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Hydrogen System for Heavy Vehicles in Sweden

Roles, Actors and Pathways for a Hydrogen Refueling Infrastructure

Master's thesis in Management and Economics of Innovation & Supply Chain Management

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Abstract

The cost for renewable electricity has decreased in recent years, making it economically feasible to produce renewable fuels, such as hydrogen, to substitute fossil fuels. Hydrogen can with onboard fuel cells be used to generate electricity to power vehicles, thus constituting a renewable alternative for the transportation sector. Vehicles powered by hydrogen are dependant on a refueling infrastructure in order to be adopted. This study, conducted in collaboration with Volvo Group, has aimed at understanding how a hydrogen refueling infrastructure could develop by conducting interviews with multiple actors expected to be involved in it.

It is concluded that the hydrogen infrastructure can consist of a system with both centralized and decentralized production units and a hydrogen production that is neither fully nor non-dedicated for the transportation sector. To manage the high costs associated with the establishment of a hydrogen infrastructure, actors are recommended to collaborate and engage in partnerships to mitigate the costs and risks of such projects. It is therefore not viable with a production unit that is dedicated for any sole purposes. Further, more hydrogen projects should be initiated in Sweden to increase the knowledge level and accelerate the development. Many actors believe that a framework laying out a pathway for the development is needed, something that the public sector could help establish. By undertaking a role of initiating and supporting hydrogen projects, Volvo Group could increase the knowledge about the technology and promote a hydrogen infrastructure development.

Keywords: Hydrogen, green hydrogen, electrolysis, hydrogen refueling infrastructure, partnerships, FCEV, fuel cell trucks

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Samuel Andersson & Axel Sörman

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Introduction

Climate change is one of the biggest and most defining challenges in the world today and poses a threat to all humankind (United Nations, 2015). Ever since the industrial revolution, energy systems of the western world have been based on fossil fuels which has increased greenhouse gas emissions and led to climate change (Apostolou & Xydis, 2019; Pivovar et al., 2018). In order to reverse this development, all industries around the world must adapt into using more sustainable energy sources (European Commission, 2019). The transportation sector contributes to 16% of the world's total carbon dioxide emissions (Roser & Ritchie, 2020) and is thereby no exception to this situation. Especially since both the worldwide share of emissions from heavy-duty freight transport and the number of kilometers driven by road-freight transportation are increasing (Calvo Ambel, 2015; Hydrogen Council, 2017).

There will not be one single solution that alone can decarbonize the industry, but rather a system of many new solutions and innovations. One such solution is to power vehicles with hydrogen instead of fossil fuels such as diesel (Çabukoglu et al., 2019; Farrell et al., 2003; Hydrogen Council, 2017). With a fuel cell, hydrogen can be converted into electricity which can be used to power an electric engine. These types of vehicles are called fuel cell electric vehicles (FCEV) and are renewable alternatives to the vehicles that mainly uses fossil fuels today. If the hydrogen used to drive these vehicles is renewable, the only emission from the vehicles is water (Dincer, 2012). Hydrogen has been used in industrial settings since the 18th century and is still regularly used today (International Energy Agency, 2020). Almost all of the pure hydrogen used today, 95% according to Philibert (2017), is produced from natural gas and coal by the process of steam methane reforming, also referred to as SMR. This is according to Santhanam et al. (2017) the cheapest and thereby the most popular method to produce hydrogen, despite it resulting in large emissions of carbon dioxide. However, it is possible to produce hydrogen from renewable energy sources. The main method to do this is through the electrochemical process of electrolysis, where an electrolyzer is used to split water molecules into hydrogen and oxygen (Ursua et al., 2011). Electrolyzers are powered by electricity, and if this electricity comes from renewable sources such as solar or wind power, the production of hydrogen is free from emissions. Therefore, renewable, or *green hydrogen* as it is often referred to (Dincer, 2012), has a great potential to decarbonize many industries and decrease the emissions of fossil fuels (IEA, 2020a). Despite the fact that academics such as Ogden (1999) and Jensen and Ross (2000) discussed the potential of hydrogen and argued for the feasibility of FCEVs already 20 years ago, they are yet to be commercially successful on a large scale (IEA, 2020a). This is largely due to the lack of infrastructure and high costs associated with both the production of hydrogen and development of such an infrastructure (Hydrogen Council, 2020). However, as the cost of renewable energy and thereby the cost of producing renewable hydrogen has decreased in recent years (Roser, 2020), the interest to use hydrogen to decarbonize processes has increased. Many different industries are eager to develop hydrogen systems, and the transportation sector is no exception (IEA, 2019).

Volvo Group, hereafter referred to as Volvo, is one of the world's largest trucks manufacturers (Statista, 2020) and will play a big role in the transportation industry's transformation to become more sustainable. They believe that the way to reduce the use of fossil fuels will be to shift towards using a mix of different sustainable alternatives, such as bio-fuels, battery electric vehicles (BEVs) and FCEVs (Volvo Group, n.d.). The different solutions have different characteristics and are best suited for different applications. BEVs take long time to charge and have a limited travel range due to the weight and size of batteries. For example, the electric truck *Volvo FE Electric* has according to Volvo Trucks (2019) a regular charging time of 6,5 hours and an eventual fast charging of 1,5 hours. Battery electric trucks are therefore suitable for driving short and predictable routes that are more or less the same every day. However, for heavy-duty truck applications that drive long range, have a flexible and variable usage and have a need for fast refueling, FCEVs are believed by some to be the solution to transition to more sustainable vehicles (Manoharan et al., 2019; Ogden, 1999). Kast et al. (2018) argue that fuel cell electric trucks technically already are a feasible solution that do not compromise the performance compared to conventional fossil fuel powered trucks. Combined with the absence of carbon dioxide and green house gases emissions during usage, FCEVs are a suitable option to conventional heavy-duty trucks in order to decarbonize the transportation sector (Manoharan et al., 2019; Ogden, 1999).

The introduction and adoption of FCEVs is not only a matter of if and when fuel cell trucks will be developed. Many researchers, such as Çabukoglu et al. (2019), Jensen and Ross (2000), and Langford and Cherry (2012) argue that the introduction and adoption of hydrogen use in the transportation sector is also dependent on the construction of a hydrogen refueling infrastructure. Researchers have for a long time argued that it is the costs of constructing the infrastructure for hydrogen refueling which has hindered the development of FCEVs (Jensen & Ross, 2000; Ogden, 1999). Moreover, Forsberg and Karlström (2007) argue that accessibility of hydrogen refueling infrastructure is crucial in order for FCEVs to be accepted and Minutillo et al. (2021) even state that: "The most important factor in the development of FCEVs in the marketplace is the hydrogen infrastructure, from its production to its distribution" (p. 13668). Çabukoglu et al. (2019), Gim and Yoon (2012), and Langford and Cherry (2012) all describe that the absence of a refueling infrastructure for hydrogen discourages the development of fuel cell vehicles, and the absence of fuel cell vehicles discourages the development of a hydrogen refueling infrastructure. This is sometimes referred to as the chicken-or-the-egg problem (Farrell et al., 2003; Gim & Yoon, 2012). In order for a successful roll-out of fuel cell vehicles, it is necessary that there is a hydrogen refueling infrastructure in place when this happens. Farrell et al. (2003) also argue that it usually takes relatively long time for these developments, which stresses the need to start this work in parallel with the development of fuel cell trucks.

1.1 Aim and Research Questions

Given the critical role of infrastructure for a successful commercialization of FCEVs as well as the improved conditions for renewable hydrogen production, the aim of this study is to examine how a possible hydrogen refueling infrastructure can be established in Sweden and to identify the necessary roles and actors that will influence this development. There are many uncertainties on how the new hydrogen value chain will develop as well as different levels of knowledge for different actors. It will therefore be important to understand what roles that will be needed and which actors that could undertake each role to support the development of a hydrogen refueling infrastructure. The study therefore aims to answer the following questions:

- How can a hydrogen refueling infrastructure develop in Sweden and what are the factors influencing this development?
- Which role can Volvo Group take in the development of a hydrogen refueling infrastructure?

1.2 Background

Hydrogen is one of the most used industry gases today and according to the International Energy Agency (2020), the worldwide demand for hydrogen has increased more than threefold since 1975. Hydrogen is primarily used in the industries of oil refining as well as ammonia, methanol and steel production (International Energy Agency, 2020). However, the increased urgency to achieve the goals set up by the Paris Agreement in combination with the rapidly falling prices of renewable energy (Roser, 2020) has made the interest to use renewable hydrogen solutions also for other processes increase. This has made some authors, such as Dou et al. (2017) to speculate about a future *hydrogen economy* and that we will see a rapid hydrogen development. This increased interest is also shown by authorities and legislators. In 2020, the European Union published their strategy on how to transform the hydrogen potential in the union into reality (European Commission, 2020) and many of its member states have followed and out forth their own strategies. In early 2021, Fossilfritt Sverige (2021) published a strategy suggesting how Sweden should act when introducing renewable hydrogen on a large scale. After the strategy was released, the Swedish Energy Agency was assigned to develop an official national hydrogen strategy by the Swedish Government (2021), which is expected to be presented later in 2021. In the European hydrogen strategy, the European

Union announces plans on investing € 470 billion in renewable hydrogen projects to increase the share of renewable hydrogen in EU's energy mix from 2% today to 14% in 2050 (European Commission, 2020). In the budget for 2021, the Swedish government announced investments of SEK 550 million during 2021 and SEK 600 million in 2022 for infrastructure of electrified transports, in which hydrogen is included (Government of Sweden, 2020). This is an increase from earlier announced investments in infrastructure by SEK 1 billion. Furthermore, there is and has for a long time existed a strong academic interest and belief in the potential solutions achievable from renewable hydrogen (Apostolou & Xydis, 2019; Jensen & Ross, 2000; Manoharan et al., 2019; Ohta, 1979). In addition, Molin (2005) has showed that there is a high public willingness to use hydrogen vehicles.

The main barrier that has hindered, and is hindering, the development and adoption of renewable hydrogen solutions is according to Lee et al. (2009) the cost, as green hydrogen production is more expensive than production via SMR. This perspective is shared by the Hydrogen Council (2020) who state that the cost of producing renewable hydrogen is what puts it of reach for everyday use. However, the Hydrogen Council (2020) further argues that the cost of hydrogen production equipment, such as electrolyzers, are expected to halve by 2030. This means that the investment costs of making a transition towards producing and using green hydrogen will decrease. Moreover, the cost of renewable energy is decreasing (Roser, 2020) which leads to that the cost of producing hydrogen from electrolysis will decrease. Fossilfritt Sverige (2021) suggests that locations in the world where the cost of renewable electricity is low will be able to produce renewable hydrogen to a competitive price already by 2022. In the strategy, it is exemplified that one such place is Scandinavia. As Sweden is a country with suitable conditions for renewable hydrogen production and the size of the country's development provides a reasonable scope in relation to the project limitations, the study will primarily consider the hydrogen transition in Sweden. However, as Volvo is a large and international company operating worldwide, considerations will be made to ensure that findings and recommendations provide long term value for Volvo looking beyond the Swedish hydrogen infrastructure development.

1.2.1 Hydrogen Projects in Sweden

As mentioned earlier, the interest for hydrogen solutions have increased greatly in the last years. This is driven by the European Green Deal, an initiative to make Europe climate neutral by 2050 from the European Commission (2019), as well as the hydrogen strategy from the European Commission (2020) where it is stated that € 470 billion will be invested in hydrogen projects until 2050. Despite the interest, the number of real projects have up until recently been low. For example, there only exists a handful of hydrogen refueling stations (HRS) in Sweden (Vätgas Sverige, n.d.), one of which is located in Mariestad. Today, this HRS produces up to 4 000 kg of hydrogen per year to supply 14 fuel cell cars owned by the municipality, but it has a capacity of producing 46 000 kg. The station has a storage capacity of 345 kg of compressed hydrogen at 200 bar. To get the electricity needed, solar panels with a capacity of 250 kW are connected next to the HRS (Alpman, 2021).

Another project is Hybrit, which is a joint-venture between the steel producer SSAB, iron miner LKAB and power company Vattenfall, dedicated to develop and implement technology of producing fossil free steel with the use of hydrogen (Hybrit, n.d.). In February 2021, the newly started company H2 Green Steel announced plans of constructing a factory to produce renewable steel with green hydrogen, that should be up and running already by 2024 (H2 Green Steel, n.d.). H2 Green Steel will construct an electrolyzer with a size of around 800 MW, in which it is possible to produce 180 000 kg hydrogen per day. In comparison, the average heavy duty truck in Sweden drove 40 410 km in 2020 (Trafikanalys, 2021). One of the few hydrogen trucks available today comes from Hyundai and has a range of 400 km with a hydrogen on-board storage of 33 kg (Hyundai, n.d.), meaning that if all heavy duty trucks were to be powered with hydrogen, the average Swedish heavy duty truck would have a hydrogen demand of around 3 334 kg/year. This indicates that the hydrogen demand, at least in an initial phase, will be far greater in industrial settings than for the transportation sector.

The Swedish Energy Agency did during the spring of 2021 open up the application period to apply for financial support as part of IPCEI from the EU (Energimyndigheten, 2021a). IPCEI stands for *Important Projects of Common European Interest* and is an initiative from the EU to support cross-border projects that are of certain importance for European development. The Swedish Energy Agency received 21 applications for the IPCEI-call, with the majority coming from power and energy providers as well as industries, showing that at least 21 actors have concrete plans of making investments in hydrogen projects. In 2021, the Swedish Government included hydrogen projects as part of the type of projects that can get support from public funding via Industriklivet (Regeringskansliet, 2020). In April of this year, the Danish company Everfuel, which constructs and operates hydrogen refueling stations, announced plans to construct 15 HRS in Sweden by the end of 2023 (Everfuel, 2021). In a European outlook, Shell plans to build a 200 MW electrolyzer in the port of Rotterdam and in the project NortH2, the company wants to build a 10 GW offshore wind farm that will generate electricity for hydrogen production (Shell, n.d.). Another Swedish example is the steel manufacturer Ovako that has begun to transform production into using renewable hydrogen instead of propane in the heating process. The technique was tested and successfully demonstrated in full scale in 2020 and is to be implemented in 2022 given that Ovako can obtain financial support (Fossilfritt Sverige, 2021). Instead of going through and waiting for a slow application process for public funding, Ovako created a consortium to ensure the funding needed, which Volvo is a part of.

Both the strategy from the European Commission (2020) and Fossilfritt Sverige (2021) state that the costs of constructing a hydrogen refueling infrastructure could be reduced by creating local clusters of hydrogen production. These clusters, or valleys as they are also referred to, would be built around areas which consist of industries that consume large amount of hydrogen and thereby could conjointly invest in production facilities of hydrogen, that is used within the cluster.

