously influence others in their networks. This can create competing interests, which they need to balance (Steen & Weaver, 2017). They can choose to engage proactively to have influence on institutions and gain competitive advantages (Turnheim & Sovacool, 2020). Networks can give an opportunity for change through collaboration and exerting influence on other incumbents (Trencher & Edianto, 2021), but it can also create a state of lock-in where the incumbent can lose its position in the transition because of the inhibition to act (Berggren et al, 2015). Through networks, incumbents can learn about new developments regarding the transition to zero-emission bus transport and collaborate on projects. However, it can be challenging to balance stakeholders when your operations change due to stakeholders and shareholders' expectations.

The four outlined dimensions provide a framework for investigating the role of incumbents in the implementation of hydrogen buses in the transition to zero-emission public transport. By using the established dimensions, different types of interviewed incumbents can be analyzed and compared on their perceived role in the implementation of hydrogen buses. Different strengths and challenges can be identified and compared, which can then be used to explore roles for incumbents and to inform management recommendations.

2.4: Summary of the theoretical approach

To analyze the dynamics of the public bus transport system and the role of hydrogen in the transition towards zero-emission, the theoretical framework is used as a starting point for further analysis of the system and the possibilities for hydrogen buses. Taking a sociotechnical system approach creates the foundation to consider all relevant actors and interactions. The barrier categories provide direction in the semi-structured interviews, which is further explained in the next section, and can provide insight into relevant areas for management recommendations. In addition, using the multi-mode framework to describe interactions can provide a broader view on the implications for the implementation of hydrogen buses. The described dimensions of incumbency are used as a basis for researching incumbents' role in implementing hydrogen buses. With this framework, this thesis aims to cover past developments as well as implications for the further development of hydrogen buses.

3: Methods

For this thesis, a combination literature research and semi-structured interviews are used, which are both forms of qualitative research. The theoretical framework is used as a foundation. This research is explorative in nature, aiming to determine the role of hydrogen buses in the transitioning system of public bus transport. Interviews are a suitable method for gaining personal perspectives and in-depth analysis through conversations. The literature research is used as a foundation for the interviews, as well as to support- and give nuance to the findings from the interviews. First, the key themes as described in the theory are operationalized. Moreover, the literature research and the semi-structured interview and analysis are discussed.

3.1: Operationalization of key concepts

In table 3, relevant concepts are defined and operationalized. This table is used as a starting point for the literature research and the interview guides.

Key themes	Definition	Operationalisaton
The public bus transport system in transition	The gradual, systematic change of public bus transport in the Netherlands from a fossil-fuel based, unsustainable system towards a zero-emission public bus transport system where actors and their actions across the value chain are aligned towards the use of zero-emission technologies.	*Literature research:* Information on key actors, the current subsidies and regulations and the workings of the concession system. *Exemplary interview questions:* - Can you tell me about recent developments in your field of work? - Could you tell me about the current regulations that influence your work? - How would you describe your role in the public transport system? - In what way are you taking part in the transition to zero-emission public transport? - How does hydrogen play a job in your role?
System barriers	The main factors that hydrogen buses in the transition towards zero-emission public bus transport in the Netherlands hamper the implementation of	*Literature research:* Literature on known barriers for the implementation of hydrogen in heavy transport and buses. *Exemplary interview questions:* - Are there current policies and regulations that in your opinion hamper the progress of hydrogen in public transport? - What is the key challenge in your job at the moment? - Are there technological/institutional aspects that might hamper the transition to hydrogen in the public transport? - Where do you feel improvements could be made to accelerate the implementation of hydrogen? What would you need?

Interactions	The interactions between battery- and hydrogen buses, based on the five building blocks as described in the multi-mode interaction framework.	*Literature research:* Overview of literature on the interaction between the two technologies, as well as literature on sociotechnical systems of both technologies. *Exemplary interview questions:* - How is your company approaching the implementation of both technologies? - Where do you see overlap in hydrogen and battery developments? - Does the fact that electric buses already gained a higher market share influence the implementation of hydrogen? - How does policy/subsidy/regulation influence the implementation of both technologies?
Role of incumbents	The roles, opportunities and challenges of the incumbents in the public transport system in the Netherlands and the implications for implementing hydrogen buses.	*Literature research:* Literature research on the developing role of incumbents in the energy transition *Exemplary interview questions:* How do you see the role of the government in the transition to zero-emission public transport? How do you see the role of incumbent/existing companies in the transition to zero-emission public transport? What other actors play an important role here and how do they participate? How did the introduction of hydrogen buses happen?

Table 3: Operationalization of key themes

3.1: Literature research

First, a primary literature research was conducted on the current state of the public bus transport system in the Netherlands. Sociotechnical transition concepts, literature on the role of incumbents and the multi-mode interaction framework are used as a guideline in the literature research. The used search engines are Google, Google Scholar, Scopus and Nexis Uni. The literature research served as a foundation for the interviews, as well as providing additional information or nuance to answers from interviewees. Using literature research helps in gaining knowledge prior to interviews and strengthens the conceptual basis (Åstedt-Kurki & Heikkinen, 1994).

3.2: Interviews and analysis

In addition to literature, semi-structured interviews are conducted to gain more insight into the role of hydrogen buses in the transition to zero-emission public bus transport.

Sampling

The interviewees were selected within connections of the researcher as well as through analysis of the relevant stakeholders in the field. A combination of purposive- and snowball sampling is used. Purposive sampling refers to the selection of individuals that are relevant to your research because of certain characteristics, such as field of work and expertise. Snowball sampling means asking interviewees if they know other actors that might be relevant to interview (Bryman, 2012). The interviewees were divided into categories, as portrayed in table 4. Some interviewees had experience in multiple categories, they are added to both categories in table 4 consequently. The interviewees were anonymized, resulting in using interviewee categories instead of names when quoting and referencing to the interviews.

Interviewee Category	**Number of interviewees**
Bus Operators	5
Public Transport Authorities	2
Energy Incumbents	4
Municipal, Regional and National Government Institutions	3
Original Equipment Manufacturers, Suppliers of Parts and Dealers	2
Start-up or R&D Companies	2
Grid operator	1

Table 4: Interviewee Categories

Semi-structured interviews

Semi-structured interviews of 30 to 60 minutes were conducted with a total of seventeen interviewees. For the interviews, an interview guide with relevant topics and some prefabricated questions based on the theory as well as the experience of the interviewee were prepared. However, the advantage of semi-structured interviews is that they are not restricted to a strict set of questions. This gave room for conversation where structured interviews might hamper this creative aspect (Bryman, 2012). Since the Dutch public bus transport system and the implementation of hydrogen is complex and dynamic, the semi-structured interview is a fitting method to obtain information (Barriball & While, 1994). It is specifically useful to explore experiences, motives and attitudes (Barriball & While, 1994), partially because follow-up questions and flexibility allow room for new insights (Kallio et al, 2016). Each interviewee brought their own experience and expertise to this research, which required flexibility and prioritizing of topics that the interviewee had more knowledge on.

A standard interview guide was created as a template for all interviews, including the themes discussed in the theory. The interview guide can be found in Appendix A. The interview guides were then adjusted specifically to each interviewee depending on their role and background, but the same general set-up was used including all topics relating to the research questions. Creating questions that are interviewee-oriented as well as open-ended adds to the quality of semi-structured interviews (Bariball & While, 1994), generating in-depth responses.

The interviews were all transcribed by the researcher and coded in NVIVO. First, open coding was used to structure the relevant answers into codes relevant to the research questions. To guide this process, a list was made with codes based on the theory. If new topics arose, new codes were created accordingly. After open coding, axial coding was done in order to place the coded pieces of text into categories (Bryman, 2012). These categories relate to the different aspects of the theoretical framework and their relation to the research questions. They were used to create an overview of relevant information for each sub question. In table 5, three examples are shown of pieces of text that were first coded openly and then axially.

Text	**Open code**	**Category**
"If the refueling station doesn't work for three days, you can't drive for three days. This fuels the discussion who should own the infrastructure."	Reliability	Infrastructure barriers
"we talk a lot. We don't always agree, but we have a different relation than most governmental institutions, we have an open book approach on many things."	Cooperation	Incumbent roles
"We collect data from all our drivers, the buses, the operation. We translate that to make the next operations more efficient".	Telematics	Interaction hydrogen-and electric buses

Table 5: Examples of the coding process

The results are structured as a contemplative narrative discussing the sociotechnical system of the public bus transport sector, followed by an analysis of the interactions between battery- and hydrogen buses and the possible implications on the implementation of hydrogen buses. Finally, the most important findings on the role of incumbents are discussed, comprising their role in the transition to zero-emission public bus transport as well as their perceived roles in the implementation of hydrogen buses.

3.4: Internship

As a part of this thesis, a seven-month internship was completed by the researcher in the commercial hydrogen mobility team of Shell in the Netherlands. The aim of this team is to implement a network of hydrogen refueling stations in Europe. The goal of the internship was to write this thesis in order for Shell as well as other interested parties to gain information on the potential role of hydrogen buses in the Dutch public transport system. Through this internship, useful connections for interviews as well as first-hand experience with an incumbent working with hydrogen were obtained. Supervision of the internship consisted of weekly meetings with the team and separate weekly meetings with the Shell supervisor. In these meetings, topics related to this thesis were discussed, as well as broader topics concerning hydrogen mobility that the team was working on. The internship was assessed through a mid-term presentation as well as an end-of-internship review and was completed successfully.