1.2.2 Renewable Hydrogen Production

Hydrogen is the most abundant element in the universe (Field, 1995). However, as only small quantities of hydrogen in its elemental form exist on earth (Lubitz & Tumas, 2007), it has to be produced by means of an energy input (Carmo et al., 2013). As mentioned, almost all of the hydrogen produced today is produced via steam methane reforming, leading to emissions of carbon dioxide (Philibert, 2017). With the use of an electrolyzer, hydrogen can be produced via water electrolysis which is a process which does not emit any carbon dioxide. Troostwijk and Diemann discovered the process of electrolysis in 1789 and it was the main method for hydrogen production up until the 1950s, when hydrogen produced via SMR became cheaper due to the low prices of natural gas (Carmo et al., 2013). In its most simple form, an electrolyzer consist of a cathode, an anode and a membrane. Water reacts on the anode side and the oxygen and hydrogen is then separated by the membrane, leading to that hydrogen gas is formed at the cathode side (Smolinka et al., 2015). A complete electrolyzer system consists of hundreds, up to thousands of such stacks. According to Carmo et al. (2013), there are three different types of water electrolysis technologies that in turn make way for three different types of electrolyzers. These are alkaline water electrolysis (AEM), solid oxide electrolysis (SOEC) and polymer electrolyte membrane electrolysis (PEM). Each technology comes with with its own strengths, weaknesses and characteristics. Carmo et al. (2013) and Schmidt et al. (2017) state that PEM electrolyzers have a short response time which enables dynamic operation and thereby is well suited to be powered with intermittent energy sources such as wind and solar. Furthermore, Schmidt et al. (2017) present that PEM electrolyzers have higher power density and cell efficiency than the other technologies. PEM water electrolysis can also produce hydrogen at higher rates compared to traditional alkaline water electrolysis (Zeng & Zhang, 2010) and is more mature than the solid oxide electrolysis technology which is yet to be commercialized (Schmidt et al., 2017). Moreover, the study by Schmidt et al. (2017) expects that PEM will be the dominant electrolysis technology in 2030. Therefore, the main focus and data used about electrolyzers in this study will be on PEM technology.

In an electrolyzer, water and energy in the form of electricity are converted into hydrogen and oxygen (Carmo et al., 2013). The chemical reaction of electrolysis can be seen in Equation 1.1 (Carmo et al., 2013).

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1.1}$$

If the electricity is produced from renewable energy sources, such as wind or solar, the hydrogen produced will consequently be renewable. According to Carmo et al. (2013) the production capacity of renewable electricity is increasing, which will reduce its costs. This has also been the case in the last years, as shown by Roser (2020). Since many industries plan to, or already have begun a transition towards renewable hydrogen solutions, the demand for renewable energy will increase greatly. Fossilfritt Sverige (2021) believes 48 TWh/year of renewable electricity will be needed in order to produce the hydrogen needed to supply the planned hydrogen projects in Sweden. In comparison, the electricity generated from wind power in Sweden in 2020 was 27,6 TWh (Energimyndigheten, 2021c), meaning that the capacity of renewable electricity production will have to increase to support the increasing number of hydrogen projects.

After hydrogen is produced, it can be fueled into a fuel cell vehicle. Fuel cells convert hydrogen into electricity in a chemical process on board the vehicle. This process is practically the same as the one that takes place in an electrolyzer, but reversed (O'hayre et al., 2016). The electricity generated from the hydrogen is fed into a small battery which can power electric motors from which a truck can be driven. As fuel cells generate electricity through a controlled chemical reaction rather than through combustion, the only emissions from a fuel cell vehicle driven by hydrogen is water (Chan, 2007). As with electrolyzers, there are multiple variants of fuel cells and the main difference between them is what type of electrolyte membrane that is used, with the PEM-technology being the most popular for vehicle applications (Manoharan et al., 2019).

1.2.3 Electrolyzer Costs and Development

One of the main components in a hydrogen infrastructure is the HRS. Apostolou and Xydis (2019) present that there are mainly two types of HRS where the difference is whether the hydrogen is produced off-site or on-site. An off-site station gets hydrogen delivered to it and an on-site station produces hydrogen close or in direct proximity to to the site. In financial terms, the on-site stations will require larger investments, mainly due to the additional components needed for producing hydrogen, while the off-site station will include a cost for distributing the hydrogen to the station (Apostolou & Xydis, 2019). A HRS that produces hydrogen on-site includes an electrolyzer which supplies the refueling components with hydrogen. The hydrogen is compressed to a high pressure before being stored at the station. From the storage, the hydrogen is then guided through a cooling unit to lower the temperature and then delivered to the vehicle through a dispenser (Reddi et al., 2017).

In order for the hydrogen transition to become feasible, both for the transportation sector and other industries, the cost of electrolyzers need to become sufficiently low so that hydrogen can be produced at a cost that is competitive with SMR production (Proost, 2019). The cost of producing hydrogen through water electrolysis mainly depends on two factors. The operational expenditures (OPEX) that mainly consists of the electricity price (Proost, 2019), and the capital expenditures (CAPEX) which are mostly related to the investment cost of the electrolyzer (Schmidt et al., 2017). According to Schmidt et al. (2017), it is the high capital costs of electrolyzers along with uncertainty regarding future cost and performance development that have hindered investments in electrolyzers. A PEM electrolyzer system consists of an electrolyzer with its stacks, power supply, a deionized water circulation system, components for processing hydrogen, components for cooling and some additional components, such as a compressed air valve (Mayyas et al., 2019). The electrolyzer production industry is still very small and for example, Saba et al. (2018) state that only one or two large electrolyzer systems per year were manufactured as late as in the 1990s and that there still does not exist any mass production of electrolyzers today. Mayyas et al. (2019) thereby state that the two most influential aspects in order to reduce the costs for electrolyzers is manufacturing engineering and economies of scale.

According to Gim and Yoon (2012), Minutillo et al. (2021), Morgan et al. (2013), Nguyen et al. (2019), Olateju et al. (2014), Ulleberg and Hancke (2020), and Viesi et al. (2017), electrolytic production of hydrogen can utilize economies of scale. The larger the electrolyzer is, the smaller will the unit price of hydrogen be (Olateju et al., 2014; Viesi et al., 2017). This is because the cost of an electrolyzer does not increase proportionally with the size (Gim & Yoon, 2012; Minutillo et al., 2021; Olateju et al., 2014). For example, Minutillo et al. (2021) show that an increase of the electrolyzer size with 300% leads to a 20% reduction of the hydrogen cost and Morgan et al. (2013) state that 60% of the capital costs could be reduced if all parts of a hydrogen production plant were to be scaled. IRENA (2020) summarizes investment costs of electrolyzers depending on scale from several studies and shows that an increase of the scale by 10 times, from electrolyzers with power in the magnitude of 10 MW to 100 MW can reduce costs by a third, from $ 750/kW to $ 500/kW. The cost of an electrolyzer in the magnitude of 1 GW would then accordingly be $ 400/kW (IRENA, 2020). In addition to the investment costs of the electrolyzer, the cost of producing hydrogen is also determined by the operational expenditures of the production facility. Minutillo et al. (2021) state that the operating costs of an electrolyzer mainly consist of the cost of the electricity to power the facility. The authors further show that the electricity cost impact of the total cost becomes larger as the electrolyzer size increases due to the economies of scale. Minutillo et al. (2021) suggest that large electrolyzers thereby could be particularly suitable in countries with low electricity prices.

There are several other factors influencing the cost of producing hydrogen from electrolysis, one of which is the utilization rate of the electrolyzer (Philibert, 2017; Proost, 2019; Ulleberg & Hancke, 2020). According to Proost (2019), the cost of hydrogen increases greatly if the utilization is less than 2 000 hours per year, leading to a cost that makes renewable hydrogen an unviable option. Philibert (2017) discusses that the requirement for high utilization could make investments in electrolyzers particularly risky in an early phase, as demand of hydrogen might not be high enough to motivate a high capacity factor. Related to this, Ulleberg and Hancke (2020) propose that small-scale electrolyzers could prove to be cost-efficient since they have a higher potential to reach a higher number of operating hours and system utilization rate when the demand is low and unestablished.

The cost of electrolyzers is also expected to decrease in the future. Since no mass production of electrolyzers is established yet, there exists a great potential for cost decrease by industrializing the manufacturing (Saba et al., 2018). Schmidt et al. (2017) state that production scaling-up alone could lead to a cost decrease of 17-30% and that this is larger than the impact of increased R&D funding. The authors argue that the main drivers for this potential lies in the ability to standardize components and achieving economies of scale in the production plant when the manufacturing of electrolyzers ramps up. Some studies discuss the potential cost reduction of electrolyzers in terms of learning curves (Reddi et al., 2017; Saba et al., 2018). The learning rate indicates how much the cost of production is reduced by every doubling of cumulative capacity produced (Saba et al., 2018). Saba et al. (2018) state that electrolyzer production has a learning rate of 18%, showing a large potential for future cost decrease. Given the increasing demand for renewable hydrogen and thereby electrolyzers, production of electrolyzers is expected to increase which will lead to decreasing costs (Saba et al., 2018).

IRENA (2020) states that the stacks of a PEM electrolyzer can achieve a lifetime of more than 50 000 hours, where the factors influencing the lifetime are the operating conditions, variable loads, gas permeation, the anode might dissolute, and the water could be contaminated. However, stacks and systems have different life times since stacks can be replaced when they become worn out. Carmo et al. (2013) state that the system of a PEM electrolyzer is expected to have a lifetime of 20 years (Carmo et al., 2013).

1.2.4 Hydrogen Distribution

Distribution of hydrogen is an important subject that will influence the final cost of hydrogen (Demir & Dincer, 2018). Pivovar et al. (2018) argue that a lot of the value in hydrogen solutions lies in the high energy density of the element, meaning that hydrogen has a high amount of energy per unit volume. However, hydrogen has a very low density and is the lightest element in the periodic table, making it difficult to store and distribute (Demir & Dincer, 2018). Demir and Dincer (2018) state that "The viable development of an H2 transmission and distribution infrastructure referred to as 'hydrogen delivery infrastructure,' is one of the most vital issues for an effective penetration of H2 into the energy system and the commercialization of the hydrogen energy driven automobiles" (p. 10421). There are mainly four alternatives to solve the matter of distributing hydrogen. Firstly, it is possible to transport hydrogen in gaseous form on for example trucks, railroad or ships. The same transportation modes can secondly be used to transport hydrogen in liquefied form. Thirdly, hydrogen can be distributed via a pipeline network. The final alternative is to produce hydrogen where it will be consumed, thus eliminating the need for distribution. In Sweden today, the main method for distribution of hydrogen is in compressed form on trucks (Fossilfritt Sverige, 2021). Liquid hydrogen is suitable when the transport distance is increased, because it has has higher density and allows for more hydrogen to be stored and distributed. To liquefy hydrogen, it does however need to be cooled down to -253°C, something that requires a lot of energy which makes this alternative more expensive (Steen, 2016).

From a cost perspective, hydrogen distribution through pipelines is most suitable when the distances are long and the hydrogen flow is large (Fossilfritt Sverige, 2021). Wang et al. (2020) present plans on a hydrogen pipeline network in Europe, since hydrogen might be needed to be distributed to some locations where local production of hydrogen is not suitable. Further, the authors suggest that by 2030, a pipeline network of 6800 km should be up and running and by 2040 the distance should be almost 23 000 km. This establishment of pipelines can be done by partly utilize already existing pipelines that are adjusted to distribute hydrogen. Of this network, 25% should be newly constructed pipelines and 75% should be adjusted from existing ones, which is estimated to cost between € 27-64 billions depending on multiple factors (Wang et al., 2020). Although, pipelines are not established today in Sweden with exception for some local ones for industrial use (Fossilfritt Sverige, 2021).

In a report from BloombergNEF (2020a), the costs of distributing hydrogen is presented. It is clear that pipelines are a suitable option for large flows of hydrogen, which means more than 10 tons/day. For smaller amounts distributed, transportation by truck is reasonable. If the distance by truck exceeds 100 km, liquid hydrogen could prove to be economically viable, and over a distances of 1 000 km, liquid forms hydrogen are the best option. The cost for truck delivery up to 10 tons/day with distances up to 100 km with compressed gas ranges from \$ 0.65/kg to \$ 1.73/kg. These costs are visualized in Table 1.1 below, adapted from BloombergNEF (2020a). It is described whether the hydrogen is distributed as compressed gas, if it is partly compressed and liquid, or completely liquid, depending on distance. It is also shown what distribution mode to use, where pipeline is assumed for volumes greater than 10 tons/day and trucks for less distance. When the distances and volumes are very high, this combination leads to a combination of pipelines and distribution by ship.

Table 1.1:
The cost of hydrogen distribution in \$/kg, depending on volume and distance (BloombergNEF, 2020a).

1 000 t/d	0,05	0,05-0.1	0,1-0.58	0,58-3.00	*Pipeline*
100 t/d	0,05-0.06	0,06-0.22	0,22-1.82	< 3.00	*Pipeline*
10 t/d	0,65-0,76	0,68-1,73	0,96-3,87	3,87-6,70	*Truck*
1 t/d	0,65-0,76	0,68-1,73	0,96-3,87	3,87-6,70	*Truck*
-	**10 km**	**100 km**	**1 000 km**	**10 000 km**	-
-	*Compressed*	*Compressed*	*Part Liquid*	*Liquid*	-

The first method for distributing hydrogen is in gas form on truck. This is, according to BloombergNEF (2020a) suitable for less than 10 tons/day and distances below 100 km. An option when the distance increases is to transport hydrogen in liquid form. Due to higher density, this provides for more energy to be transported with the same volume. However, this also increases the energy demand and makes it more expensive. Liquefying hydrogen thereby requires larger demands, to justify the higher costs that comes from liquefying the hydrogen. Distributing hydrogen as compressed gas is the most common method used in Sweden. When the amount of hydrogen that needs to be distributed is increased in combination with increased distance, pipelines are the best option considering costs (BloombergNEF, 2020a; Fossilfritt Sverige, 2021). The drawback with this alternative is the high investment costs needed to establish such a network, something that might not be viable given the initial small quantities of hydrogen demanded in the early phase.