3.5: Reliability and Validity

In this section, the reliability and validity are analyzed for this thesis. The terms of Guba & Lincoln (1994) specifically designed for measuring reliability and validity in qualitative research are used as a part of the reliability and validity to provide a proper fit. According to Guba & Lincoln (1994), the terms reliability and validity imply that there are absolute truths about the social world, while the terms they use support the idea that there can be more than one truth to a social system. This aligns with the system approach taken in this thesis. Therefore, the concepts of Guba & Lincoln (1994) are used to enhance the understanding of the reliability and validity of this thesis.

Reliability is split into internal- and external reliability, which are both discussed here.
External reliability relates to the possibilities of replicating the research. Guba and Lincoln (1994) have re-defined this concept into the term 'dependability'. Dependability is difficult to establish due to changes in the system over time (Bryman, 2012), but it entails that all records should be kept of all phases of the research. For example, a part of the interview questions is

provided in the operationalization table to establish transparency and replication (De Casterl'e et al, 2012). Additionally, all interviews are transcribed so further prompting- and follow-up questions can be retraced.

Internal reliability relates to the degree of consistency among different researchers with the same data, obtaining a degree of objectivity (Bryman, 2012; Guba & Lincoln, 1994). Pre-written questions in the interview guides are phrased with the same concepts and words for different interviewees to reduce the chance of double meaning and misinterpretation. The reliability is also established by first reading all transcribed interviews thoroughly several times before coding. This way, valuable information is not missed, and it can help identifying patterns or inconsistencies in interviewees' responses (Barriball & While, 1994). First coding openly and then axially also helps with obtaining a more objective view of the responses by analyzing the codes multiple times. However, while peer feedback was used to check results, only one researcher wrote this thesis, which might hamper degree the inter-observer consistency.

To ensure the validity of this study, internal-and external validity are studied. the concepts of 'credibility' and 'transferability' are studied, which are the qualitative terms for internal- and external validity respectively (Guba & Lincoln, 1994).

Internal validity describes the match between the observations that the researcher makes with the theoretical ideas they develop. Guba & Lincoln (1994) use the term 'credibility'. Credibility is achieved by using good research practices, as well as validating findings with respondents or through triangulation. Triangulation means the use of multiple theories and validation from multiple researchers if possible. This research uses a theoretical framework consisting of three different theoretical approaches. All participants had the option of receiving a transcript of their interview to check for any faults. After completion of the research, all participants receive a copy of the thesis. This way, if any inconsistencies or faults in observation were made by the researcher, this could have been pointed out. However, there was no respondent validation prior to finishing the research. This can be seen as a shortcoming on internal validity, but it also reduces the chance of any political influence exerted on the results obtained by the researcher.

The external validity refers to the generalization of results across social settings. This is often a problem for qualitative research, since social settings can't be recreated and evolve over time (Bryman, 2012). Guba & Lincoln (1994) use the term 'transferability', stating that the use of an extensive description of the ways of working and the details of the system, other researchers have a chance to assess the possible transferability to other research areas. This thesis provides an overview of the system in the results and explains the way of working in this chapter, therefore complying to the standards of external validity.

The concepts of reliability and validity touch upon ethical themes, which are discussed further in the next section.

3.6: Ethical Aspects

There are two ethical aspects that are relevant to this research, for which transparency is important. First of all, to ensure that all participants in this study agree to the recording-, transcribing- and use of the interviews, an informed consent form was signed prior to the interview. The informed consent form can be found in the appendix. Interviewees were asked prior to the interview to state that they know what the interview is about and what their role in this research is. All interviewees were anonymized in the thesis.

Secondly, this thesis was part of a graduation internship in the commercial hydrogen mobility team of Shell, which is stated in the informed consent and again at the start of each interview. Moreover, this research is uploaded in a thesis database, and is therefore shared publicly. This is stated transparently in the informed consent form in order to give interviewees a chance to decide if there is any confidential information they prefer not to share. Complying with anti-trust laws and not sharing confidential information is an important ethical consideration, especially in a relatively new market segment such as hydrogen buses. The internship at Shell was an addition to this research in broadening the network for interviewees and getting more insight in an incumbent company. A downside could be that some interviewees might have been reluctant with sharing information, but no indication of a lack of information from interviewees was present.

4. Results

4.1: The Regional Public Transport System

To understand how hydrogen fits into the Dutch public transport system, the concession system is explained in this section. The concession system in the Netherlands came into existence in 2001, when the authority of the Dutch public transport system was divided over the regions and the operations were tendered out to private bus operators. This has resulted in all public transport now being regulated in thirteen different regions. The regions are divided over the provinces and two municipal authorities: Amsterdam and the metropole region of the Hague and Rotterdam, operated by publicly owned transport companies (Bakker & Konings, 2018). Moreover, the provinces of Groningen and Drenthe have joined forces in 2004 by founding OV-Bureau Groningen Drenthe, therefore becoming one region instead of two (OV-Bureau Groningen Drenthe, 2021). A visualization of the regions can be found in figure 1. The regions are governed by public transport authorities (PTA's), who decide on the public transport requirements for the region. These are stated in concessions, describing the necessities of (a part of) the region over a set period between 8 and 15 years (Veeneman, 2016). Bus operators can respond to this concession by putting out a tender, explaining how they would operate the concession, what materials are used and what the costs are. This is a bidding process, where points can be obtained for cost efficiency, kilometers of public transport offered and the level of service. Moreover, fulfilling zero-emission requirements generates points. The PTA's then decide which operator gets to execute the concession, and are also responsible for checking regularly if all the agreements are fulfilled (Interviews operators and PTA). After a concession has been awarded to a party, the concession period starts approximately one year later. The length of concession periods is not the same for all regions, resulting in different concessions coming to the market at separate times. This results in ongoing competition between bus operators over multiple concessions simultaneously.

Since the zero-emission agreement of 2016, all tenders must show compliance to the zero-emission requirements from 2025 onwards by not introducing new diesel buses to the market. This resulted in a different appreciation in the tender process. Where previously cost efficiency and level of service were the most important aspects to earn points on a tender, zero-emission requirements are becoming equally important and PTA's allocate points to it since 2020 (Veeneman, 2016; Interview operator 4). Moreover, the concession period has been extended with two or three years in some regions during the COVID-19 pandemic, to properly prepare for the implementation of zero-emission vehicles and to reorganize the geographic division of the concession (Crow & DOVA, 2020). This resulted in some operators changing parts of their fleet to electric vehicles during these concessions (Interview operator 2). Zero-emission buses are more expensive than diesel buses, and it takes more time to depreciate the costs. Extending concessions can help decrease the total costs of ownership. Traditionally, operators acquire all assets, including buses. When changes are made during concession, PTA's and operators increasingly share costs, and PTA's increasingly assume roles in applying for subsidies to cover these costs (Bakker & Konings, 2018; interview operator 1 and PTA). This shows that the system is undergoing changes to facilitate the implementation of zero-emission vehicles.

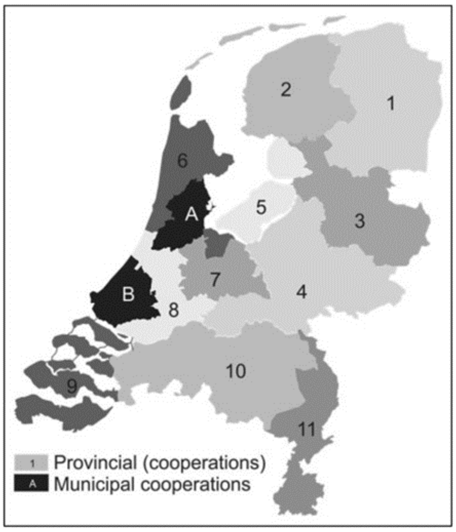

Figure 1: Overview of the public transport regions (Veeneman, 2016).

With the 2016 agreement in to aim for zero emissions in public bus transport in 2030, the introduction of zero-emission buses started. In 2016, the first electric buses were introduced. The Netherlands has approximately 5300 public buses (Monitor ZE Bussen, 2023), of which most are still diesel buses. According to all operators, diesel buses are reliable, they have a long range and operations are relatively easy to manage. The shift to zero-emission buses requires more flexibility. Charging- and refueling must be managed due to shorter ranges and when zero-emission buses are not completely dependable due to technical issues, back-up diesel buses are still necessary according to some operators. This makes the costs higher and operations more complex. In 2021, 24% of all buses were battery electric, while less than 1 one percent of the bus fleet consists of hydrogen buses (monitor ZE bussen, 2023). Figure X shows the division of different types of zero-emission buses across the regions in the Netherlands. These numbers illustrate a rapid growth of the market share for zero-emission buses, but some difficulties remain, especially for hydrogen buses. In the next section, the hydrogen developments and barriers are discussed.