1.2.5 Hydrogen Storage

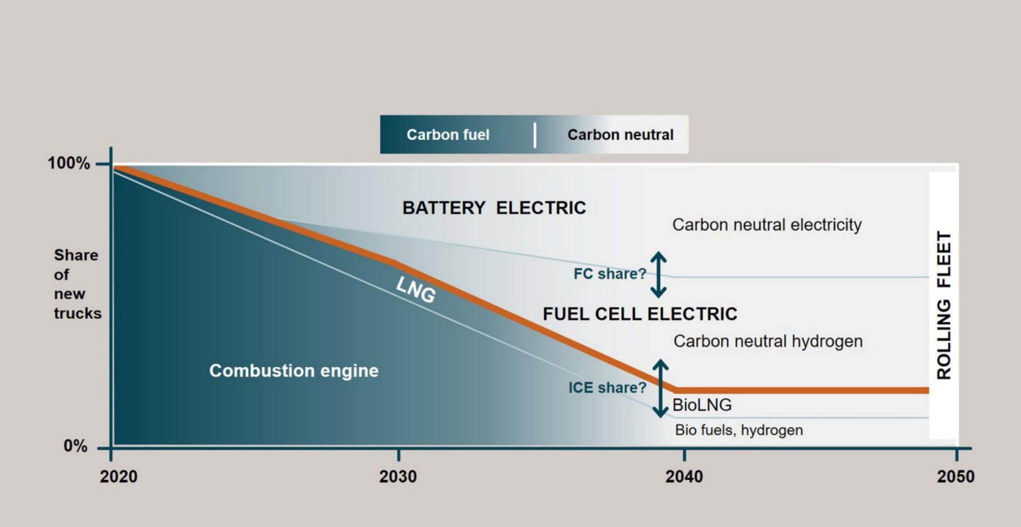
Hydrogen has the possibility to be stored and used when needed to even out the supply and demand. As hydrogen both can be converted from electricity and be used to produce electricity, it can be used to store electricity and balance the intermittent renewable electricity production, thus creating a stable power grid (Smolinka et al., 2015). This is possible because of the high energy density, and thus can make sure to face the challenges of the high electricity needs in combination with the potential of long-term storage (Steen, 2016). It is possible to store hydrogen in salt caverns and other natural formations, or by constructed caverns. The constructed caverns are relatively expensive. Steen (2016) further mentions the possibility to store the hydrogen in a pipeline. By producing hydrogen from electrolyzers, this can be added into the pipeline network of natural gas which in itself will act as a storage and reduce the need for dedicated hydrogen storage.

Fossilfritt Sverige (2021) mentions some examples of hydrogen storage in Sweden. One example presented is the demonstration facility for Hybrit, a project with the ambition to create fossil-free steel, where an underground storage will be built. With a capacity of 100 m^3 for the demonstration storage, it is believed that a storage 1 000 times larger can be used to balance the power grid as a complement to the hydro power. In the future, Hybrit will have a capacity of 100 GWh for increasing flexibility as well as matching supply and demand (Fossilfritt Sverige, 2021).

1.2.6 Volvo and FCEVs

Volvo strives to do their part to make sure that the goals of the United Nations (2015) will be fulfilled and that their products and services will be emission free by 2050. However, since Volvo's products have a long lifetime, the transition to only offer fossil-free vehicles needs to be made by 2040 in order to phase out all fossil vehicles until 2050 and meet the goals set up by the Paris Agreement. As mentioned, this will be achieved by offering a mix of BEVs, FCEVs and vehicles with internal combustion engines that for instance are fueled with bio-fuels (Volvo Group, n.d.). Volvo started production of battery electric trucks in 2019 and has set a goal of offering fuel cell trucks in the later half of this decade. An illustration over this plan can be seen in Figure 1.1 below. As seen in the figure, combustion engine vehicles are dominating the share of new trucks being produced today, hence a rapid transition will have to take place.

Figure 1.1:
Volvo's time plan on how to reach a fossil free fleet by 2050. Reprinted with permission from [Volvo Group].



To support the development of sustainable alternatives and fuel cell trucks, Volvo has engaged in several projects within the transportation sector. One of the largest projects is the joint-venture with Daimler Truck AG, called *cellcentric*. The joint-venture has the aim to speed up the development of fuel cells and was launched by the end of April 2021 (Volvo Group, 2021). Another recent project within this field is called *H2Accelerate*. In this project, Volvo collaborates with truck manufacturers Daimler Truck AG and IVECO as well as oil and energy providers OMV and Shell in order to create the right conditions for a large transition towards heavy FCEVs (Shell, 2020). A third initiative showing the increased activity regarding fossil-free vehicles is Volvo's recent addition of a new business area called *Volvo Energy*, which was presented in the beginning of 2021. Volvo Energy will manage electromobility, which is something that includes the work with fuel cells (Volvo Group, 2020).

1.2.7 Swedish Electricity Production and Market

A prerequisite as well as the major reason for the increasing interest and demand in hydrogen solutions is access to cheap renewable electricity. The electricity production in Sweden is partially based on renewable energy sources, with the non renewable share mainly coming from nuclear power (Energimyndigheten, 2020). In 2020, the total electricity production in Sweden was 159 TWh, with the majority coming from from renewable energy sources. In that year, the three largest energy sources were hydro power, nuclear power and wind power, producing 45%, 30% and 17% of the total production (Energimyndigheten, 2021c). According to Energimarknadsinspektionen (2021b), wind power is the energy resource with the lowest variable cost. Furthermore, BloombergNEF (2020b) states that wind power has become the cheapest source of electricity generation and the development of new wind power farms is increasing. In Sweden, wind powered electricity production increased by 39% in 2020 compared to the year before, amounting to 27,6 TWh. This was the largest change for any of the energy sources (Energimyndigheten, 2021c). This increase occurred despite many investments and installations of new wind power production units were postponed to 2021 due to the Covid-19 pandemic. Energimyndigheten (2021b) believes that the installed capacity of wind power will continue to increase and that an additional power of 3 000 MW will be installed in 2021. Energimyndigheten (2021b) further estimates that the total electricity production in Sweden will increase to 179 TWh in 2023 and that the production of wind powered electricity will increase to 42 TWh in the same year. Globally, it is expected that renewable energy from wind and solar will grow to catch up and pass coal and oil in terms om production capacity (IEA, 2020b). Thereby, renewable energy sources, mainly hydro and wind power, already have, and will continue to have, a big role in the electricity production in Sweden. The expansion of renewable and thereby intermittent energy sources in Sweden will also likely lead to a more volatile electricity price in Sweden (Svenska Kraftnät, 2015). This increases the need for energy storage, which can be achieved with the use of hydrogen, but it also affects hydrogen production as the production cost will become more variable.

Electricity is traded on the marketplace Nord Pool Spot, which is an energy-only marketplace that includes the Nordic and Baltic countries, and is owned by the countries' transmission system operators (Energimarknadsinspektionen, 2021b). According to Energimarknadsinspektionen (2021a), the actors involved in trading electricity are electricity producers, large electricity consumers and electricity traders. Most of the electricity is traded on Nord Pool's day-ahead market, also called the spot market, where the prices for the collective system as well for the individual areas are set through an auction process (Energimarknadsinspektionen, 2021b). The final price for the consumer is determined by the electricity price, margin of the electricity trader, taxes and an electricity grid cost where the electricity grid cost consists of one fixed part, and a variable part (Energimarknadsbyrån, 2020). The fixed part represents the cost to get access to the electricity grid and is dependent on how large the outtake is, whereas the variable part represents the cost to transport the electricity and is dependent on how much electricity that is consumed (Energimarknadsbyrån, 2020). In Sweden, electricity used for electrolytic processes are exempted from taxes (Skatteverket, 2020). The electricity grid cost differs depending where in Sweden the electricity is consumed. Furthermore, the average electricity cost has been very stable and only contributed for a small part of the total price for industries with a large electricity outtake in the last years (SCB, 2020). Because of this and the tax exemption, this study will only use data from Nord Pool's spot price when making assumptions about the electricity price.

There are three different types of networks for electricity distribution in Sweden (Energiföretagen, 2021). The first level is the high voltage transmission grid, where long-distance bulk quantities of electricity is transported. The second level is the regional grid which transports electricity from the transmission grid to the third level, the local grid. The local grid is the grid the distributes electricity out to the end-consumers (Energiföretagen, 2021). In Sweden, the majority of the electricity is produced in the northern parts whereas most of it is consumed in the southern part of the country (Energimarknadsinspektionen, 2021b). To cope with this situation, Sweden is divided into four bidding markets. The two northern areas SE1 and SE2 have a surplus of electricity, while the to southern areas SE3 and SE4 have a shortage of electricity. This means that the electricity needs to be transported from the north to the south. Because of limitations to the electricity distribution grid, it is sometimes not possible to transport the electricity demanded, creating bottlenecks that lead to situations where even though it is possible to produce enough electricity to satisfy the demand, it is not possible to transport it to the consumers (Energimarknadsinspektionen, 2021a). This has made both industries and consumers in the southern parts of Sweden worried about the future electricity price and supply, and for example, Göteborg Energi (2021) has highlighted the problem saying that industries and the transportation sector will not be able to make a transition towards being renewable if the electricity grid is not expanded in the region.

1.2.8 BEV Infrastructure Development

The introduction of BEVs is also an undergoing transition for the transportation sector which requires the development and construction of a new infrastructure. The adoption and market penetration of BEVs have come farther than the FCEVs and despite the different characteristics of BEVs and FCEVs, the development of a BEV-infrastructure and value chain could indicate the direction for a development of a hydrogen refueling infrastructure. Despite the sales of electric cars accelerating and that almost a third of all new registered cars in Sweden in 2020 where rechargeable (BIL Sweden, 2021), BCG (2021) state that the market still is in a very early stage and describes it as an anthill where participants are scurrying to test opportunities. Patterns are however, according to BCG (2021), emerging and both Arthur D Little (2021) and BCG (2021) present the roles needed for an infrastructure. These roles consist of an electricity provider, a hardware provider, site and asset owners, an operator and a service provider. These roles could be fulfilled by vertical specialists focusing on one role, or integrated actors that fulfill several roles in the value chain. Arthur D Little (2021) believes that the role of hardware and asset ownership are the roles with the highest revenue potential, despite the large investment requirements. Since the goal for the OEMs is to offer as many charging opportunities as possible, the role of an OEM should be to aggregate a system of charging possibilities and offer a convenient and easy-to-use experience (BCG, 2021). Arthur D Little (2021) stresses the importance of handling and participating in the development now, stating that actors who lose time now will have to pay for it many times over in a few years. Furthermore, both Arthur D Little (2021) and BCG (2021) believe that the market will consolidate and that large actors will try to capture larger parts of the value chain.

2

Theory

This chapter presents theory that supports the analysis and give explanations to the factors that influence the development of a hydrogen refueling infrastructure. The theories included discuss innovation and technological change as well as the phases of technologies, stating that the hydrogen infrastructure development is in an early phase, which is often called the era of ferment. Organizational theories show that it is preferable to organize in networks when working with the development of new technologies, but that the collective action problem could hinder the actors of the network from undertaking the activities needed. Furthermore, the waiting game theory explains why some actors could be hindered from making investments in hydrogen infrastructure. Possible solutions to this are consortia and public-private partnerships, which are presented along with their benefits and drawbacks. Lastly, the equation for calculating levelized cost of hydrogen is presented, along with a description of what a value chain and a design space are.

2.1 Innovation and Technological Change

The term *creative destruction* was coined by Schumpeter (2003) and describes the process of when the emergence of a new technology disrupts an industry, resulting in a new industry that develops and replaces the old one. This is what drives innovation and the society forward (Schumpeter, 2003). The creative destruction creates a time between the introduction and successful diffusion of an innovation, of which a company will be the only one serving the market and temporarily can raise their revenues over their costs. This profit called *Schumpeterian rents* and the behaviour of seeking Schumpeterian rents is what leads to innovation and technological development (Sautet, 2014). Development and diffusion of new technologies, products and industries tend to follow a logistic curve where their development starts off slow, then grows quickly to lastly shrink over time, corresponding to an S-curve (Anderson & Tushman, 1990; Griliches, 1957). According to Dosi (1982), discontinuous changes and innovations are associated with the emergence of a new paradigm and after the paradigm has been set, continuous changes and innovations then follow this trajectory. Dosi (1982) further claims that this creates cyclical movement where a new technology creates a new paradigm that incrementally evolves until a new and better technology emerges and creates a new paradigm, thus sparking a new life cycle. Abernathy and Utterback (1978) showed these dynamics by arguing and proving that the character of innovation of a technology changes depending of for how long it has existed and the maturity of the technology. This work, together with the notion of Schumpeterian rents explain how products and industries evolve as what is often referred to as the *product* or *industry life cycle* (Klepper, 1997). This theory can also be conceptualized to a technology life cycle, as technology tends to follow the same dynamics. The first stage of the life cycle is often referred to as an *era of ferment* (Anderson & Tushman, 1990). The era of ferment is characterized by extensive technology and market uncertainty. The high technical uncertainty is characterized by large variety and change in the technology design, rapid product innovation and an increasing general interest in the technology, something that leads to a lot of new actors entering the market (Anderson & Tushman, 1990). There is also a lack of a powerful prime mover which is able to drive the change (Jacobsson & Bergek, 2004). The phase ends when a dominant design emerges, either through the competitive environment or determined in a collaborative environment (Anderson & Tushman, 1990).

2.2 Testing and Development of new Technologies

Developing and bringing new technologies to market is hard work that includes a lot of uncertainties. For example, Karlström and Sandén (2004) argue that it is difficult for new technologies to enter a market and that different actions are suitable in different phases. Eisenmann et al. (2012) state that development of new technologies is related to both resource constraints and uncertainty about the viability of the technology and its adoption. To mitigate this when the technology is in an era of ferment, the authors propose a method they call *hypothesis-driven approach* which helps to maximize learning and thereby establishment of the technology and guidance to how a dominant design might evolve. The purpose of this approach is to develop hypotheses about the technology and how it can be used, and then test these hypotheses with falsifiable tests (Eisenmann et al., 2012). The authors highlight that the tests should be as close to reality as possible, but at smaller scale to allocate the smallest amount of resources possible. By making such easy but practical tests, real feedback and knowledge about how users view the technology will be generated and this helps reduce the risk of offering a technology that no one wants (Eisenmann et al., 2012). According to Griliches (1957), successful new technologies typically enter a smaller niche market before diffusing and reaching more widespread use. Such niche markets are suitable places to test new technologies in practice and learn about the technology and customer demands before proceeding with the development (Eisenmann et al., 2012).

2.3 Networks and Partnerships

According to Powell (1990) companies can organize in three distinct ways, namely using a market, hierarchy or network approach. A network builds on collaboration between actors that are characterized by mutual trust and blurred boundaries, in contrast to the arms-length-relationships in market and vertical integration of hierarchies (Powell, 1990). The author state that the network approach thereby allows companies to combine the flexibility and scalability of a market approach with the knowledge transfer of a hierarchy approach. Powell (1990) further argues that networks thereby are especially suitable when working with technological innovation, since this often requires cumulative knowledge. Furthermore, a network approach makes it possible to reduce risk by having several actors sharing it (Powell, 1990). Moreover, Powell et al. (1996) state that innovation takes place in networks of learning, rather than in individual firms. The authors further argue that this is especially prominent in fields with rapid technological development and change.