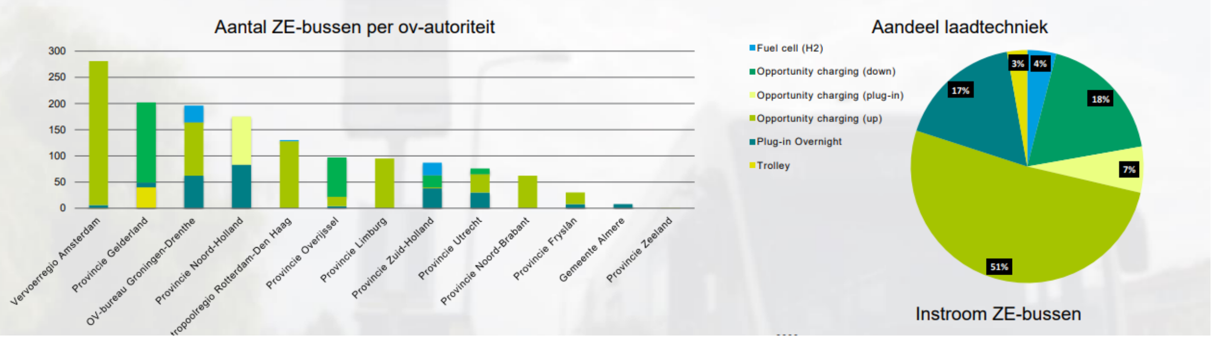

Figure 2: distribution of zero-emission buses across the different regions (copied from: Monitor ZE Bussen, 2023).

4.2: Hydrogen dynamics and system barriers

In this section, developments around hydrogen buses and relevant system barriers are discussed.

The introduction of hydrogen buses

The developments regarding the introduction of hydrogen buses are briefly described to establish the current state of the market and as a starting point to discuss barriers to the large-scale implementation. In 2014, the ministry of infrastructure and water management enabled five pilot experiments with 12 hydrogen buses in Groningen, Zuid Holland, Gelderland, Noord-Brabant and MRDH. In 2019, a cooperation agreement was signed by Zuid-Holland, OV Bureau Groningen Drenthe and INW to implement fifty hydrogen buses in the Netherlands. The developments have resulted in a total market share of approximately 1% for hydrogen buses in the Netherlands. This means that of all zero-emission buses in the Netherlands, 4 percent are now hydrogen buses (Monitor ZE Bussen, 2023). In 2020, there were four public hydrogen refueling stations for buses and other heavy-duty vehicles. These are owned by Airliquide and Pitpoint (Pitpoint, 2018; H2Platform, 2020). Another station opened in Heienoord, owned by Everfuel (Everfuel, 2023) and used by Connexxion buses. Finally, there are stations in Groningen and Emmen, which are owned by Shell (Shell, 2021). The station in Groningen is based on the grounds of Qbuzz, who use this station privately for their hydrogen buses. This means there are now 56 hydrogen buses in the Netherlands (Monitor ZE Bussen, 2023), who refuel mainly at two private sites and have the opportunity to refuel at nearby public sites.

To understand the developments of hydrogen throughout the value chain, the different ways of producing hydrogen are explained. Three different ways to produce hydrogen are discussed, which are generally labeled using different colors: green, blue and grey. When hydrogen is labeled as ‘green’, this means that hydrogen is produced through electrolysis with renewable energy sources such as wind and solar. Grey and blue hydrogen is produced using natural gas and steam. In this process, CO2 is generated. Blue hydrogen is produced the same way as grey hydrogen, but it includes the capturing and storage-or use of the emitted CO2 (TNO, z.d.). Green hydrogen is the preferred option for buses due to the lack of CO2 emissions during production and the use of renewable energy sources. Green hydrogen is still scarce, but new projects are developing. For example, a new 200 MW electrolyzer is under construction in Rotterdam, which is the biggest electrolyzer in Europe so far (Shell, 2022). Green hydrogen in the transport sector is gaining importance on national and European level. In the European Renewable Energy Directive it is stated that green hydrogen can be directly used to meet the standards for zero-emission transport (European Commission, 2023a; Jetten, 2022). The developments in green hydrogen and the accompanying policy show commitment to the use of green hydrogen in transport and are designed to support the scale-up of hydrogen mobility.

Understanding the commitment to hydrogen to transport in the Netherlands requires further knowledge of subsidies and regulations relevant to the implementation of hydrogen buses. Subsidies and regulations are adapting to implementing hydrogen in mobility with a focus on reducing costs and expanding infrastructure. On the European level, the JIVE-1 and JIVE-2 projects together partially facilitated the implementation of 290 hydrogen buses before 2022 in Europe with a total budget of 57 million euros (Waterstofmagazine, 2022). The long-term goal is to bring down the price of hydrogen buses significantly through the scale-up of production. Not only subsidy, but also regulation on a European level is developing. The new regulation for the deployment of alternative fuels infrastructure (AFIR) states that a hydrogen refueling station is to be deployed from 2030 onwards at every 200 kilometers along the European TEN-T core network as well as in significant urban regions in Europe (European Comission, 2023b). On a national level there are specific zero-emission bus subsidies, called the Spuk-ZE bus subsidies. The total budget is 40 million euros, granting 75,000 euros per hydrogen bus with a minimum of 10 buses per susbsidy application (RVO, 2022). This subsidy is replaced by a new hydrogen mobility subsidy scheme, with a budget of 22 million euros which still has to be allocated. However, the focus is on heavy transport and hydrogen refueling stations (Ministerie van Infrastructuur en Waterstaat, 2022). Moreover, in the Netherlands, there is a system in place where credits can be gained for every Gigajoule of renewable energy that is directly delivered to reduce emissions in mobility. Every Gigajoule is worth one renewable fuel unit, called 'HBE'. The HBE's can be earned by registering with the emission authorities in the Netherlands, and they can be traded in the market. Green hydrogen is also eligible to generate HBE's (Nederlandse Emissieautoriteit, 2021). This could have a positive effect on the hydrogen price if it is created with renewable energy, but uncertainty prevails around the future worth of these HBEs. As one dealer active in hydrogen buses states: *"I heard that HBE's can make a difference of 6 or 7 euros per kilogram of hydrogen, that could affect the business case significantly… However, I would like to know more about how it works".* These recent policy developments show promise for the development of hydrogen buses, but it is not the only contributing factor to a successful implementation.

Incumbents involved with hydrogen buses stress the need for learning to work with hydrogen early so scaling up is easier, while also highlighting the need for a high drive to work through the complexities. Bus operators who are not yet using hydrogen buses claim they see importance in learning to use it, but also state that choosing hydrogen buses depends partially on the preference of the PTA. Operator 3, for example, would be interested in using hydrogen buses, but the occasion to start with hydrogen simply has not occurred yet. For the parties active in hydrogen right now, a few highly driven incumbent actors combined with incentive from the government play a significant role. An interviewed PTA states that he has pushed for hydrogen for a long time despite pushback and a lack of existing infrastructure. This resulted in a public tender to build a refueling station on their site, which was won by an interviewed energy incumbent. Within this energy incumbent, multiple interviewees underlined the complexity of the project, but also stress the importance of the drive to improve on both sides of the deal to create collaboration opportunities for hydrogen buses and refueling stations. Learning to deal with complexities now can provide a foundation in future projects and decrease the costs through scalability, as well as increase the competitive advantage of the companies involved. While there is a growing interest in hydrogen and hydrogen buses across the value chain, the implementation has not yet occurred on a large scale due to various factors. In the next section, the main barriers to the implementation of hydrogen buses are discussed.

Systematic barriers to the implementation of hydrogen buses

This section gives an overview of the main systematic barriers to the implementation of hydrogen in the bus sector. In chapter 2, categorized examples of barriers were given based on Trencher et al (2020), Dolci et al (2019) and Kovac & Marcius (2021). The barrier categories are used as a basis to elaborate on the system barriers that interviewees encounter. These partially overlap with the examples of barriers given in the theory, but this section provides more details for the barriers specific to hydrogen in the public transport system. These barriers are used as input for analyzing the interaction with electric buses as well as the role that incumbents can play in implementing hydrogen.

First of all, a growing concern among more than half of the interviewees, especially among the operators, is the availability- and high price of green hydrogen supply and hydrogen refueling stations. When using hydrogen buses, green hydrogen is the preferred option for most interviewees. In the public bus sector, high costs are an issue because these are partially paid with public money. Partially due to a persistent decrease in the number of travelers since the COVID-19 pandemic, according to the interviewed operators and PTA's, revenues are still lower than before the pandemic. Operators and PTA's agree that the higher costs accompanying zero-emission developments should ideally not be charged to travelers. In addition to a lower number of travelers, energy prices have gone up significantly, which is partially due to the ongoing war in Ukraine (Interviews operators and energy incumbent). When making green hydrogen, renewable energy is used. Because of a conversion rate and energy loss, more energy is needed for creating hydrogen than for direct use of electricity in batteries (Interview energy incumbent). This results in a relatively higher increase in price for hydrogen than for the direct use of electricity. The remaining uncertainty about the number of travelers and the price of hydrogen makes some operators and PTA's financially risk averse, which is a barrier for implementing hydrogen buses. Linked to these issues is the lack of available hydrogen refueling stations. The complexity of obtaining private refueling stations or finding reliable public stations nearby is perceived as a barrier for all interviewed operators working with hydrogen. Building hydrogen stations is costly and obtaining the right permits is time- and resource intensive according to operators and energy incumbent interviewees. There is only a small number of refueling stations available for buses, and some operators prefer to have a refueling station on their own site to save time and operational costs. Overall, the high cost and limited availability of green hydrogen and hydrogen refueling stations present a significant obstacle on the supply- and infrastructure side for the implementation of hydrogen buses.

A second barrier is the high price of hydrogen buses as well as the availability of the preferred type of hydrogen buses are perceived as a barrier. Zero-emission buses are more expensive due to new technology and a lack of scale in production. Moreover, the energy- and material prices have gone up since the war in Ukraine according to interviewees. This has a negative effect on the affordability of hydrogen buses. There is a specific zero-emission bus subsidy in place until the end of 2023, called the Spuk-ZE bus. This subsidy consists of 40 million euros in total, covering 75,000 euros per hydrogen bus, with a minimum of 10 buses per subsidy request (RVO, 2022). However, according to operators, this still does not lower the costs of the hydrogen buses enough to compete with electric-or diesel buses. The buses currently on the market are working really well according to operator 1. Operator 5 has experienced technical failure with the hydrogen buses and can only use 50% of them*: "At this moment, I don't see the benefits yet, unless they are used for large distances where there is, well, no opportunity to stop and take the time to charge"*. It is common for new types of vehicles to experience some technical difficulties, but this is not the main barrier for operators to buy the buses. As stated by a significant part of the interviewees, the use for hydrogen buses is perceived to be the long-distance lines where the range of electric buses might be a problem and recharging takes too long. The preferred type of buses to typically operate this line, the regional buses and the touring cars, are entering the market in 2025 or 2026 (Interview hydrogen bus dealer and operators). This is too late for operators to include them in some upcoming concessions. The availability of the buses and their high price are therefore important barriers on the supply- and demand side.

A third barrier concerns the rigidity of the concession system and the lack of flexibility this creates for new technologies such as hydrogen buses. The first issue is the short implementation time for operators after obtaining a concession. In the current system, an operator has approximately one year to acquire all assets and have the bus operations running. A separate tender process is started for the build of the hydrogen refueling station, which takes time. After the build of the station is appointed, according to an energy incumbent, it can take more than the regular 32 weeks to obtain a building permit for hydrogen refueling stations. The safety region as well as the environment service have strict requirements and the public can also ask questions. A previous bus station built by an energy incumbent required intense safety assessment due to the lack of knowledge and experience with hydrogen refueling stations in the Netherlands. As one energy incumbent interviewee stated: *"Better safe than sorry. It did lead to longer and longer time to obtain the permit, having the firefighters come visit, the safety region, looking at the drawings again... It took us more than 40 weeks to obtain the permit and build the station"*. the one-year period between the tender and the start of the concession might not be suitable anymore without the proper support from PTA's. A second issue relates to the length of the concessions and the lack of flexibility for implementing zero-emission vehicles. Moreover, despite some concessions being prolonged during the COVID-19 pandemic, most concession periods remain unchanged, creating a lower financial incentive for hydrogen due to longer cost depreciations (interview operator). As one PTA states*: "I would have liked to see that a substantial part was hydrogen. But with the concessions, a window like that closes for 10 to 15 years".* It is usually the role of the operator to obtain all assets including the buses. It is difficult to change during the concessions. As one PTA states*: "it's not even allowed to change things officially, so if you do that during a concession, the order of magnitude has to stay the same as in the original contract."* One interviewee from an energy incumbent adds to this*: "Either the operators are seen as the one to solve it (zero-emission), or the other way around, the operator looks to the PTA who wants all these energy transition things. But you need both of them".* There are high expectations from operators which are difficult to meet due to uncertainty and high costs. According to many interviewees including operators, a municipality and a PTA, the lack of flexibility in the concession system is perceived as a barrier for the implementation of hydrogen buses.

The fourth barrier that came forward in the interviews is the way national government provides incentive for demand of- and investment in hydrogen. This is a combination of a supply-and institutional barrier. One way to provide incentive is by allocating subsidies. The national government has allocated 22 million euros towards a new hydrogen subsidy scheme for hydrogen refueling stations and trucks, but the exact allocation of this money still remains unclear (interview RWS, Ministerie van Infrastructuur en Waterstaat, 2019). The high prices for hydrogen could be subsidized in a similar way to the LNG subsidy scheme. This subsidy scheme provided a lowering of the price with 0.187 euros per kg LNG from 2020 until 2022 (Overheid wettenbank, 2022). According to operator 5, attempts have been made by a combination of parties to obtain a similar subsidy scheme. However, national government has declined this call on the premise that subsidies per kilogram of hydrogen are not allowed in the Netherlands (Interview operator 5). According to an interviewee at the national government, it is unclear why this call was declined. Most operators agree that a subsidy on the hydrogen price would bring down the total cost of ownership for hydrogen buses, and therefore increase incentive to use them. Moreover, an energy incumbent stresses the need for higher subsidy to reduce the price of hydrogen buses to create demand and scale up supply.

As an opposing view, operator 2 and a supplier of parts state that the subsidy phase might already be over, and the implementation of hydrogen is not furthered by more subsidies. They argue that subsidies are used to support an upcoming market, but the market now must function on its own. Dolci et al (2019) and the other interviewed incumbents however argue that hydrogen will only develop with appropriate regulations and subsidy. Next to subsidy, clear and fitting regulation is also necessary. The safety restrictions regarding hydrogen refueling stations are not always clear and according to bus operator 5, a national approach to safety regulation would be beneficial, especially when battery- and hydrogen buses are recharged and refueled on the same terrain. Currently, regional authorities are often involved. Safety regulations are sometimes seen as excessive as well as unclear, resulting in a barrier to engage in hydrogen projects. Because of the lack of clarity on regulation and the lack of fitting subsidy schemes, the lack of stimulation from the national government is still perceived as a main barrier by most interviewees.

In table 6, an overview of the four main barriers can be found. Following on that notion, regulation and subsidies for hydrogen are often not created in isolation from the market. To investigate this further, the interactions with electric buses must also be explored.

Barrier	**Type of barrier**
Lack of green hydrogen & hydrogen refueling stations	Supply & Infrastructure
Availability and costs of hydrogen buses	Supply & Demand
Rigidity of the concession system	Institutional
Lack of stimulation from the national government	Institutional & Demand

Table 6: Overview of the main systematic barriers in implementing hydrogen buses

The described barriers are specific to the implementation of hydrogen buses and add to barriers to the implementation of hydrogen already found in literature. The specific system interactions creating barriers for the implementation and scale-up of hydrogen buses were analyzed. It should however be considered that the implementation of hydrogen buses does not happen in isolation. To obtain a complete view on the possible role of hydrogen, the entire system needs to be taken into account. As stated previously, electric buses have a significant market share already and there are implications to entering a changing market where another technology already gained a market share. In the next section, the interactions between the two technologies and the implications of these interactions on the possibilities for hydrogen buses are discussed.

4.3: Interaction between electric- and hydrogen buses

There are three main interactions established from the interviews that influence the role of hydrogen buses in the Dutch public transport. The multi-mode interaction framework serves as a foundation to describe the direction of the interactions and the implication for the implementation of hydrogen buses. The described interactions are all three dynamic interactions over time, which occur on multiple parts of the value chain simultaneously. The multi-mode interaction framework supports the notion of dynamic interactions that go beyond horizontal competition and gives the opportunity to describe the context of the interaction and how developments over time influence these interactions. In this section, the interactions, their direction and the influence on the implementation of hydrogen buses are discussed.

Grid congestion

First of all, a theme that campe up in all interviews, is the influence of grid congestion on the implementation of electric-and hydrogen buses and on the energy transition in the Netherlands as a whole. There is congestion of the grid in multiple parts of the Netherlands, which is shown in figure X. This means that new connections to the grid might not be possible anymore soon in some regions. This is an issue for the increase in electric buses. Electric buses run on batteries, which require electricity. Electric buses often charge at the same time at a depot, which requires are large grid connection. Obtaining such a connection is becoming increasingly difficult and it can take more than the usual time to obtain a connection due to a high pressure on grid operators. The grid connection required to operate a hydrogen refueling station is significantly smaller due to lower energy needs to run a station as well as the lack of a peak in electricity use, which is seen with charging electric buses.

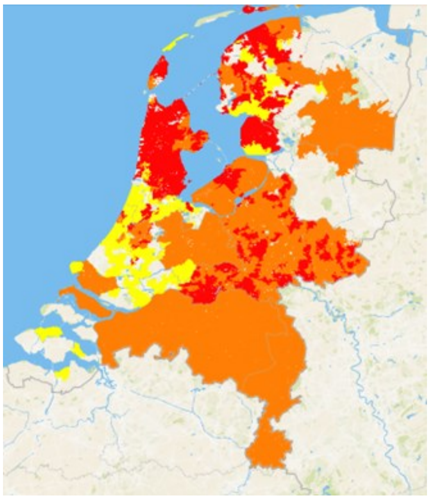

Figure 3: Overview of grid congestion in the Netherlands. Yellow: limited grid capacity. Orange: awaiting congestion management, limited- or no grid capacity. Red: no grid capacity, no congestion management available (Copied from: Netbeheer Nederland, 2023).