There are some risks associated with organizing in networks. According to Glasmeier (1991), networks are suitable for promoting innovation within an existing technological framework, but it is difficult to achieve the same results in dynamic and fragmented periods of a systemic change. This is largely due to what is referred to as the *collective action problem* (Glasmeier, 1991). According to Glasmeier (1991), the concept means that all actors in a network must benefit from an action for them to act upon it. In a situation where many members of a network would benefit from an action, but each actor has an associated cost to the action which hinders them from undertaking it, the collective action problem hinders the action from being performed. Glasmeier (1991) further uses the decline of the Swiss watch industry as an example to illustrate the collective action problem, by arguing that the network organization was slow to react and form a single voice to respond and adapt to the new technology of electronic watches. This highlights the difficulties of undertaking a large systemic change in a network.

When working in a network it is also important to understand incentives, roles and risks for all the actors involved, and work and set expectations accordingly to this. Adner (2006) states that the success of an innovation not only depends on the performance of the company, but also of the performance, integration and dependencies within the innovation system. The success of future fuel cell vehicles will not only depend on the performance of the trucks, but also of the performance of surrounding factors and complements in the network, such as add-on services, maintenance, the price of hydrogen and the refueling infrastructure. Adner (2006) argues that new networks and ecosystems present risks, one of which are integration risks. According to the author, integration risks are the risks associated with having a solution adopted along the value chain and in order for a network to take form, the entire value chain must be aligned for the product to be fully adopted. This speaks for that there must exist a network of hydrogen refueling tank stations in order for customers to adopt FCEVs, but also that there must exist alignment, agreement and incentives along the entire value chain for the network to develop.

It is becoming more important for companies to compete with their network or ecosystem against others (Rese, 2006). Rese (2006) discusses the relationship between an OEM and supplier, and that one advantage of a close relationship is the cost reduction that can be achieved through coordination. Second, it could also lead to a productivity improvement within the network. Majava et al. (2013) further discusses some benefits from partnerships, some being asset flexibility, achieving economies of scale, better utilization of resources and reduced risks. But, to get there it is important to show trust and commitment to the partnership, have complementary skills between the firms and to have a proportional risk sharing. In other words, what can be achieved when companies partner up are that costs are reduced, both through coordination but also through higher utilization of assets, and that the risk is shared. Furthermore, Goedkoop and Devine-Wright (2016) state that establishing the trust required for a partnership, a lot of time and resources have to be spent.

2.4 Waiting Game

Sometimes, as with the case of Schumpeterian rents, there are large first mover advantages to be reaped by the player that is first to market with a new technology. However, sometimes it could be advantageous to wait and see how the market reacts to a competitor's launch of a new technology before moving forward with the development. If several companies in the same sector do this, it leads to a passive situation where the actors wait for someone else to make the first move, also referred to as a *waiting game* (Robinson et al., 2012). Bakker and Budde (2012) suggests that hype of a technology can help to overcome these waiting games. The authors state that hype and increased public interest in a technology can light a spark for actors to increase activity and to be the first one succeeding with the developed technology. However, Bakker and Budde (2012) also emphasize the risk of setback that can follow a hype, leading to a decreased level of innovation. The authors furthermore use the hydrogen development and fuel cell cars as an example to illustrate the risks of hype and according to the authors, hydrogen technology has historically undergone both hype and disappointment because it is a system that depends upon many actors to succeed.

Another dimension determining the success of emerging technologies is whether they are environmentally friendly. Bakker and Budde (2012) state that renewable technologies are more likely to get the acceptance of the general public. due to their positive societal and environmental impact. However, these technologies usually perform worse than the conventional alternative, thus leading to a need for public funding to increase performance while lowering the cost. Another example mentioned by Bakker and Budde (2012) related to hydrogen refueling infrastructure, is that the fuel cell cars and hydrogen usage relies on an available infrastructure. Since no actor is willing to establish infrastructure elements unless there are no cars ready to use them and no car manufacturer will develop fuel cell vehicles before the infrastructure is ready, this creates a waiting game and a chicken-or-the-egg situation, as presented earlier.

Technological expectations are according to Bakker and Budde (2012) strong when multiple actors share them and they can help to coordinate and decide upon future processes. The more resources and beliefs that are put into the work, the more does the chance of it to be successful increase, thus leading to high expectations. Bakker and Budde (2012) conclude that the actors that put most effort into the development tend to gain the most out of it when there is a hype. To manage this, the authors claim that it is not the company itself but rather the actors supporting the company that will do it. An example of this could be to establish long-term agreements or contracts that try to work against the potential disappointment phase and instead continues the hype. Bakker and Budde (2012) lastly comment that the waiting actors can lose competitiveness if the technology is delayed due to the waiting game.

2.5 Public-Private Partnerships

When a technology is in an era of ferment, market power alone is not enough to support its adoption. At this stage, government investing in the new technology is especially important (Jacobsson & Bergek, 2004). One solution to this is public-private partnerships, which is a term that refers to the coordinated projects that take place between companies and the state (Linder, 1999). According to Klijn and Teisman (2003), the main idea is that both actors would achieve added value and the important part is the synergy effects that only would be achievable through a public-private partnership. Klijn and Teisman (2003) made a case study on three Dutch cases regarding public-private partnerships. One takeaway is the fact that it is difficult to make a reality of the plans for the public institutions. Usually, these plans are made on national level, but it is the local institutions and actors that are responsible for the actions and to make sure the ambitions are fulfilled. Klijn and Teisman (2003) argue that private actors have a focus on retrieving a market share and profits. Whereas private actors are devoted to consumer preferences and operate on the behalf of their shareholders, public actors are devoted to a public cause. Klijn and Teisman (2003) thereby argue that public actors are more risk averse than private actors, leading to tensions and public institutions trying to reduce risks associated with a project, resulting in a less innovative outcome. However, Un and Montoro-Sanchez (2010) argue that public funding is likely to have a positive outcome on innovations in service industries, since these can complement private funding and help with the complementary resources needed for innovation.

2.6 Levelized Cost of Hydrogen

Levelized cost of energy (LCOE) is a measurement used to assess the energy generation cost of different technologies. The LCOE is calculated as the unit of the average total cost of constructing and operating an electricity generating asset, over the electricity generated during the production asset's lifetime (Hansen, 2019). When the output of a process is hydrogen instead of electricity, the formula of LCOE can be derived into levelized cost of hydrogen (LCOH), which shows the cost of producing hydrogen for different technologies (Corporate Finance Institute, n.d.). There are many different methods and measurements to evaluate the cost of hydrogen, but according to Minutillo et al. (2021), LCOH is considered the most important indicator among such evaluation indexes. The equation to calculate the

LCOH is shown in Equation 2.1:

$$LCOH = \frac{\sum_{n=1}^{t} \dfrac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{n=1}^{t} \dfrac{m_t}{(1+r)^t}} \tag{2.1}$$

$CAPEX$ and $OPEX$ are the capital and operating expenditures, r is the discount rate, m represents amount of hydrogen produced in kg, n is the lifetime of the system and t is the year in operation.

2.7 Value Chain

A value chain is according to Kaplinsky (2000), all the activities that are needed for a service or product to reach a final consumer and beyond, from the beginning to the end. Kaplinsky (2000) presents a very simple example of a value chain consisting of three activities that are design, production and marketing, and within each activity there could be multiple activities. For example, production could include inward logistics and packaging. The author also mentions some important aspects of value chains, where governance is one of them. There are two types of value chains in relation to governance. A buyer-driven chain is when the buyer has an important role regarding governance. It is also possible to have a producer-driven chain, which means the producers have the most important roles, to coordinate and assisting both customers and suppliers in the chain (Kaplinsky, 2000).

One important aspect presented by Walters et al. (2008) regarding managing the value chain is to focus on the entire chain instead of some parts. Since multiple organizations could be included in the chain, and these companies in turn develop their work and strategies continuously, the value chain will become more and more complex and the detailed perspective is not suitable (Walters et al., 2008). Although, Peppard and Rylander (2006) argue that the traditional value chain was more applicable to industries some time ago. Instead, since offerings are becoming dematerialized, it is more reasonable to view a value chain as a value network. In the network inter-firm relationships play an important role and value is co-created between actors. For instance, this opens up for alliances or take competitors into consideration, something that is missed in a value chain (Peppard & Rylander, 2006).

2.8 Design Space

A design space is, according to Stankiewicz (2000), a technique that can be used to illustrate technological development. It consists of a number of operants that, when they are extended to their limit, create a design space which shows what is theoretically possible in the development (Stankiewicz, 2000). One example is the design space by Hojčková et al. (2018) that uses two dimensions to examine the development of possible renewable electricity systems, P - *number of production* *units* and *G - number of independent grids.* The authors can with the help of the design space then develop three extreme scenarios that are used for analyze the situation. Stankiewicz (2000) argues that design spaces can be seen as socially constructed cognitive spaces and that an existing design can be changed and modified by either adding a new dimension or by restructuring an existing dimension. By using a design space, it is possible to create clear representations depending on the different operants, where different positions in the design space creates different possibilities and situations (MacLean et al., 2020).

3

Methodology

This chapter presents the methodology of the study. First, the research design is presented, showing that this study primarily used a qualitative approach and can be labeled as abductive. Then, a description of the research methods used, literature studies and interviews are presented. This is followed by an explanation of how the data was analyzed through a three step coding process. Lastly, the research quality of the study is discussed.

3.1 Research Design

There are according to Williams (2007) three common research approaches that can be used in a study: quantitative, qualitative and mixed approaches. Which of the approaches to use depends on what type of data that is required to answer the research question (Williams, 2007). A qualitative research approach involves discovery (Williams, 2007) and is according to Yin (1994) suitable to answer how and why questions. Furthermore, Creswell and Creswell (2017) and Holme et al. (1997) state that a qualitative research approach is preferred when the study investigates an unknown reality and when the data is unstructured and needs to be subjectively interpreted by the researchers. The purpose of this study was to explore and understand how a hydrogen refueling infrastructure could develop in Sweden as well as what factors that would affect such a development. Because it was an explorative study of a new and unexplored development, a qualitative research approach was deemed as suitable and chosen to answer the research questions.

There are several possible qualitative research methods, one of which are interview studies. Turner (2010) states that interviews provide in-depth information about interviewees' experiences and viewpoints of a certain matter. Therefore, an interview study was an appropriate method to gain perspectives from different actors about their views on what a future hydrogen infrastructure network could look like and develop. In this study, a total of 19 interviews were conducted. The participants mainly consisted of representatives from companies that are believed to be a part of the hydrogen value chain in the future, either directly by producing and consuming hydrogen, or indirectly by offering services required for hydrogen production. To gain a broader understanding of the hydrogen infrastructure development, industry experts as well as representatives from the public sector and authorities on a local, regional and national level were also interviewed. Furthermore, 8 meetings with representatives from Volvo were conducted to discuss their views on hydrogen development and to better understand what factors that will affect the transportation industry.

According to Börjeson et al. (2006), it is suitable to develop scenarios when conducting research about future states or descriptions of development. To illustrate the different alternatives for how a hydrogen infrastructure can develop in Sweden, four different explorative scenarios were therefore developed. These were derived from and illustrated in a design space, as Stankiewicz (2000) argues that a design space is an appropriate tool to illustrate and analyze technological evolution. Furthermore, Hedin and Martin (1996) describe method triangulation as the use of multiple methods and states that it is recommended to use it in qualitative studies to enhance the credibility of the findings. To test and evaluate the feasibility of the scenarios that were developed, calculations were made and compared. The measurement LCOH was used to do this, as Minutillo et al. (2021) argue that LCOH is considered the most important indicator of hydrogen production costs. The calculations were conducted to better understand what factors that affect the costs of producing hydrogen and thereby understand what can or will be done, as well as how future external developments will affect the three scenarios. Data for the calculations were compiled in a literature study as well as from some of the interviews. This means that the study uses a mixed method approach, which is primarily qualitative but with some quantitative elements.

Bell et al. (2018) make a distinction between inductive and deductive research approaches. A deductive approach derives hypotheses from existing theories or knowledge, which then are tested on the reality and either confirmed or discarded. An inductive approach on the other hand, aims at generating theories or hypotheses from empirical observations or findings. The two different approaches can be combined and complement each other, which is called an abductive research approach (Bell et al., 2018). This study used interviews as the primary data collection method, where the standpoints and perspectives from the interviewees were gathered and then summarized and generalized into recommendations for the development of a possible hydrogen refueling infrastructure. Rather than starting off with an initial hypothesis that was later tested, the subject of hydrogen refueling infrastructure was explored, which are clear indications of an inductive research approach. However, the study also consisted of deductive elements. The scenarios that were developed were not only analyzed based on the answers from the interviewees, as the feasibility of the scenarios also were evaluated by calculating the potential costs for hydrogen production in the different scenarios. This can be seen as a form of deductive hypothesis testing. Given that the study consists of elements that are both inductive and deductive, it should thereby be classified as an abductive study.

The general research approach of the study is similar to the definition of *grounded theory* by Easterby-Smith et al. (2018). The authors describe grounded theory as a qualitative research approach where theory is generated based on the empirical findings. This approach is usually based on interview studies where the researcher iteratively collects and analyzes interview data to enhance the understanding of an unexplored area. Bitsch (2005) thereby states that this approach can be used when the study originates from a broad research area rather than specific research questions. Taylor et al. (2015) argue that a grounded theory approach allows the researcher to choose new and adjust data collections during the data collection period. This study did not originate from a clear hypothesis or research question, and the process of collecting data and conducting literature studies was worked with iteratively, where the scenarios and the design space were adjusted as the sample size increased. Therefore, it could also be argued that elements of a grounded theory approach was included in the study.

3.2 Research Method

There were mainly two qualitative methods used to collect data for the study. Firstly, a literature review was conducted to obtain knowledge about hydrogen technology and the current state of its development. The main method to collect data was however to conduct 19 semi structured interviews.