Concerns about grid congestion are rising among the interviewed bus operators, but the issue is not yet urgent enough to stop implementing electric buses. The grid is being expanded gradually to accommodate the energy transition, but as stated by an interviewed grid manager, it is challenging since there is shortage of supply and workers. Regional government helps with obtaining grid connections even before concessions are given out (Interviews operator 1 & energy incumbent), which can lead to a potential state of lock-in. Once the grid connections are obtained and electric buses can be charged at the depot, there is less incentive to switch to hydrogen buses. According to national government as well as an interviewed grid manager, there is not yet a pro-active policy in place to deal with further congestion, which touches upon a wider social issue. Grid connections are now obtained through a first-come first-serve system. This neglects the wider implications of claiming space on the grid without prioritization and disregarding other urgent needs for electrification in the energy transition. Operator 3 acknowledges this problem: *"What will stand in our way, is net congestion. I can solve that for my operations, but then I create problems for someone else."* Many incumbents see the policy and actions of the national government and grid operators as reactive and insufficient to deal with grid congestion. Interviewees from an energy incumbent point out that for bus transport, hydrogen is an alternative, while other sectors may not have that option. This increases the incentive to look for solutions including hydrogen buses when grid congestion persists.

The interaction between hydrogen- and electric buses due to grid congestion manifests in a continuing growth in electric buses as long as the grid can support it. This can create a lock-in effect, where the need for hydrogen buses can decrease. The direction of this interaction is amensalism, meaning that no policy in place for grid connection preference results in business-as-usual for battery buses, but has a negative effect on the growth of market share for hydrogen buses. However, as soon as grid congestion becomes a problem in a region and bigger grid connections can't be obtained to charge a larger part of the fleet, the effect could turn into parasitism, where hydrogen buses can be implemented on a larger scale due to grid congestion, while the market share of electric buses could go down due to a lack of grid support. The direction and intensity of this direction highly depends on simultaneous dynamics such as the developments in policy and grid expansion.

Navigating global events and political turmoil

Global events such as COVID-19 and the war in Ukraine can cause uncertainties that influence the implementation of electric- and hydrogen buses in the Netherlands. First, due to COVID, there has been a decrease in passengers in the public buses. While this was partially taken care of with financial support from the government (Interview national government, operators and PTA), there are still less passengers than before the pandemic, resulting in lower income and less money to invest for bus operators. This can result in conservative financial decisions. Since hydrogen buses and refueling stations are still more expensive than battery buses and grid connections, this can negatively affect the hydrogen bus market share.

Moreover, electricity and gas prices have risen significantly, which is partially due to the war in Ukraine (Wang et al, 2023; Interviews incumbent energy company). This has resulted in higher total costs of ownership for battery buses and an even higher total costs of ownership for hydrogen buses. According to an energy incumbent interviewee, the production of the currently used hydrogen uses gas and electricity, which have both seen increases in price. This makes it more expensive to use hydrogen compared to using electricity directly in electric buses. Operator 2 commented on the influence of global events on his operations: *"The biggest challenge, that has everything to do with the fast changing world. If you think you're good at something, like hydrogen, well, great. Then the war in Ukraine comes. Everything influences the price of hydrogen, which makes the business case turn negative".* With the zero-emission goal set for 2030, investments decisions are made now to obtain short-term profit and long-term emission reduction. With the increased uncertainty due to global events, electric buses remain the cheaper option which is attractive for operators and PTA's.

External developments can cause turmoil across the value chain of both technologies. However, the interaction effect generated by global events such as the pandemic and the war in Ukraine affect hydrogen buses more severely. This is due to a larger increase in total cost of ownership as well as a higher sensitivity to change for new technologies. There is confidence in the sector that the zero-emission goal is feasible, but the uncertainties together with the approaching deadline has so far led to decisions that are best for short-term profit, which are electric buses for now. External events decrease the incentive to implement hydrogen buses, while the market share of battery buses increases. This could imply the interaction direction is amensalism, where hydrogen buses experience a negative effect, while the developments around battery buses might remain the same as they would have been without COVID and Ukraine. However, with global events remaining difficult to predict and interpret, the interaction could change over time depending on the influence of future events on various parts of the value chain.

Implicit support for electric buses

A theme that influences electric- as well as hydrogen buses on multiple parts of the value chain is the policy and steer from the national and regional government. A lack of stimulation for hydrogen buses was already briefly discussed in chapter 4.1, but in this section the implicit support for electric buses and the influence of broader policy and regulation on the implementation of hydrogen buses is discussed. First, the way the government steers and supports hydrogen developments is connected to the policy approach regarding grid congestion. Both lack clear long-term goals, but the lack of clarity according to interviewees means that electric buses remain the best option for operators. A dealer for hydrogen buses says: "*PTA's don't steer towards battery electric, but they do prepare for it. They sometimes find new bus depot locations, and as for a grid expansion, but they often don't look at the hydrogen option at all*". This also becomes clear from the way tenders are framed towards favoring electric buses. Grid connections are in some cases obtained before the tender becomes public, while obtaining hydrogen stations, in most cases, remains the responsibility of the operators within a short timeframe. An interviewed PTA commented: *"When choosing hydrogen, not only is hydrogen itself more expensive, but you also need to invest in refueling infrastructure. But if you choose battery electric, the piece of the grid expansion is thrown out. They will become societal costs, and we have* *no idea how big they will be".* This touches upon a wider societal issue: interviewees fear that a lack of policy regarding wider energy transition issues might generate societal costs in the future, while technologies such as hydrogen can partially prevent this from happening. This lack of steer towards hydrogen and implicit steer towards using electric buses results in incentive for investing in electric buses.

The reason for the national government to not actively favor technologies results from the notion that the government trusts market mechanisms to bring down prices and create a level playing field (Bakker & Konings, 2018). However, choosing not to have policy in place to support hydrogen buses and insufficiently dealing with issues such as grid congestion comes with the risk of delayed or even deferred investments by incumbent companies (interviews energy incumbent). In other countries, for example Germany and France, the policy in place creates more favorable conditions to invest in hydrogen infrastructure, mostly through subsidies on investment costs (interviews operators and energy incumbents). Better conditions elsewhere could motivate incumbents working with hydrogen to invest in hydrogen projects in other countries (Janipour et al, 2020; Interview energy incumbent). Therefore, a broader policy with clear goals, mandates and subsidies regarding zero-emission mobility is necessary according to interviewees. A municipal authority supports this: "*what we structurally miss from the national government, is the lack of control and direction. There is no structure where the different governmental institutions hold each other accountable and say: we will do this together".* An interviewee from the national government states that he agrees with the need for broader zero-emission mobility policies and is working on bringing relevant parties together throughout the value chain. However, due to the approaching 2030 zero-emission goal, clarity and steer might come too late.

The interaction of policies that affect both technologies have a direction of parasitism. This entails that electric buses gain a market share, while hydrogen buses lose potential market share due to an implicit steer in national policy as well as choices made by regional authorities.

Overlap in the use of digitalization

Regarding the digitalization that is used for both technologies in the operation, there is an overlap for electric-and hydrogen buses. Both require a more detailed planning and operations due to the smaller ranges compared to diesel buses and potential failure in infrastructure. Especially recharging and refueling needs to be planned out much more carefully than for diesel. With electric buses, many interviewed PTA's and operators have gone through a learning curve. Additional assets and human resources were acquired to optimize the system, and all operators in the Netherlands now have experience with the operations. Most operators and PTA's can access real-time information from their buses to charge battery buses efficiently, keep track of battery status and to manage planned routes. Using real-time monitoring systems is called 'telematic monitoring equipment', or 'telematics'. With the use of telematics, operational costs go down and efficiency of operations improves. The use of telematics can ensure reliability, prolong the lifetime of the vehicle, and potentially manage insurance costs by providing data (Humphries, 2022; Knowles & Baglee, 2014). Not only for battery buses, but also for hydrogen vehicles it is a promising development (Humphries, 2022; Interviews with operators).

The learnings obtained by using telematics for electric buses largely overlap with the knowledge necessary to work with telematics in hydrogen buses. According to operators already using hydrogen buses, the telematics are less complicated than those for battery buses. Consequently, the need for new information and employees is low for using telematics hydrogen buses. This way, telematics can be used for electric- and hydrogen buses simultaneously, making it more convenient for operators to use both types of buses in their fleet. Both technologies benefit from the developments around telematics, implying that the direction of this interaction is commensalism. Hydrogen buses are benefiting from the developments of telematics in electric buses, and by using them in both technologies, the entire operation becomes more efficient, therefore positively affecting electric buses simultaneously. This could lead to more convenience in the implementation of hydrogen buses.

The described interactions show that interaction between technologies in the same system can go beyond competition and are influenced by system developments. The interactions also show that many incumbents come across interaction between electric- and hydrogen buses on various parts of the value chain. The interactions are summarized in table 7. A part of the described interaction has a possible negative influence on the implementation of hydrogen buses. Together with the barriers described in 4.1, this creates challenges and possibilities for incumbents in implementing hydrogen. In the next section, the role of incumbents is described in more detail.