3.2.1 Literature Review

In order to compile the background and theory section, a literature review was conducted. The purpose of the literature review was twofold and was thereby conducted in two phases. Firstly, it helped to set the context of the study and to gain knowledge about the current state of hydrogen applications, as well as understanding what research that had been conducted on the topic. The knowledge obtained was used both to develop questions for, and to analyze the interviews. The second phase of the literature review was done in parallel with the data collection and was conducted with the purpose to construct the scenarios to illustrate the empirical findings and to find theories to base the analysis of these scenarios on. The literature review included scientific articles, reports and press releases related to hydrogen production and use in both industrial applications and transportation. National hydrogen strategies, law acts, publications and websites from public sector organizations were also included. Webinars and online presentations about hydrogen were also attended. Articles were found by using scientific databases such as the one of the Chalmers Library, Google Scholar and Scopus. Moreover, articles were recommended by the supervisors. Literature was also found through the use of snowball sampling, i.e. looking at the reference lists of already selected articles (Wohlin, 2014). Since the technology of producing hydrogen with electrolysis has existed for close to 300 years but has experienced an increased interest in the last years, newer articles that were written in the past 10 years were premiered and preferred in the study if possible. However, older articles that were widely cited were also included. Furthermore, since hydrogen usage is a very current research area where new things and news are published every week, the literature review was worked with iteratively and updated during the entire writing process.

3.2.2 Interviews

The main data collection method used in this study was interviews with representatives from companies and organizations that will be involved in the hydrogen transition. The purpose of conducting interviews was to get qualitative data and subjective perspectives to be able to understand what different actors believe and how they plan to move forward working with hydrogen solutions. There are mainly three types of interview studies that can be used: structured, semi structured and unstructured (Bell et al., 2018). Given the exploratory nature of the study and that the purpose was to obtain the respondents' opinions and perspectives, a semi structured approach was used. When using a semi structured approach, a predefined questionnaire is used but it is possible to mix the order of questions based on the answers from the interviewee, and ask follow-up questions that are not predefined by the questionnaire (Denscombe, 2009). Thereby, a semi structured approach allows for more flexibility than a structured, which was deemed necessary for this study. According to Patel and Davidson (2003), semi structured interviews also allow the respondent to declare thoughts and opinions without the influence from the interviewer, which gives answers that are not contaminated by the thoughts and hypotheses of the interviewer. The use of a semi structured approach was also deemed as an appropriate mix of efficiency and exploration. When using a semi structured approach, it is possible for the interviewee to bring up solutions or perspectives that could have been missed if a structured approach with a predetermined path would have been used (Gill et al., 2008). On the other hand, Gill et al. (2008) further elaborate that unstructured interviews risk spending a lot of time talking about areas that are not of interest to the study, since they are conducted completely without a questionnaire or predetermined subjects to discuss (Patel & Davidson, 2003).

Marshall (1996) describes three different sampling techniques for a qualitative study: convenience, judgement and theoretical sampling. Convenience sampling is a technique were convenience is premiered and the most accessible subjects are selected, whereas judgement sampling involves a little bit more thought as the researcher actively selects the sample to answer the research questions. Theoretical sampling is an iterative process where theory that emerges from the data is used to select a sample to examine that theory. Marshall (1996) further argues that there is an overlap between the three broad categories. As several industries are looking to make a hydrogen transition, it was of particular interest for this study to include views and perspectives from as many different industries as possible. Therefore, a judgement sampling approach was chosen to select the interview sample. The first step of the sampling was to identify what industries and actors that will play a role in the hydrogen transition, which was done with the help of the literature study. After a breakdown of sectors had been done, the sampling began by contacting organizations in each sector, with the goal to cover at least one interview from each sector. Contact information to the respondents was either found online or with the help from the supervisors. A summary of the different sectors identified as important for the development of a hydrogen refueling infrastructure can be seen in Table 3.1. The study also utilized what Marshall (1996) refers to as snowball sampling, where the interviewees were asked if they knew or had contact information to someone that could be interviewed for the study. By using this approach, it became easier to get in contact with the correct person at each organization. Based on some interviews, new actors and industries that will have a use of hydrogen were discovered. It could thereby also be argued that elements of theoretical sampling also was used in the study.

Table 3.1:
Summary of the sectors identified as important for the study to cover.

Industry	Role & Use of Hydrogen
Steel	Hydrogen Production & Consumption
Chemistry	Hydrogen Production & Consumption
Refinery	Hydrogen Production & Consumption
Energy Provider	Energy Provision & Hydrogen Production
System Integrator	Construct & Operate Electrolyzer and/or HRS
Transportation	Hydrogen Production & Consumption
Forestry	Hydrogen Production & Consumption
Public Sector (local)	Hydrogen Producer & Coordinating Activities
Public Sector (regional)	Investments & Coordinating Activities
Public Sector (national)	Investments, Set up Regulations & Coordinating Activities
Industry Experts	Knowledge

In total, 19 interviews were conducted which accounted into more than 14 hours of interview time. The interviews were based on the template that can be found in Appendix A, albeit the order and follow up questions differed between the interviews. All of the respondents had a role which meant that they, in one way or another, worked with hydrogen and the development of hydrogen infrastructure. Information about the interviews is summarized in Table 3.2 The main focus of the interviews was to get information about how the organization that the interviewee represented works with hydrogen, their approach towards cross-sectoral collaboration and what they thought about the future development in terms of value chains, roles and hinders. Both the authors of this report participated in the interviews and all of the interviews except one were held online via video-conference software. The single interview that was not held online was instead conducted over phone. All but one interview were held in Swedish, which instead was held in English. The interviews were recorded with the permission of the respondents to ensure that the responses were captured correctly. The parts of the recordings that were believed to be most relevant and of interest for the study were then transcribed to enable efficient data analysis.

Table 3.2:
Summary and information about the interviews conducted.

Organization	Industry	Date	Duration
Vätgas Sverige	Industry Expert	2021-02-24	53:36
REH2	Transportation	2021-03-09	53:31
Ojnveden	Industry Expert	2021-03-15	29:30
Euromekanik	System Integrator	2021-03-15	31:38
Rabbalshede Kraft	Energy Provider	2021-03-16	53:47
Vattenfall	Energy Provider	2021-03-17	44:48
Nilsson Energy	System Integrator	2021-03-19	30:51
Mariestads kommun	Public Sector (local)	2021-03-22	54:33
Ovako	Steel	2021-03-22	36:40
Fossilfritt Sverige	Public Sector (national)	2021-03-22	54:33
Västra Götalandsregionen	Public Sector (regional)	2021-03-23	01:08:49
Lindholmen Science Park	Industry Expert	2021-03-25	52:13
Preem	Refinery	2021-03-25	29:33
SCA	Forestry	2021-03-29	01:01:30
Höganäs	Steel	2021-03-29	27:26
Port of Gothenburg	Transportation	2021-03-30	53:19
Stena Teknik	Transportation	2021-03-30	30:48
Shell	Energy provider/Refinery	2021-04-07	45:41
Nouryon	Chemistry	2021-04-20	54:35
Total interviews: 19		Total time	14:06:09

3.3 Data Analysis

Data was gathered from 19 different interviews. According to Easterby-Smith et al. (2018) it is possible to identify multiple codes when analyzing qualitative data. These codes could be summarized and divided into categories, which in turn could be developed into concepts or themes as they are interpreted. Bitsch (2005) has a similar view to this, called open, axial and selective coding, which refers to three levels of analysis. Open coding is mainly about identifying different units, similar to the first step as suggested by Easterby-Smith et al. (2018). Axial coding and selective coding can also be related to the other steps presented by Easterby-Smith et al. (2018). These stages were used to analyze the data gathered from the interviews.

All interviews were recorded and thereafter summarized and transcribed. The interviews were divided between the authors and summarized individually. When summarizing, the major aspects were noted and if some ideas or thoughts of the interviewee were especially interesting, this was marked with a comment. For instance, small talk between the participants was not included in the transcription, but otherwise the majority of the data from the interview was noted. The authors then went through the transcriptions together and picked out interesting parts and answers, each of which were given a code word. After this phase, which can be seen as the first step of coding, Easterby-Smith et al. (2018) suggest that the codes should be developed into categories. This is when code words that relate to a similar topic are grouped together. In this study an example of a category is costs, which includes all type of costs, both investment costs and operating costs, related to the renewable hydrogen transition. The final coding step from Easterby-Smith et al. (2018) concerns the development of concepts or themes, based on the categories. Continuing with the example of the cost category, it was at this stage that it was linked with the hinder category, representing that the interviewees view high costs as a potential hinder to the development of an infrastructure. For this study, the codes and categories were analyzed further in Microsoft Excel. This was done by entering all the interviews horizontally and all codes and categories vertically. This creates a grid, in which all aspects were marked depending on what each interviewee believed. The marks covered for instance if the actor believed in the concept, if it was important or if it was seen as a challenge. All codes and categories thus received a score which shows the most important aspects of the hydrogen infrastructure development.

3.4 Research Quality

Bell et al. (2018) believe that trustworthiness is the main criteria when evaluating the quality of a qualitative study. According to Bell et al. (2018) and Shenton (2004), trustworthiness has four aspects: credibility, transferability, dependability and confirmability. Credibility relates to internal validity of the study and that it is ensured that the study tests or measures what is intended (Shenton, 2004). Credibility is ensured for instance by providing the findings from the study to the people that have been participating (Bell et al., 2018). Further, the main topic of research has been presented to all interviewees in order to increase credibility and the interviews were recorded to decrease the risk of missing or misunderstanding information. Shenton (2004) states that using well established research methods, method triangulation and debriefing results with superiors, all of which has been used in this study, are ways to increase the credibility of a study.

Transferability refers to the external validity and to what extent the study can be used in the future for other researchers to compare their studies against (Bell et al., 2018; Shenton, 2004). This was done by providing contextual information about subjects such as the number of and information about the participants involved in the study, data collection methods and the amount of data collected, as is suggested by Shenton (2004). Ideally, this would make it easier for other researchers to understand the context and thus, making it possible to use this study for comparison against their own studies. Dependability of a study can be determined in terms of the documentation that is provided about how the study was designed and implemented (Bell et al., 2018). Being able to audit the study and conclude whether it has been conducted in a proper way influences the dependability. Bell et al. (2018) suggest that complete documentation from the study and its processes should be presented. In this study this has been done by providing a list over the interviews and what type of actors that were interviewed, along with a template of the interview guideline as well as a description of how the data collection and sampling was conducted. The fourth and final aspect of trustworthiness is confirmability which can be described as the influence of the authors' own thoughts to the study (Bell et al., 2018). Shenton (2004) discusses that it is difficult to ensure real objectivity in qualitative studies, as the intrusion of biases are inevitable. To make sure this was not the case, the interviews were recorded, summarized and then discussed amongst the authors so the understanding was equal from each interview. This has been the same for all processes that have been done in parallel between the authors. For instance, if coding has been done by one of the authors, this has been discussed when it was done to make sure the other author believe the result is reasonable. Furthermore, in line with the recommendations from Gioia et al. (2013), the report clearly describes the trail of how data was collected to how it was analyzed and the conclusions were drawn.

In studies like this, it is possible that a lot of the work is divided between the authors in order to increase efficiency. Although, this has not been the case for this study, as both authors have been eager to be involved in all parts of the work. This means for instance, that both authors have been present during all interviews and conducted them together. For smaller parts that have been done individually, for instance transcribing and summarizing interviews, these have later been discussed to make sure both authors were involved and up to date. Therefore, the work has always been made in parallel, and no author is more or less responsible for different parts of this study. The report has been written jointly and the the results are fully backed by both authors.

4

Analysis and Findings

In this chapter, the findings from the interviews are presented. First, the themes that emerged from the coding of the interviews in the data analysis are introduced. This is followed by the development of a design space in which four scenarios are presented. Based on the interview data and theory from the literature study, strengths, weaknesses, roles in the value chain and feasibility of each scenario are presented. In relation to this, it is further analyzed how Volvo could be involved in the development. Lastly, calculations of the LCOH for hydrogen production and distribution are presented and discussed.

4.1 Findings from the Interview Study

The most important aspect regarding the hydrogen infrastrcture development is the need for collaborations between actors. Almost half of the interviewees that discussed the need for collaboration also emphasized that this was crucial. Related to the collaboration aspect, it is also important to have a system perspective. This means that actors should not focus on internal processes, but try to find ways in how the entire system could function. Having a system perspective was also one of the other main takeaways from the interviews, and by doing this a majority of the interviewees argued that synergies would be easier to achieve. Although, the question regarding which actor that should coordinate this was brought up with no clear answer. Some argued for the actor initiating the project to coordinate it, while some argued for a public actor to take that role. One aspect brought up in one of the interviews is the potential power imbalance that might appear, and argued for a third party to be the coordinator. Further, similar on the topic of collaborations, the value chains that could develop can take many shapes and this was agreed by a majority of the interviewees. A few of them also mentioned this as a challenge, especially since hydrogen is applicable in many different settings.

The second most discussed aspect was that the public sector should establish a framework for how hydrogen solutions could develop in Sweden. Within this area, it was both believed and expected that requirements regarding emissions will become tougher, something that would make hydrogen solutions more attractive and support the hydrogen infrastructure development. A majority of the interviewees discussed this, but also that the public sector needs to support actors financially to invest in hydrogen solutions, at least in the early phase as renewable hydrogen solutions and electrolyzers are expensive. Further, on a higher level, the role of the European Union was discussed and it was emphasized that despite Sweden have some unique natural conditions making it a suitable country for hydrogen production, a global perspective is important since Sweden can not develop a unique system separated from the rest of the world.

Electricity was discussed in almost all interviews since the renewable hydrogen solutions will require a lot of it. Although, no interviewee saw the production of renewable electricity as a challenge. Instead, the capacity on the power grid was seen as a greater challenge, and some argued that the grid requires an upgrade, which would take many years. One possible solution to this was by some argued to be to construct off-grid solutions, where for instance wind power parks are directly connected to the electrolyzers. Further, a majority of the respondents also discussed the possibility to balance the grid since hydrogen can be produced, stored and later used when electricity is needed. Many interviewees also argued that this is one of the main reasons for why hydrogen is becoming more and more relevant, although very few had a clear idea or a plan for how this would work in practice.

Another theme that emerged from the data analysis is that more hydrogen projects need to be initiated and deployed that show how hydrogen solutions work. The belief was that by doing so, actors would see how it functions and increase their knowledge, making hydrogen solutions more common in Sweden. In turn, this was said to speed up the development which would lower the cost of investing in hydrogen solutions since the manufacturers and system integrators would increase their learning. The aspect of lowering costs was also discussed in many of the interviews, as a shared view was that the costs are too high and need to be lower. This would make it easier to invest in hydrogen solutions. As mentioned, one idea regarding this challenge was that the public sector would take action and provide funding for these types of investments.