Interaction	**Interaction direction**	**Implication for hydrogen buses**
Increasing grid congestion influences possibilities for both electric-and hydrogen buses	Amensalism	Pro-active steer to obtain grid connections for electric buses gives hydrogen buses a disadvantage, but: areas where grid congestion is too high, hydrogen buses could gain an advantage
Navigating political turmoil and uncertainty due to global developments.	Amensalism	Uncertainty and changes affect hydrogen buses more than electric buses because hydrogen is already more expensive.
Implicit support for electric buses	Parasitism	Support for creating a hydrogen market is not perceived as sufficient for implementation. Electric buses gain market share due to the slow developments in hydrogen in approaching the 2030 zero-emission goal.
Overlap in learnings regarding digitalization	Commensalism	Learnings from digitalization and the use of data and telematics in operations and maintenance of electric buses can be transferred to the use of hydrogen buses. This gives hydrogen buses a steeper learning curve, lower additional costs and make operations for both buses run more efficiently.

Table 7: Overview of interactions between electric- and hydrogen buses

4.4: The role of incumbents in the implementation of hydrogen buses

From analyzing the barriers and interactions, three aspects in which incumbents can take up roles in the implementation of hydroben buses: ‘vested networks and increased collaboration’, ‘changing strategies and new business models’ and ‘scaling up through set routines’. The dimensions of incumbency, as set out in the theoretical framework, are used as a foundation for explaining why incumbents are suited for these roles. Interviewed incumbents in the system consist of the following categories: energy-, hydrogen- and infrastructure companies, public transport authorities, bus manufacturers, bus operators, municipalities, grid operators and regional- and national governments and policymakers. Investigating the potential roles of different types of incumbents creates an integrated view on the strengths of, as well as challenges for, incumbents in the implementation of hydrogen buses in the Netherlands.

Vested networks and increased collaboration

A topic that was frequently mentioned as a strength of incumbents by interviewees is the strength of vested networks, resulting in collaboration throughout the value chain. An overarching theme in the described barriers for hydrogen buses is the high costs for hydrogen projects. In the interactions, it became clear that external factors can increase uncertainty, which makes hydrogen buses vulnerable. Navigating uncertainty and high cost requires collaboration on different parts of the value chain, from the production of new buses and hydrogen up to the end-use by operators.

Collaboration between different incumbents occurs throughout various parts of the value chain, improving the position of incumbents in implementing hydrogen buses. Increased cooperation between PTA's and bus operators is seen with hydrogen projects, including increased cooperation on funding for pilot hydrogen projects as well as collaboration on implementing innovative changes during concessions. Operator 3 explains how this has developed over time: *"Especially between 2010 and 2020, the PTA's started joining the conversation for the first time. And now it's not as much as it was, but it's still there".* Operator 1, who works closely with a PTA on the implementation of hydrogen buses, adds: *"We always look at opportunities for, for example, funding together. How can we stimulate innovation from a partnership?"* He also noted that collaboration and conversations with other parties, such as the grid operators, are taking place around grid congestion and hydrogen. Moreover, for example, bus operator 1 is increasingly collaborating with the bus manufacturer on different aspects of the bus, including the access to data*. "When we go to bus suppliers, we don't just buy a bus, we tell them what happens if you sell us a bus. We help them with the aftersales aspect, which often isn't there"*.

Hydrogen bus projects require having a network across the value chain to maintain a strong position while dealing with uncertainty. Partnerships between operators, PTA's and energy incumbents, for example, are complicated, but according to an energy incumbent, it is essential to not begrudge the other parties, to have patience and to allow everyone their share in the project. The PTA involved in the same project as the energy incumbent states: *"You have to work with people who like the process. It's not always fun, but this is a crucial success factor".* Within the interviewees, public incumbent actors such as PTA's are often seen as driving forces behind hydrogen projects, giving them a leading role in collaborations. A new type of collaboration is proposed by many interviewees including operators and energy incumbents, which entails sharing a hydrogen refueling station between hydrogen buses and hydrogen trucks, as opposed to having refueling stations on bus depots. This could strengthen the integrated position of hydrogen as a zero-emission fuel, decreasing the initial investment costs for operators. The described collaborations show that incumbents who have a network across the value chain based on partnership and trust have a stronger position to implement hydrogen buses, assuming roles for incumbents in maintaining partnerships and using their vested networks for innovative purposes.

Additionally, the lack of steer and incentive from the national government as well as the complexities in providing a network of hydrogen refueling stations requires the combination of knowledge to produce solutions. Within the national government, knowledge is seen as an important driver for hydrogen in mobility (Interview national government). One interviewee for example wants to bring incumbent and start-up actors across the whole value chain together for knowledge sharing around hydrogen mobility. There is a role for national as well as regional authorities to bring together all relevant parties and share knowledge, within incumbent actors as well as between incumbents and start-ups.

Changing strategies and new business models

As stated in the interactions, data-driven operations and new ways of working to implement hydrogen are becoming more prevalent, influencing the business models of different types of incumbents. Three types of incumbents are discussed to explore the changes in their business models and their roles in implementing hydrogen accordingly.

Bus suppliers are finding ways to double production of hydrogen buses, which requires risk-taking and new assets. A supplier of parts adds to that: *"The last few years there has not been a single diesel bus delivered in the Netherlands, they have all been zero-emission. So that is a development we see, and we are prepared to, for example, repair those components".* The way bus manufacturers develop their business model adds value to the entire system and helps overcome the barrier relating to the supply of hydrogen buses. However, according to operators, the bus manufacturers are often start-ups. For incumbents, a potential role is to take on the scale-up of technologies provided by start-ups.

For operators, two developments are important. First, they are increasingly becoming data-driven companies. As stated in the interactions, data-driven operations and telematics are increasingly implemented in zero-emission buses. Employees with knowledge on data are necessary, as well as operation planners with knowledge of the technological aspects of batteries and fuel cells. Operator 1 has scaled up from ten to fifty IT-, data- and business analysts. Some operators acquire employees who are familiar with the energy market and the purchasing and selling of energy. Operator 5*: "We have one person focusing on this entirely. It's way more important now".* Operator 1*: "we are becoming a company active with electricity as well. Sort of like a dealer, this is a next step. You could turn it into profit".* The profits made from this new source of profit could potentially be used to pay for the initial higher costs of hydrogen. These new developments amount to remaining innovative as a company, which is important for incumbents to stay relevant in a changing system. Incumbent operators have the financial- and intellectual resources to acquire data analysts and the equipment necessary for these new ways of working.

Energy incumbents also go through changes. Survival of the firm means that within the energy transition, innovative technologies and ways of working have to be explored (Turnheim & Sovacool, 2020; Berggren et al, 2015). All interviewees from one energy incumbent see the need for integrated solutions in mobility, including hydrogen. Employees that work in the hydrogen department are content with the entrepreneurial mindset of the teams and the resilience to deal with complexity and changes. Changes in the business model are mostly prevalent in the projects that they undertake. For example, a new focus for some employees on smaller-scale projects has arisen in order to learn to work with hydrogen. Projects with hydrogen in public bus transport are not yet profitable, but they are important because interviewees see a role in developing the market and learning about working with hydrogen before scaling up. However, making a profit is still important for energy incumbents, but for hydrogen this is not obtained in the short term. The role of energy incumbents is summarized by an energy incumbent interviewee working with hydrogen: *"I think all energy incumbents have a similar role. Developing mature and robust solutions, creating confidence with customers. And we all need to invest to make the business take off and we won't fail"*. If energy incumbents take their role in the supply of hydrogen and refueling stations by investing in projects that might not yet be profitable but will create confidence in hydrogen, this helps in overcoming the supply-side barriers as well as creating demand.

Another element that energy incumbents deal with is their reputation. Their network and clients view them as traditional energy companies and not as sustainable companies. This can create prejudice and reluctance to collaborate with an incumbent company, which energy incumbents should consider. To help with creating credibility, some interviewees believe that integrated customer solutions for hydrogen- and electric vehicles should be offered simultaneously. Incumbent energy companies often possess the knowledge and resources to facilitate both technologies, but the integration of different lines of business remains a challenge according to one interviewee: *"we are very good at overseeing the entire value chain, and we have the right contacts. But often, we take things on at one department, while we should actually talk with more people, and think from different perspectives towards different solutions. And then put down an integral or overseeing offer."* A challenging role for energy incumbents therefore lies in aligning the business model with the integrated needs of bus- and other transport companies which can be obtained by listening to people working with hydrogen buses.

Routines for decision making

Incumbent companies often have set routines regarding decision-making and operations, which can be a strength as well as a contributor to lock-in effects. As stated in the barriers, high investment costs for refueling stations and buses result in hydrogen bus projects not being financially attractive yet. Interviewed employees from energy incumbents stress the importance of these decision-making routines, especially regarding financial security in the future, but also point out their flaws. For example, decision-making in large incumbents takes time and is often focused on short-term profit, while start-ups can move faster and focus mainly on innovation. However, the routines in place in large energy companies also provide leverage and expertise in scaling up when the time comes. For incumbents, hydrogen is often a developing business developing next to a line of existing businesses. Hydrogen is not the sole source of profit, potentially leaving room for more flexibility in the decision process (interviewees energy incumbent).