The last aspects regarding the hydrogen infrastructure development that were discussed during the interviews were the distribution of hydrogen and the knowledge level. The answers from the respondents were not aligned regarding these aspects. In a majority of the interviews, the distribution was mentioned as a great challenge. Different ideas regarding this was brought up, where pipelines, transportation of gaseous hydrogen on truck and a decentralized system of electrolyzers with no distribution were mainly discussed. Liquid hydrogen was only mentioned by a small number of respondents but was believed to be too challenging from a technical perspective today. What can be mentioned is that among the different methods for distribution, all seemed equal and no clear answer to which method to use appeared. Further, the knowledge level of hydrogen solutions today in Sweden was discussed, where some argued that the knowledge level is low and others believed it was high. Although, during one interview it was mentioned that the knowledge base is under creation, meaning no actor has enough knowledge. As the development is in an early phase and the knowledge base is varying, a majority of the interviewees argued that the transition should come in different phases. It was believed that the industries with the highest emissions today should be first movers because in these settings hydrogen solutions have the highest impact. Further, it is unclear how these organizations could be involved in the development of a refueling infrastructure for FCEVs. Some actors might not be interested at all, which is difficult to know in this initial phase. It is also clear that actors can have different time frames for the development, where some are more eager to implement hydrogen and some are planning for it in the future.

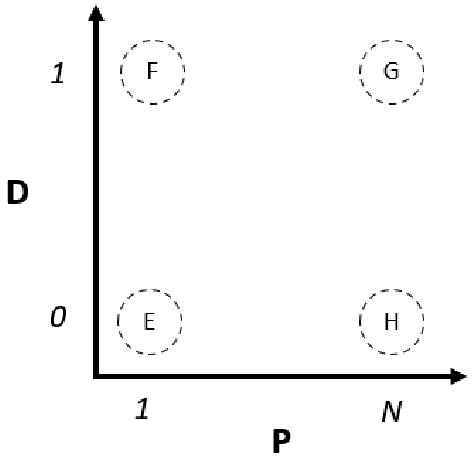
4.2 The Design Space

The study uses a design space similar to the one presented by Hojčková et al. (2018) to illustrate and examine the emerging technology of a hydrogen refueling infrastructure. Although the framework by Hojčková et al. (2018) is used to examine the development of possible renewable electricity systems, it is considered to be applicable for this study since the hydrogen development also refers to a system transition of an emerging and changing technology. With the help of the framework and in line with the method described by Börjeson et al. (2006), four different explorative scenarios for a possible hydrogen infrastructure are developed based on the interviews.

Compared to the framework by Hojčková et al. (2018), the design space is adapted to better fit the situation of the development of hydrogen refueling stations by changing one dimension, just as Stankiewicz (2000) proposes. Since hydrogen refueling stations will not be connected to each other on a grid the dimension G - number of independent grids, is changed to *D - Dedication of production to the transportation sector*. D ranges from 0 to 1 where 0 refers to a situation where the hydrogen is produced with no dedication to the transportation sector. This could for instance be when an industrial company produces hydrogen to use in its internal processes. *D = 1* does instead refer to a situation where the production of hydrogen is dedicated only to the transportation sector. An example of this could be if the production of hydrogen are solely for refueling stations in a similar way to how conventional fuels are produced today. This change is made since the potential development provides for different situations where the transportation could develop its own system with actors producing hydrogen to be used in vehicles, while the system also could develop by utilizing other actors that will produce hydrogen for internal use.

The dimension P - number of production units is kept from the framework by Hojčková et al. (2018) and is also related to the size of each production unit. Since the demand for hydrogen can be assumed to be the same no matter the number of production units, fewer production units would require each production unit to be larger in order to serve the same demand. The hydrogen production can thereby come in various forms, as centralized with few large scale units, *P = 1*, or decentralized with many small scale units, *P = N*. These two extremes can be found as alternatives today for many actors and will differ a lot in scale, thus making it relevant to keep the dimension. The two dimensions create a design space, which can be seen below in Figure 4.1, with the extreme situations E, F, G and H which corresponds to different scenarios of a hydrogen production. Each scenario represent a different setting for how a hydrogen infrastructure can be developed in Sweden, with multiple factors affecting them and different value chains.

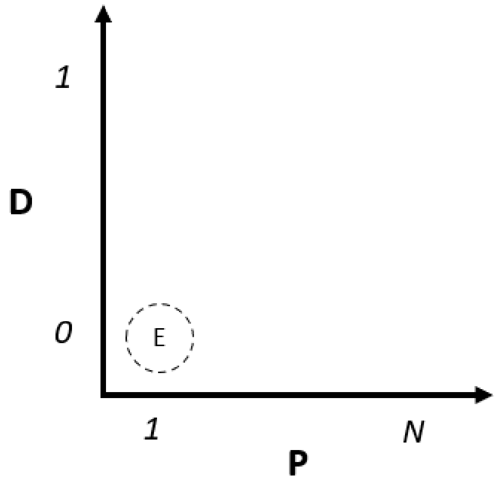
Figure 4.1:
The design space with the four different scenarios positioned, adapted from Hojčková et al. (2018).



4.2.1 The Non-Dedicated Centralized Scenario

There was a strong belief among the interviewees that hydrogen solutions will have the largest benefit for industrial applications, as it is the only alternative to decarbonize many processes. Therefore, the main focus in the initial phase should be to support the development of a hydrogen infrastructure for such applications. If this scenario was to develop, several large scale electrolyzers would be constructed around large industrial sites. Examples of such industries include both industries that use hydrogen today but produce it via steam methane reforming, such as the chemical industry or refineries, but also industries such as the steel industry that will make a transition to use hydrogen. In Sweden, such examples are already developing today in the case of Hybrit and H2 Green Steel. This would lead to that a large capacity of hydrogen production is developed in Sweden, which the transportation sector potentially could utilize. This fact was also clear from the literature study as both the EU hydrogen strategy (European Commission, 2020) and Fossilfritt Sverige´s strategy (Fossilfritt Sverige, 2021) were developed with the main focus on industrial applications. The demand for hydrogen is expected to be far greater for industries than for transportation, especially in the nearest future. Since industrial applications will use a lot more hydrogen than the transportation sector, it might be reasonable for the transportation sector to join in on these investments and scale up the production. This would create a system based on large scale centralized electrolyzers producing hydrogen that is mainly dedicated to other sectors than the transportation sector, leading to a non-dedicated centralized scenario as illustrated in Figure 4.2 below.

Figure 4.2:
The non-dedicated centralized scenario marked in the design space.



In the non-dedicated centralized scenario, it is possible to achieve lower production costs of hydrogen since economies of scale in the hydrogen production would be leveraged. Moreover, several actors could make a joint investment for the production equipment, such as the electrolyzer. Since the hydrogen demand will be lower for the transportation sector compared to most industries, the transportation sector could be able to utilize infrastructure of the large industrial users and thereby save costs. The cost to increase the capacity of a large already existing hydrogen production facility to supply the demand of the transportation sector would be lower than the cost of constructing new hydrogen production sites dedicated only for the transportation sector. One of the main takeaways from the interviews was that almost every interviewee stressed the need for collaboration between different actors from different industries. For a hydrogen transition to take place, the different actors must collaborate and share the investments. As one respondent put it: "no single actor will be able to justify the investment if only looking at the situation from within their own vertical, we must have a wider system perspective". For the hydrogen transition to take place, it therefore seems as several industries would need to collaborate in networks. Powell (1990) argues that this allows for more flexibility and that it is a suitable setting when working with innovation and technological development. The idea of collaborating in networks is also in line with the recommendations of establishing hydrogen valleys or clusters from European Commission (2020) and Fossilfritt Sverige (2021). This solution would be especially suitable at an early stage, when the number of hydrogen trucks and industries that have made a transition towards hydrogen will be few, meaning that the demand will not be large enough to justify an investment.

4.2.1.1 Possibilities and Challenges for the Scenario

The benefit for the transportation sector is that it will not need to invest heavily in constructing a hydrogen infrastructure dedicated to the transportation sector only. Electrolyzers requires a large investment cost today and in this scenario, the transportation sector can benefit from other actors' investments. The scenario requires that industrial actors are willing to allocate parts of the hydrogen production for transportation uses, and different actors could have different reasons for this. For instance, some might have excess capacity in their electrolyzer which could be utilized for producing hydrogen for the transportation sector. In contrast, some industries also use the oxygen that is produced by an electrolyzer, leading to an excess of hydrogen which another actor or industry, such as the transportation sector, could use. Regardless the reason, the industrial actor will have to make some changes to their business model, transitioning from producing hydrogen for their own processes to become a facilitator of hydrogen and possibly even a tank station operator. Some interviewees from industrial organizations raised concerns whether their companies would be willing to make this transition.

The scenario would require Volvo and the transportation sector to engage in partnerships and collaborations with actors that they currently do not have any partnerships with. Partnerships and collaborations in networks require a mutual trust between the parties in order to succeed according to Majava et al. (2013). Although, Goedkoop and Devine-Wright (2016) argue that this is something that requires long time and lot of resources to establish. However, as many of the industrial users have experience of producing and managing hydrogen, Volvo could by engaging in such partnerships utilize these partners' knowledge about hydrogen and faster learn about the technology, which could help future innovations and the development of a hydrogen infrastructure. Since the non-dedicated centralized scenario would require collaborations between actors from different industries, there is a risk that conflict of goals might arise. For example, different hydrogen processes have different requirements for the purity of the hydrogen, which was stated in some interviews. If the demands for the characteristics of the hydrogen differ between the actors in a collaborative and sector transcending cluster, it could become difficult to establish a partnership, since everyone would have to agree upon some trade-offs. These potential conflict of goals are not large enough to reject the scenario, but is something to be aware of. Given the small demand of hydrogen for the transportation sector in comparison to the industrial users of hydrogen, and that the hydrogen will be primarily dedicated to these industrial actors, the transportation sector's negotiation power in the value chain would be rather low in this scenario. This could affect how goals of conflict are resolved, but also how the refueling infrastructure develops.

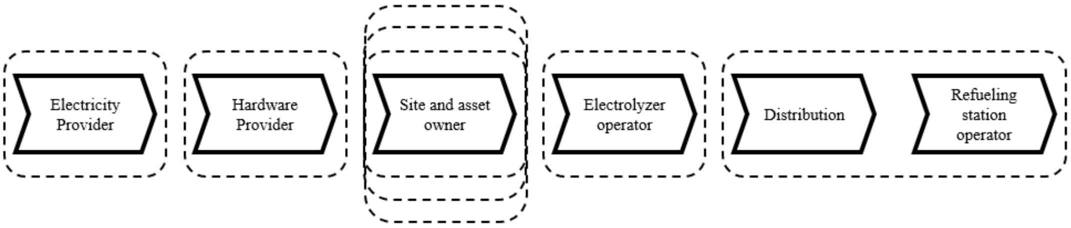
From a transportation perspective, a hydrogen refueling infrastructure requires a network of hydrogen tank stations. This means that several industrial actors that are geographically spread out over Sweden must make a transition towards hydrogen solutions for this scenario to become a viable solution to the infrastructure problem. The construction of a hydrogen tank station network will thereby become dependent on whether several industrial actors are willing to make large investments in electrolyzers and hydrogen production facilities. The coordination of these activities could prove to be difficult and many interviewees highlighted this as a potential problem. The problem becomes even more complex since the entire hydrogen development is in what Anderson and Tushman (1990) would describe as a very early stage of ferment, where most actors still are uncertain about what will happen and how the development will evolve. It is thereby possible that the collaboration between the different actors will experience a collective action problem, as described by Glasmeier (1991). As several actors of the proposed network might not be willing to undertake the cost associated with the investment of an electrolyzer, a network of hydrogen stations will not be constructed which will hinder the development of FCEVs, as described by Farrell et al. (2003) and Gim and Yoon (2012). This became evident from the interviews, as different industrial actors have different approaches to a hydrogen transition regarding interest in hydrogen, time frame and the possibility to establish a refueling station. From the interviews, it did especially seem like some industrial actors had longer time frames and did not view hydrogen solutions as a priority in the nearest future. Moreover, making large investments in electrolyzers will take a long time, both to decide and execute. Volvo has set a goal to only offer carbon neutral vehicles by 2040, and expect to offer FCEVs by the later half of this decade. This means that there needs to exist a network of hydrogen refueling stations at least by the latter half of the 2020s and given the uncertainties regarding the number of actors involved and size of the electrolyzers, it is not certain that enough hydrogen production sites will be up and running by the time that fuel cell trucks are commercialized.

4.2.1.2 Value Chain

Based on the interviews and the proposed value chain of BEV infrastructure from Arthur D Little (2021) and BCG (2021), a potential value chain for this scenario is constructed. The value chain of this scenario consists, as suggested by Kaplinsky (2000), the expected activities from start to end and begins with an energy producer. A large electrolyzer will consume very large amounts of electricity, so there must exist a large supply of renewable electricity. More importantly, a large electrolyzer will require great power, meaning that the power distribution grid must be able to distribute that amount of power to the site. Different industries have different capabilities to increase their electricity supply depending on where they are located. From some interviews it became clear that not all industries have the possibility to invest in a large electrolyzer today due to limitations of the power distribution grid. Some industries looking to invest in an electrolyzer would thereby need help from an energy provider to expand the distribution grid to their plant. Another alternative to support a large electrolyzer could also be to construct an electricity generating facility, like a wind power park, that is dedicated to power and directly connected to the electrolyzer. this would eliminate the need to expand the power distribution grid, similar to Shell's plans in the Netherlands. This would however require a very large investment cost.

The hardware equipment for an electrolyzer and a tank station is provided by a dedicated actor, such as an electrolyzer manufacturer or a system integrator. The electrolyzer could then be owned by several actors, if the cluster approach is adopted. The next role in the value chain is the operator of the electrolyzer. This role could be fulfilled by an industrial user that both produces and consumes hydrogen, in other words a prosumer. In many cases, the prosumer already produces hydrogen onsite today, albeit via steam methane reforming. This means that the actor is used to handling the gas and have knowledge about the safety requirements related to hydrogen, something that many interviewees highlighted as something that should not be underestimated. However, given that some interviews indicated doubts whether all industrial companies would be interested in changing their business model and become a tank station operator, this role could also be fulfilled by a company that have experience of handling fuels and tank station operation. Lastly, if the production site is not located close to where trucks can stop and fuel, the hydrogen will be distributed to a tank station. This role of distributing the hydrogen and operating the tank station is performed by an actor that is dedicated to processes like this, most likely one of the current tank station operators. An illustration that summarizes the description and shows how a potential value chain could look like for this scenario can be seen in Figure 4.3 below.

Figure 4.3:
A potential value chain for hydrogen infrastructure of the non-dedicated centralized scenario.



Note. This figure demonstrates a potential value chain, where each dotted line represents an actor, thus illustrating which roles each actor can undertake. The three dotted lines around *Site and asset owner* represents that several actors in a partnership or cluster can own the electrolyzer together.

This non-dedicated centralized scenario involves many different actors and alternatives for the roles, which relates to the ideas of Peppard and Rylander (2006) with more actors creating something that is more like a value network rather than a value chain. Large industries that only have produced hydrogen for internal processes earlier, now get an opportunity to expand their operations and consolidate a larger part of the value chain, by both owning and operating the electrolyzer as well as operating the tank station. However, as this might not be a part of their core operations, new actors could seize the opportunities to fulfill these roles and become a part of the value chain. Consequently, the value chain could either consist of different actors in every role, or it might also contain a group of actors managing the value chain.

4.2.1.3 Volvo's Role

As the hydrogen produced in this scenario is primarily dedicated to industrial use and not for transportation purposes, the transportation sector's control over the value chain will be rather small. To what extent actors like Volvo can influence this development is difficult to answer since the hydrogen production will be owned and operated by other actors. The decisive tipping point for this scenario is whether the large industrial users make the decision to invest in large electrolyzers. If Volvo promotes FCEVs and initiates partnerships in clusters around large industrial users, Volvo could increase the demand for hydrogen solutions and affect the development in the direction of this scenario. Given the size of Volvo and that the technology is in an era of ferment, Volvo could play a big role of legitimizing the technology which could influence other actors to also look into hydrogen solutions. In return, Volvo would in the future get access to hydrogen produced at a low cost.

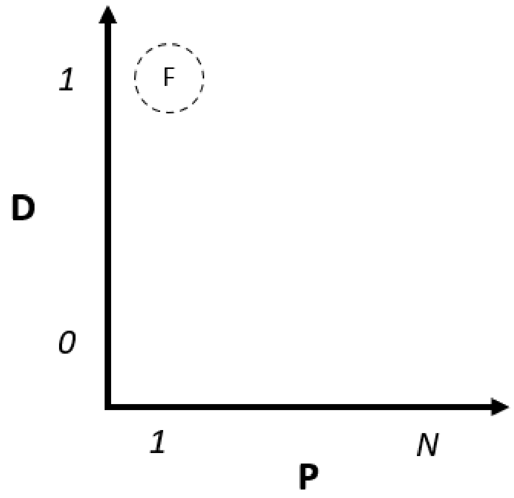
4.2.1.4 The Scenario Over Time

European Commission (2020) and Fossilfritt Sverige (2021) argue that the cluster solution is particularly suitable in the initial phase of the hydrogen transition. As is discussed by Griliches (1957) and Karlström and Sandén (2004), successful new technologies often enters a smaller niche market before diffusing. By creating clusters among actors with a large hydrogen usage, such niche markets could be developed in which the hydrogen solutions could develop. The clusters would be built around, and utilize, that the actors with the highest demand of hydrogen make the transition first, which then would spillover to other actors. By starting off with the largest users of hydrogen, large electrolyzers would have to be constructed. This would lead to a higher demand of electrolyzer, encouraging the manufacturers to increase their scale which in turn would lower the capital expenditures, thus making it possible for smaller actors to invest in electrolyzers. Initially, there will be few clusters in Sweden, meaning that the network of hydrogen refueling stations only supplied with hydrogen dedicated for industrial processes will not be large enough to cover the demand of long haul trucks. The time it takes for these clusters and each actor to decide whether to invest in large electrolyzer might be too long for there to be an infrastructure network established when fuel cell trucks are commercialized. Over time, more clusters will be developed and the clusters will become connected (Fossilfritt Sverige, 2021), leading to a transformation into a network rather than clusters. With more clusters, this potential development might turn more into a decentralized system rather than a centralized as presented in this section, at least for the transportation sector. In every cluster the hydrogen production would be centralized, but from a transportation perspective, as a truck moves over several clusters, there would be more hydrogen refueling opportunities all over Sweden coming from multiple actors. The importance of then finding business models suitable to this development was brought up by some interviewees as well, which is further related to the uncertainty in the value chain.

4.2.2 The Dedicated Centralized Scenario

This scenario describes a solution which is similar to the production and distribution of conventional fuels. A potential implementation of this scenario would use a completely centralized approach, using a very large electrolyzer to supply most of the hydrogen demand for transportation, as illustrated in the design space below in Figure 4.4. The hydrogen would then be distributed to different HRS all over Sweden. The electrolyzer would be located in an area where renewable electricity is very cheap, for example in the north of Sweden where the windy conditions make a great place for producing cheap electricity from wind power. The large production would make the production cost per kilogram of hydrogen lower, as shown by Gim and Yoon (2012) and IRENA (2020). The combination of cheap renewable energy and large modules make the production cost of hydrogen relatively low. Although, the total cost of hydrogen also includes the cost of distribution and unless the supply and demand take place in the same location, this will increase the total cost. Assuming the hydrogen production is in the northern parts of Sweden, a lot of hydrogen will need to be distributed long distances to cover the demand in the south leading to high distribution costs as per BloombergNEF (2020a).

Figure 4.4:
The dedicated centralized scenario marked in the design space.



4.2.2.1 Possibilities and Challenges for the Scenario

Since this scenario provides for a completely dedicated hydrogen system to transportation, the control is increased for the actors in the transportation sector. They would have more control and increased possibilities to influence the development in this case. Furthermore, the transportation sector would not be as dependent on whether other actors in other industries make a hydrogen transition in this scenario. For example, it will instead be possible to locate hydrogen refueling stations where they are best suited based on the road network, rather than where hydrogen demand for industries is the highest or an industrial actor decides to invest in an electrolyzer. This level of control could be very important for the transportation sector, since the entire infrastructure potentially could be developed to fit their needs. The actors included in this scenario are more or less the same as for the value chain of conventional fuels, meaning that existing relationships and partnerships could be engaged and further developed for the hydrogen infrastructure development. As Goedkoop and Devine-Wright (2016) point out, establishing a new partnership can take a very long time, time which would be saved in this scenario as the partnerships already exists. Furthermore, Rese (2006) argue that it is becoming more common for companies to compete with, rather than against actors in their network, and that cost reductions can be achieved through coordination in close relationships. A fully centralized large scale electrolyzer will require a lot of renewable electricity. However, according to Energimyndigheten (2021b) and IEA (2020b) as well as the interviews, the capacity of wind powered electricity will increase substantially in the coming years, meaning that electricity production will not be a problem.

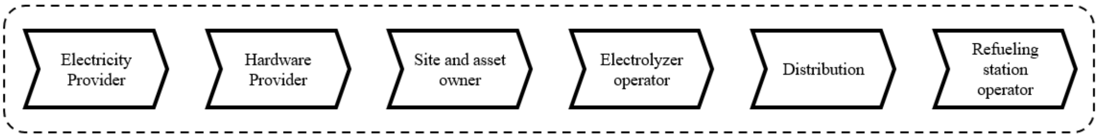
The main challenge related to this scenario is the distribution of hydrogen. In a centralized approach, the cost reduction that is possible to achieve thanks to the large scale of production will have to be compared with the costs of an increased distribution. Large amounts of hydrogen will need to be delivered to all refueling stations located in Sweden. As shown by BloombergNEF (2020a), distribution of hydrogen becomes very expensive when the distances are long. Another potential obstacle is the large investment costs associated with large electrolyzers. Even though the cost of electrolyzers is expected to decrease in the near future (IRENA, 2020; Saba et al., 2018), it is still a large cost in the initial phase. This becomes even more prominent since the demand is not established and can be assumed to be low at an initial phase, especially for the transportation sector. This makes it difficult to justify an investment of a large electrolyzer. Further, when elaborating on a potential future, few interviewees brought up this scenario for discussion.

4.2.2.2 Value Chain

In the value chain for this scenario, the main influencing aspect is the large size of hydrogen production facility and the already existing system of heavy-duty transportation. It can be assumed that a large actor needs to take this role in the value chain since it will require large investments as well as resources, knowledge and network to be able to carry out the integration. Because of this, there might be an opportunity for this actor to take on more roles in the value chain. A hydrogen producer could decide to establish renewable electricity production to supply the electrolyzers with power. In other words, the large production make room for further responsibilities in the value chain, since the actor can be less dependant on others, both upstream and downstream. Comparing the scenario to how the large actors that produce conventional fuels operate, they produce fuels on their own sites and then sells it on their own refueling stations which they also operate. These actors will have an opportunity to translate their value chain also for hydrogen production and distribution. An example of such an actor could be the oil company Shell, who's hydrogen projects include the construction of a large offshore wind farm outside the

Netherlands, as well as a large electrolyzer in the port of Rotterdam (Shell, n.d.). This means that the value chain of this scenario has the potential to become very consolidated and controlled by one single actor. An illustration of the proposed value chain is seen in Figure 4.5.

Figure 4.5:
A potential value chain for hydrogen infrastructure of the dedicated centralized scenario.



Note. This figure demonstrates a potential value chain for this scenario, where all the roles are operated by one actor. This is illustrated by the dotted line surrounding all roles in the value chain.

4.2.2.3 Volvo's Role

The hydrogen in this scenario is dedicated to the transportation sector. Since Volvo is a large actor in the transportation industry, they will have a lot of control and opportunity to influence the development of this scenario. During multiple interviews, legitimacy was mentioned as an important aspect for adoption of hydrogen solutions and that these would need be proven to be efficient and successful by large actors for others to act upon it. Given the size and power of Volvo in the value chain, Volvo could thus be a part of the establishment and promotion of the hydrogen refueling infrastructure. Volvo has a lot of knowledge and data on their trucks, which for instance could be used to decide where hydrogen refueling stations should be located and how many stations that are needed to cover the demand of trucks in Sweden. This information is of importance, both to the actors that need hydrogen, but also to the producer, when developing the refueling infrastructure. Further, given that the hydrogen in this scenario would be dedicated for the transportation sector, Volvo could take a larger role in the establishment of standards and technical specifications of the refueling stations.

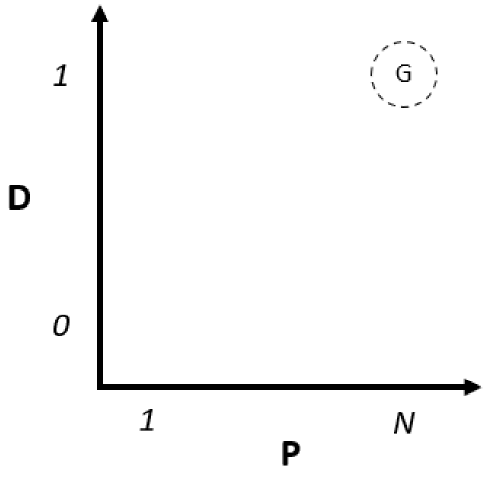
4.2.2.4 The Scenario Over Time

This scenario, with a large centralized hydrogen production dedicated for the transportation sector, requires a large demand of hydrogen in order to keep the load factor of the electrolyzer high. It is reasonable to assume that this will not be the case, as the adoption of FCEVs will shift gradually over time, much like the earlier described technology life cycle. This means that this scenario would rather become a viable option in the future when hydrogen demand has increased. By then, it is moreover expected that the cost of electrolyzers have fallen (IRENA, 2020; Saba et al., 2018), which would make the investment cost for a large centralized electrolyzer lower. On the other hand, Arthur D Little (2021) argues for the importance of participating now in the development of BEV infrastructure, stating that actors that do not do that will pay for it in the coming years. As the development is assumed to be similar for the hydrogen infrastructure, it could be risky to wait for better market condition to develop before taking action.

4.2.3 The Dedicated Decentralized Scenario

The third scenario describes a situation of many decentralized electrolyzers that each are directly connected to hydrogen refueling stations. The production would thereby be dedicated to the transportation sector. An illustration of this scenario in the design space is shown in Figure 4.6. The hydrogen production of each electrolyzer is relatively small and takes place on every station, thus eliminating the need for distribution of hydrogen. Since the production units will be decentralized and placed along roads and large truck stops where the capacity of the power distribution grid could be limited, the scenario provides for opportunities to power the electrolyzers with off-grid electricity production sites. This is the case for the refueling station in Mariestad (Alpman, 2021) and a variant of this scenario is proposed by Everfuel in their plan of establishing hydrogen refueling stations in Sweden (Everfuel, 2021).

Figure 4.6:
The dedicated decentralized scenario marked in the design space.



In this scenario, despite that the investment cost for each electrolyzer is not as large as in the centralized cases in absolute terms, the investment costs is still the main cost contributor. Furthermore, the hydrogen refueling stations will produce hydrogen to a higher production cost due to smaller electrolyzers and by potentially not being optimally located for low electricity prices. Instead, they will be located in favor to the transportation sector, for instance where a major share of trucks pass by every day. Although the production cost is higher compared to other cases, this would be compensated by a reduced or even eliminated distribution cost. As elaborated by Apostolou and Xydis (2019), the sites that produce hydrogen on-site would not need any distribution, a cost which otherwise would have been added to the hydrogen price at the dispenser. This price could, as shown by BloombergNEF (2020a), be relatively high.

4.2.3.1 Possibilities and Challenges for the Scenario

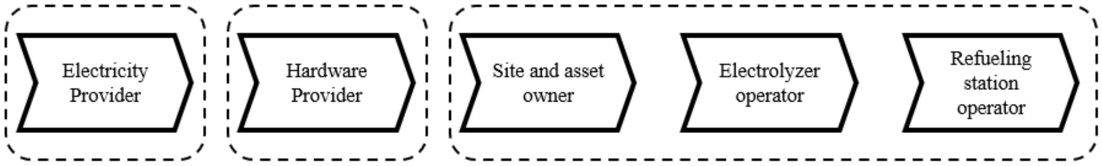
One main advantage with this scenario is, as presented, the absence of distribution. The problems of distributing hydrogen was pointed out by many interviewees as a major challenge and hinder to the hydrogen transition. Many respondents argued that it does not exist any suitable technical solution to distribute hydrogen, as it uptakes too much space in gaseous form but requires to much energy to convert to and handle in liquid form. Therefore, the best solution to the distribution problem seems to be to eliminate the need for hydrogen distribution which is the case in this scenario. In this scenario it will be easier to scale the production appropriately to the demand and expand this when the demand increases, thus making sure that all of the electrolyzer's capacity will be utilized. The respondents did also discuss the possibility of connecting the electrolyzers directly to an electricity production unit, such as a wind power farm, instead of connecting it to the grid. This could be a viable option for wind power operators which could construct electrolyzers and use the electricity to produce and store hydrogen instead of selling it to the grid in cases when the electricity price is low. The alternative cost of the electricity would then be very low, potentially even zero at times when the electricity price is negative. This scenario would also make it possible to locate the production sites and hydrogen refueling stations where it is optimal for transportation, due to their potential independence from the electricity grid and other industries. This scenario would consist of several small scale electrolyzers in a decentralized system, which makes it easier to follow the recommendation of Eisenmann et al. (2012) to start off small scale and conduct practical tests to increase learning.