While developments are slower due to set ways of decision-making, the eventual scaling up of hydrogen production and the use of hydrogen in the bus sector could mature rapidly with the right skills and knowledge. An example is given by an interviewee from an energy incumbent: "*Big companies can develop mature solutions. However, startups can act faster and make quicker decisions, and go all in and win or lose. For incumbents, hydrogen can be just an element, making it less risky"*. He adds: *"It's different skillsets, what you need to do. On the one hand, there is longer term business developing and maturing, and then it is operating sites. These are different processes"*. Both are essential parts of the energy incumbent's business, requiring resources and skills. Start-ups on the other hand are perceived to have a role in boosting hydrogen developments across the value chain and making fast decisions.

For incumbents in the public space, such as operators and PTA's, the resources to scale up are limited. Rijkswaterstaat states that they rely on companies like Shell to scale up their hydrogen business. Moreover, operators have shown a drive to implement hydrogen despite the lack of financial resources. This shows that decision-making processes can change and that a pioneering role for incumbents could help the scale-up of the implementation of hydrogen buses and refueling stations. In the future, costs could go down due to upscaling and incumbent energy companies will have a role in the wider implementation, and the government could increase their role by creating clarity. This decrease in costs is crucial for operators according to operator

3:*“as operators, and I think all operators do this, we choose from a TCO perspective. Hydrogen needs to be competitive”.*

A potential role for operators, governmental institutions and energy incumbents revolves around flexibility. Rigid decision procedures have the advantage of financial security and are risk-averse, but in the energy transition, and especially with hydrogen, some risks and costs are necessary, and these risks should be shared. National government can help by implementing subsidies for the hydrogen buses which is perceived as an important subsidy.

5. Discussion

In this chapter, a critical reflection is given on the research results and their place in- and contribution to the existing body of literature. Limitations of the research are discussed, as well as the wider social- and theoretical implications. Finally, suggestions for further research are provided.

With regards to the perceived barriers regarding the lack of governmental stimulation, the role of subsidies is a topic that almost all interviewees talked about extensively. This research adds to literature on barriers for hydrogen as well as on policy mechanisms to support hydrogen by giving examples of the different subsidy needs in the market. It provides examples of cases where the development of hydrogen for public transport is hampered by a lack of policy-and subsidy support. One of these examples is that -operators and energy incumbents find the costs for hydrogen and investing in infrastructure too high, which does not make the total costs of ownership for hydrogen buses competitive. An interesting result comes from the different views that interviewees have on the need for subsidies. Some interviewees such as an energy incumbent and a part of the operators argued strongly for subsidy on the costs of hydrogen buses, others claim a subsidy for the prize of hydrogen at the pump should be offered. Subsidies on operational costs in the energy transition are also encouraged by some of the interviewees of Janipour et al (2020). A small group of interviewees believe we are already past the subsidy phase, but these interviewees also agree that hydrogen buses are still expensive and therefore not yet competitive. The Dutch government sees difficulties in deciding where to implement subsidies and which technologies to support without undermining market mechanisms. The specific needs for subsidy vary from operational cost to capital expenses as well as infrastructure, even within the same interviewee categories. This shows that there is room for improvement in the current subsidy schemes, adhering to different types of actors and their needs.

The previous point overlaps with the findings regarding the interaction between electric- and hydrogen buses due to the implicit steer towards electric buses. A notable finding was that regional governmental actors, in some cases, actively prepared for electric buses, while not considering the use of hydrogen buses. The wider implications of grid congestion and what will happen if other companies cannot get a grid connection anymore is not considered enough by the national government. Future research could focus on the effects of grid congestion on the Dutch energy transition, as well as how hydrogen can have a role in alleviating congestion beyond mobility. This thesis shows the growing concern of interviewees around grid congestion, and it demonstrates the belief of interviewees that hydrogen buses can be a solution in public transport to help limit the problems of grid congestion. Smart grids and smart charging are possible solutions and techniques to do this are already available (Tamis et al, 2017). Ideally, a combined solution of smart charging and the use of hydrogen buses could be designed to obtain the most efficient way of using energy in public transport.

Secondly, the use of electricity is not always free of fossil fuels. The Netherlands has a renewable energy share of 33% (CBS, 2022), which means that 67% percent of the energy mix does not come from a sustainable source. It is difficult to determine the exact energy mix those electric buses use since they are connected to the grid, but entirely green energy cannot be guaranteed. For hydrogen, however, it can be controlled what type of hydrogen is used and how green hydrogen is produced. Multiple interviewees stated that obtaining zero emissions is the goal, and not the promotion of one technology. This requires operators, PTA's and governmental institutions to critically review how to obtain the most sustainable way of providing public transport, including the source of the energy used. Currently, Dutch policy regarding hydrogen relies heavily on European policy. This thesis shows that a national approach focusing on the needs of different actors is important. Anderson et al (2023) argue that a focus on targeted policy is justified if it strengthens the energy transition, but Firdaus and Mori (2023) do advice to not implement policy changes too abrupt, since it can intensify regime resistance.

The use of the multi-mode-interaction framework to analyze the interaction between battery- and hydrogen buses is a contribution to the literature on sustainable mobility. The most important findings state that system interactions create a favorable position for electric buses, sometimes at the cost of the market share of hydrogen buses. These directions of the interactions are called amensalism and parasitism. However, one interaction on the digitalization and new ways of working have a positive effect on hydrogen buses. While competition and comparisons between aspects of the two technologies have been made before (Ligen et al, 2018; Cunanan et al, 2021), other researchers such as Hardman et al (2013) were early in pointing out that both technologies face similar challenges in the mobility system. This thesis adds to the expansion of the effects of interaction by pointing out that interactions can have multiple directions on different parts of the value chain, as well as change over time. The notion of system dynamics influencing technologies is not new. For example, Moradi and Vagnoni (2018) found that the lack of support for niche technologies, such as hydrogen, can be influenced by politics, economic factors, and a lack of investments from incumbents. However, this research adds to the existing literature by redefining interactions and giving specific implications of these interactions for the implementation of hydrogen buses. Future research could expand the theory around system interactions between two technologies in markets that are changing due to the energy transition to improve the tools for analyzing these interactions. This thesis can be seen as a starting point for future research in that direction.

This research also investigated the role of incumbents in the transition towards zero-emission public transport. The traditional role of incumbents as a delaying factor in transitions was challenged and explored through the possible roles for incumbents in implementing hydrogen buses. This new understanding of incumbents follows the thinking portrayed in the papers from Sovacool et al (2020) and Sp'ath et al (2016), exploring chances for incumbents to not only participate in, but also lead a transition.

First of all, roles for national and regional government become clear from the results. The definition of incumbents in this thesis included governmental actors in line with the definition of Sovacool et al (2020), which is not always the case in, for example, Magnusson & Werner (2022). Several roles for national government were found in this research such as providing steer and bringing relevant actors and knowledge together. For PTA's, categorized under regional government, a role could be taken in overcoming the barriers regarding the rigidity of the concession system. The interviewed operators made it clear that there is a need for a longer depreciation period of expensive assets such as hydrogen buses, and that changing towards technologies that are complex and come with uncertainties requires more flexibility in the concession. This supports the findings of Bakker and Konings (2018), who states that depreciation of zero-emission assets needs multiple concession periods. There have been some positive developments in the collaboration between PTA's and operators. There is more involvement from PTA's and more willingness to collaborate on financial initiatives such as obtaining subsidies for hydrogen buses. These roles for national and regional government can overcome barriers regarding the concession system as well as provide a clearer steer towards all actors involved with hydrogen buses.

Another relevant finding in this thesis is the use of existing networks, coordinated by a small group of driven incumbents, and building trust to cooperate on projects .The coordination and drive mostly came from public actors such as PTA's, which fits within the findings of Mühlemeier (2019), who argues that incumbents operating in the public space take a significant role in sustainable transitions. This research confirms that conclusion specifically for the transition to zero-emission public bus transport with regards to hydrogen. This thesis also adds the notion that entrepreneurship and a long-term strategy focused on the energy transition is present in energy incumbents by taking on projects that do not yet turn a profit. According to some interviewees, incumbent energy companies have the highest potential benefit from the hydrogen market, giving them some of the responsibility for initial investments. They also use their network extensively to lobby for- and cooperate on hydrogen projects. This confirms resource-dependence theory, stating that firms use interorganizational networking to influence technology choices, where Magnusson & Werner (2020) add that the use of network to push a technology is common in zero-emission mobility transitions. Both private and public institutions drive the implementation of hydrogen buses, but public organizations are more clearly taking a leading position.

Another finding regarding incumbents relates to the decision processes and the focus on short-term profit, which can be complicating factors for incumbents in the transition. Firdaus and Mori (2023) state that assets acquired by incumbents add to path dependency, creating difficulties in changing course in the energy transitions. Difficulties in investing in hydrogen are embedded in rigid decision processes focused on profit, as opposed to start-ups, who tend to make decisions faster. Nevertheless, incumbent firms with high investment resources have an advantage in scaling up the production of hydrogen and its infrastructure and creating a viable business case. Decision processes in incumbent organizations can hamper change, but they can also ensure fluent upscaling of a technology based on getting the timing and financial risks right. Hydrogen is often a part of the business for energy incumbents, not the sole source of profit. Other lines of business can help pay for higher investments. Start-ups are seen by incumbents as a booster for the scale-up of hydrogen. The collaboration between start-ups and incumbents can be a contributing factor for implementing sustainable technologies (Horne & Fichter, 2022). This thesis touches upon the role of start-ups as boosters of innovation in general, but future research could focus on the specific interactions between start-ups and incumbents in the hydrogen market and the implications for hydrogen buses.

This research has provided an overview of the current system, the interaction between hydrogen-and electric buses beyond competition and the roles of incumbents in implementing hydrogen in public bus transport. Contributions to theory as well as societal implications were discussed, but some limitations were also encountered. Since this research investigates the system dynamics, interactions and the roles of incumbents, there was less possibility for an in-depth analysis of specific societal topics that might require more attention in future research. An example of this is the impact that COVID-19 and the war in Ukraine have on the bus sector, since this is directly relevant for travelers, PTA's and operators. Moreover, the role of digitalization and telematics touches upon technical aspects which are not explained in depth in this research, but more in-depth case studies of individual incumbent companies or institutions would be an interesting type of future research. This thesis explained different roles for different types of incumbents, but within the same type of incumbent, different organizations might have different roles. In future research, more specific behaviors and barriers can be identified to determine more detailed roles in implementing hydrogen buses.

This research aims to be an overview of the system dynamics and the possibilities to overcome system barriers through understanding the complex interactions at play as well as the possible roles for different incumbents. It is an addition to research on the Dutch public transport system and the role of hydrogen in public bus transport in the Netherlands, as well as a foundation for research into the roles of incumbents in transitions.

6. Conclusion

This research aimed to answer the following research question:

"What is the role of hydrogen fuel cell buses in the transition towards zero-emission public bus transport in the Netherlands?"

To answer this question, a literature research and 17 semi-structured interviews were conducted. An overview of the Dutch public transport system and the most relevant system barriers were given. The high investment costs for hydrogen buses and infrastructure as well as a lack of steer from the government, for example, were barriers that make scaling up difficult for hydrogen buses. The established barriers were also at the core of the further analysis of the results.

Interactions between hydrogen-and electric buses were examined using concepts from the multi-mode interaction framework to determine the influence of these interactions on the implementation of hydrogen buses. Some of the barriers, such as a lack of steer from the government and the rigidity of the concession system, manifested in an implicit steer towards electric buses from the regional government. Most of the examined interactions have a negative effect on the implementation of hydrogen buses. Grid congestion for example is not yet pressing enough for operators to switch to hydrogen on a large scale. Additionally, PTA's are actively acquiring grid connections for battery buses years in advance, potentially creating a lock-in for the entire length of a concession. Moreover, the lack of policy regarding grid congestion gives electric buses an advantage, but due to the dynamic nature of the transition, this interaction could change over time to the advantage of hydrogen buses. Finally, digitalization and the use of data are increasingly moving to the core of business models for hydrogen- as well as battery buses. The learnings obtained in the implementation of electric buses have a positive influence on the interaction of hydrogen buses.

Regarding subsidies and policy from the national government, most interviewees agree that initial- as well as operational costs should be subsidized in order to make hydrogen buses affordable. The public sector is not in a position to make large investments due to a decrease in passengers since the pandemic, as well as an increase in energy prices due to the war in Ukraine. Despite the financial position of the public bus sector to invest, the national government sees hydrogen buses as possible flagships for the use of hydrogen due to high visibility and alignment with the zero-emission goals. However, when the costs for implementing hydrogen are lower in other countries where policy and subsidy create a better financial environment, multinational energy incumbents could choose to delay implementation of hydrogen infrastructure in the Netherlands and give priority to other countries. These system dynamics creating uncertainty affect hydrogen buses more than electric buses. The interactions show that the market of hydrogen- and electric buses does not only consist of competition in a stable environment. More complex system dynamics are at stake that influence the role of hydrogen in public bus transport over time in multiple directions simultaneously.

To investigate the role of different types of incumbents in implementation of hydrogen buses, different strengths and opportunities were analyzed. Having strong connections across the value chain stood as a strength in implementing hydrogen. It is useful to have credibility in your network and the ability to bring the right people and skills together. Public actors, including PTA's, have shown leadership and drive in bringing actors together for hydrogen bus projects. Moreover, the acquired and accumulated financial resources and human assets turned out to be crucial for bus operators and incumbent energy companies. Operating a bus concession requires large initial financial investments and knowledge on how to run the business, which incumbent operators have. For incumbent energy companies, the ability to scale up through experience and financially safe decision models is essential for the survival of the company as well as for the implementation of hydrogen buses. However, these decision processes are slow and rigid, and can also hamper expensive investments in hydrogen infrastructure. Government incumbents are increasingly using their networks to bring together incumbents as well as start-ups to generate knowledge sharing and an integrated, holistic hydrogen mobility strategy. Incumbents in the system in general are seen as leaders in scaling up and providing direction, while start-ups are perceived as boosters of innovation.

To answer the main research question, all previous factors are important. Hydrogen buses are mostly seen as a necessary addition to electric buses, mostly for long-distance lines and when charging of electric buses might become problematic due to time or grid congestion. Many incumbents see the importance of having multiple technologies in their portfolio in the energy transition. The main system barriers are related to the high total costs of ownership and the lack of policy steer. This thesis provides an overview of different roles that incumbents have in implementing hydrogen in a market where electric buses have gained significant market share already. Hydrogen buses have an increasing role in contributing to the goal of zero-emission public bus transport in 2030, as well as a flagship role for hydrogen in transport. If hydrogen buses prove to be successful, more applications for hydrogen might develop. This can reduce emissions even further, contributing to the energy transition as a whole.

Management recommendations

Based on this research, management recommendations are provided for different types of incumbents.

- The national government could be proactive instead of reactive towards grid congestion policy. Hydrogen should be considered as an alternative for public buses and for other applications which could relieve the grid. Regional governments can prepare for hydrogen refueling stations as much as they prepare grid connections. National government can improve the steer towards hydrogen through mandates
- Clear national regulation about safety measures regarding bus depots would help operators to combine hydrogen- and battery buses. This also helps energy incumbents to offer more integrated solutions.
- Subsidy schemes from the national government can accommodate the different needs in the system through communication and sharing of knowledge. This should include subsidizing capital expenses such as the buses as well as operational costs, such as a subsidy on the hydrogen prize.
- The Netherlands is seen as a first mover in Europe in the energy transition, especially regarding public transport. Operators could improve their future business model by collaborating with operators and energy companies to make sure that telematics can be installed and used properly.
- Incumbent energy companies should work closely together with operators and PTA's and understand their needs. Partnerships on sharing hydrogen refueling stations between bus- and transport companies could reduce initial costs for both parties. National government could act as a mediator in these partnerships, focusing on knowledge sharing and bringing parties together. Incumbent companies should also consider integrating solutions for their customers. Operators might use both electric- and hydrogen buses and coming up with integrated charging- and refueling solutions meets the demand.
- Collaboration between operators and commercial road transport can be guided by energy incumbents to share hydrogen refueling stations. This reduces costs and increases certainty of demand for the energy incumbents.

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Appendix: Standard Interview Guide

Standard format, each interview guide is adjusted to the interviewees expertise

Introduction questions

- Who are you and what do you do?
- How does this relate to hydrogen/public transport?
- What are recent developments in your field that you found interesting?
- Can you tell me more about *something they just mentioned*?

Public bus transport system in transition + barriers

- How does your function relate to the Dutch public bus transport?
- What is your role in the energy transition?
- (how) does hydrogen play a role in your job?
- What is your view on possibilities for hydrogen in public transport?
- What is going well in the transition? Is there anything necessary that would make your operations/your job/the implementation of hydrogen easier?
- Are there current policies or regulations that, in your opinion, hamper the progress of hydrogen in public transport?
- How do you perceive the role of national and regional governmental institutions in the transition to zero emission public transport?
- Is there an aspect to hydrogen or hydrogen buses that might technologically be a constraint in the implementation of hydrogen buses?
- What is the key challenge in your job at the moment? Does this relate to the challenge for hydrogen?
- Is there anything about the Dutch public transport system that you think could improve/is too complex?
- Where do you see opportunities for hydrogen? How can the implementation of hydrogen benefit from these opportunities?

Interactions

little introduction if necessary on the fact that electric buses already have a significant market share

- does the fact that electric buses gained market share already affect the implementation of hydrogen buses?
- are there external effects that influence the choice of technology for your company/in general (depending on interviewee)
- Is there any policy or regulation that influences both technologies?
- Does your company work with both technologies? Can you tell me more about it?
- is there overlap in expertise or operations in using both technologies?

Role of Incumbents

- Did you have influence on the introduction of hydrogen buses?
- What kind of actors are you collaborating with on hydrogen projects?
- What goes well in these interactions?
- Is there room for improvement in these interactions?
- How do you see the role of governmental institutions in the transition?
- What kind of companies do you think play a role in the implementation of hydrogen?
- What kind of companies will have to take the next steps until 2030? And what would these steps look like?

Other

- Are there any topics you want to discuss?
- Do you have someone in your network who might be interesting for me to interview?