There are on the other hand also some challenges related to this scenario. Even if the distribution cost is assumed to be zero, the hydrogen production cost will be higher compared to the centralized scenarios due to size. The production will be made with small electrolyzers which will make the investment costs per unit hydrogen higher as showed by Mayyas et al. (2019). Further, since the location of the refueling station is assumed to be chosen by where the refueling is optimal considering truck routes and not from where the electricity is cheap, if the electricity is bought from the grid, the cost might be higher and more volatile compared to if the production site would have been placed to optimize the electricity cost. The scenario could be summarized with the hydrogen production not being planned and optimized to provide the lowest cost, but instead it is developed to satisfy the transportation sector. Furthermore, the scenario will consist of smaller scale electrolyzers, thus making it possible for smaller actors to be part of the development. However, given the large investment costs of electrolyzer, smaller actors might not be able to make these investments without external financial support. This could hinder the development and lead to that a waiting game unfolds, as described by Robinson et al. (2012).

4.2.3.2 Value Chain

The roles in the value chain for this scenario could be performed by several different actors, many of which potentially are newly started companies. In addition to the need for an actor to provide the electrolyzer equipment and electricity to power the production, the roles of owning and operating the electrolyzer and the tank station will according to most interviews be done by a new actor, since it does not exist any company within this business area today. Even in the case of an energy provider looking to increase the value of wind power electricity by owning an electrolyzer, it would still most likely require an actor to operate the electrolyzer and the tank station. An example of this is the earlier described case in Mariestad, where the municipality owns and operates a hydrogen refueling station. The increase of new actors was by many respondents expected to lead to more competition, faster development and creation of new business models, which in turn are expected to speed up the transition. The value chain of this scenario will be more flexible and will differ for each case, but one potential illustration is shown in Figure 4.7.

Figure 4.7:
A potential value chain for hydrogen infrastructure of the dedicated decentralized scenario



Note. This figure demonstrates a potential value chain for the described scenario. Each dotted line represents an actor and what roles they can fulfill. Especially the last roles in the value chain are expected to be performed by a new actor. Also note that no distribution is needed in this scenario.

4.2.3.3 Volvo's Role

The transportation sector will have huge opportunities to influence the development presented in this scenario, as it can be assumed that many small actors will be active in the establishment of a hydrogen refueling infrastructure. Power and control will then be mainly passed on to transportation sector, that both possess knowledge and even financial resources to support a development that will benefit the company. Referring back to the chicken-or-the-egg problem, large transportation actors such as Volvo can support the construction of an infrastructure so that tank stations are ready when fuel cell trucks are commercialized. Volvo can even act to align the different activities and undertake a coordinating role, by for example collaborate and communicate with different actors regarding suitable locations for refueling stations, capacity demands and technical requirements. Given Volvo's large size in comparison to the new actors, Volvo also has relatively large financial resources that could help new actors with investments to ensure a secure hydrogen supply for fuel cell trucks. That would make the investment costs somewhat smaller for actors, thus shrinking the barrier for investing, which was something mentioned as a challenge during the interviews. Bakker and Budde (2012) supports this view, by stating that the more resources and beliefs actors invest in projects, the greater the chance for success becomes. This would also help overcoming a potential waiting game that might arise.

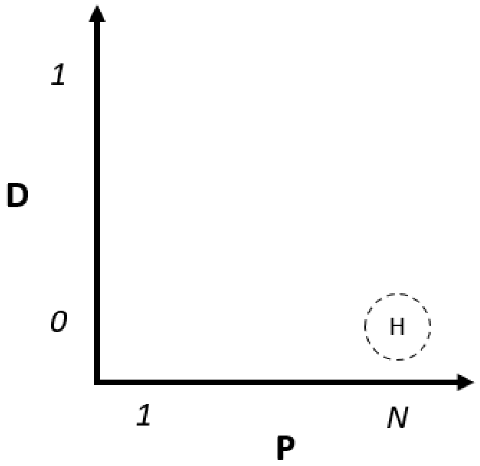
4.2.3.4 The Scenario Over Time

Since this scenario involves opportunities for several new actors to undertake roles in the value chain, it can be assumed there will be more actors involved in this value chain. Given that the hydrogen infrastructure development situates in an era of ferment with large uncertainties, several different solutions will be proposed and tried, which will accelerate the development. Eisenmann et al. (2012) stress the importance of running tests and getting knowledge from practical experiences when working with innovations and new technologies. Such tests are easier to conduct with small scale electrolyzers, since it leads to lower investment costs and reduced risk. The smaller investment costs and activities from new actors will furthermore lead to that more tank stations will be constructed, meaning that it will be faster to develop a network of hydrogen tank stations, which is necessary for the adoption of fuel cell trucks. Therefore, the decentralized dedicated scenario is suitable for the initial development of the hydrogen solutions. The question is however if the new smaller actors can make the required investments in electrolyzers and if these tank stations will be able to compete with centralized solutions in the future, since those arrangements will be able to produce hydrogen at a lower cost.

4.2.4 The Non-Dedicated Decentralized Scenario

The final scenario to be presented is where the hydrogen production is decentralized and not dedicated to be used by the transportation sector. This scenario could utilize electrolyzers used in real-estate or by farmers, if such a solution would get widespread use. Given the increased share of intermittent energy sources for electricity production, it is discussed that electrolyzers and hydrogen could be used to balance volatility in electricity production and price, and be connected to buildings to provide electricity and heat. This scenario would lead to that there would be many relatively small electrolyzers spread out all over the country. Both examples with farmers and residential areas investing in an electrolyzer have been brought up during the interviews as possibilities. However, there are few, if any, practical examples of such a development taking place and most respondents did not bring this up as a likely solution at a large scale in the nearest future. A possible implementation of the scenario would be that farmers have an off-grid electricity production through solar panels on a roof. An electrolyzer would then be used to produce and store hydrogen with excess electricity, that would be converted back to electricity when the solar power cannot produce electricity. This hydrogen production could then in theory be utilized by the transportation sector. This would lead to a truly decentralized system that consists of several independent producers of hydrogen, that could sell their excess hydrogen to actors, such as the transportation sector. The hydrogen can be assumed to be relatively cheap since the electricity is locally produced and does not need any grid connection. A visualization of where the scenario is found in the design space is seen in Figure 4.8 below.

Figure 4.8:
The non-dedicated decentralized scenario marked in the design space.



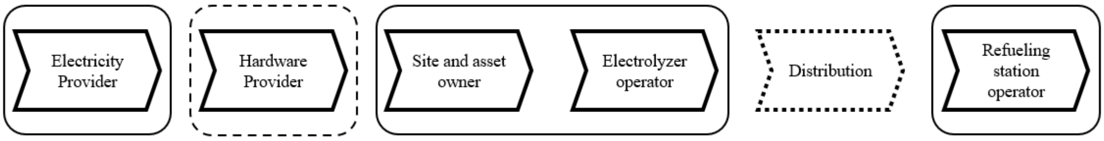
4.2.4.1 Possibilities and Challenges for the Scenario

Since this scenario involves many actors possessing electrolyzers, this leads to a great coverage of hydrogen refueling opportunities in Sweden with many units. No, or very short, distribution would be needed if refueling stations were established in relation to the production units. As mentioned earlier, few respondents elaborated this scenario as a possible outcome of the hydrogen development. As Sweden for large parts use sustainable alternatives to heat buildings and has a renewable source to balance the electricity grid with its large hydro power capacity, it is unlikely that a large transition towards using hydrogen for this would be widely adopted. It is however more likely that this development will occur in other European countries, where the electricity production and heating of buildings are different. Another issue of this scenario is the fact that the supply of hydrogen could differ from time to time and place to place, making it very unreliable.

4.2.4.2 Value Chain

In this scenario, the actors producing hydrogen could also be the ones generating electricity and managing the refueling operations. This would mean the actor was present in the entire value chain. Although, this opens up for many types of constellations since almost anyone can decide to enter the value chain. According to Walters et al. (2008), the value chain becomes more complex as more actors and organizations are being involved. In this scenario, it is therefore important to have a system perspective, something that also was argued for by a majority of the interviewees. Another important aspect is the level of knowledge these actors possess. A farmer is not an expert within hydrogen, fuel cells or other relevant areas, which would require for someone to manage this. This could be a system integrator. The value chain for this scenario could then look like Figure 4.9. In that case the farmer provides the electricity and owns and operates both the electrolyzer and the refueling station. A system integrator would however be needed to make sure the system is installed. Further, distribution might be needed, depending on contextual factors.

Figure 4.9:
A potential value chain for hydrogen infrastructure of the non-dedicated decentralized scenario.



Note. This figure demonstrates a potential value chain for the described scenario. It is possible for one actor to take multiple roles in the value chain, which is showed with the full line surrounding four of the roles. Although, it will be needed for other actors to take on the remaining roles, which is showed with the dotted line for the *Hardware Provider*. Further, *Distribution* might not be needed, which is why the role in itself is dotted. If distribution is needed, then this needs to be managed by one actor.

4.2.4.3 Volvo's Role

The transportation sector will lack control and power in this scenario because the hydrogen is not prioritized to be used for transportation. Furthermore, it is not certain that actors that decide to set up an electrolyzer want to allocate hydrogen for refueling stations. There are further investments and more activities involved in constructing a refueling station in addition to the electrolyzers, which is something that actors like Volvo could support. It will however be difficult for Volvo to further support and influence this development since it is dependent on that several independent actors will make a transition to use hydrogen.

4.2.4.4 The Scenario Over Time

As discussed, it is unlikely that this scenario will happen in Sweden at the current state of the energy system. However, since the cost of electrolyzers are expected to decrease (IRENA, 2020; Saba et al., 2018) and the share of renewable energy sources for electricity production are expected to increase (Energimyndigheten, 2021b), it could become more viable for real estate owners or farmers to invest in electrolyzers in the future to secure energy supply. The majority of respondents did however not discuss this scenario and it is unlikely that this solution will become widespread enough to supply the demand of the entire transportation sector. Instead, it is probably more likely that these solutions could provide for extra capacity in an already existing network.

4.3 LCOH calculations

In order to better understand the feasibility and what factors that influence the hydrogen cost in the different scenarios, the LCOH of hydrogen production and distribution for three different electrolyzer sizes are conducted. The result from the calculations are expected to provide a better understanding on what influences the cost of hydrogen and how this might be affected by different developments in the future. Three cases are designed with different electrolyzer sizes, ranging from 10 MW (Small) to 100 MW (Medium) to 1 GW (Large). These sizes are chosen to suit the examples of scale discussed for the different scenarios and from what interviewees indicated that the size of electrolyzers in their planned projects could be.

4.3.1 Small

The small case consists of an electrolyzer with the power of 10 MW. An electrolyzer of this size, or smaller, is assumed to be used in the decentralized scenarios. As explained in the decentralized scenarios, the electrolyzer is assumed to be placed in proximity to the tank station, which eliminates the need to distribute hydrogen. The LCOH thereby only depends on the production cost. Data from IRENA (2020) that says that an electrolyzer with the size of 10 MW costs \$ 750/kW is used. Since almost all of the proposed plans for hydrogen refueling stations initially will be placed in the south of Sweden, an electricity price of SEK 0,34/kWh is assumed, since this is the yearly average price of electricity in electricity areas SE3 and SE4 (Nord Pool, 2021). Assuming a dollar rate of SEK 8,4/\$ as per 2021-05-06 (Dagens industri, n.d.), a capacity factor of 40% as this is deemed to be the minimum amount that an electrolyzer can be used without having an unreasonable cost (Proost, 2019), a discount rate of 10% and a project lifetime of 20 years (Carmo et al., 2013), this leads to a LCOH of SEK 29,4/kg using Equation 2.1. In this case, the cost of electricity, in other words the major operational cost of the production, accounts for 58% of the total costs. A detailed description of the calculation is found in Appendix B.

4.3.2 Medium

The medium case consists of an electrolyzer with the power of 100 MW. Industrial companies that evaluate the possibility of investing in an electrolyzer are looking at electrolyzers of this magnitude. For this case, it is assumed that the electrolyzer would be used by many actors, much like the proposed cluster solutions. This leads to a need for the hydrogen to be distributed from the electrolyzer to a tank station. However, this distance would be rather short since the solution of a cluster builds on the idea that the hydrogen users are located close to each other. Using the data from Table 1.1 and assuming a distribution of less than 10 000 kg/day at a distance less than 100 km with gaseous hydrogen on trucks, the cost of distribution would in this case be $ 0,68/kg. IRENA (2020) shows that an electrolyzer with the size of 100 MW has an investment cost of $ 500/kW. Since the electrolyzer can be located anywhere in Sweden in this case, an electricity price of SEK 0,33/kWh is assumed since this is the average spot price for all of Sweden in the last 5 years. As the electrolyzer could be part of a cluster and have a larger capacity in this case, a capacity factor of 50% is assumed. With an assumed discount rate of 10 %, a dollar rate of SEK 8,4/$ and an expected lifetime of 20 years (Carmo et al., 2013), the LCOH of hydrogen production is SEK 23,1/kg using Equation 2.1. Adding the cost of distribution gives a a total cost of SEK 28,8/kg. In this case, the cost of electricity, accounts for 71% of the hydrogen production cost. A detailed description of the calculation is found in Appendix C.

4.3.3 Large

In the large case, it is assumed that a very centralized approach would be implemented, corresponding to one single electrolyzer supplying much of the hydrogen demand. Such an electrolyzer is assumed to have the size of 1 GW. A centralized approach requires that the hydrogen is distributed from the site of production to the site of consumption. The data from BloombergNEF (2020a) in Table 1.1 shows that the cost of distributing large amounts of hydrogen long distances have a cost of around $ 3/kg. According to IRENA (2020), it is assumed that an electrolyzer with the size of 1 GW have an investment cost of $ 400/kW. Such an electrolyzer would need to have a high utilization in order to be economically viable, which is why a capacity factor of 60% is assumed. If a centralized electrolyzer of this size was to be constructed in Sweden, it is assumed that it would be placed where the electricity is cheapest, which is in the electricity area SE1. Based on the average spot price for electricity in SE1 for the last 5 years, an electricity price of SEK 0,3/kWh is assumed. With a discount rate of 10 %, a dollar rate of SEK 8,4/$ and a system lifetime of 20 years (Carmo et al., 2013), the LCOH of production for this case is SEK 19,4/kg. Adding the cost for distribution gives a total cost of SEK 44,6/kg. The electricity corresponds to 77% of the production cost in this case. A detailed description of the calculation is found in Appendix D.

4.3.4 Sensitivity Analysis and LCOH Discussion

The LCOH depends on many factors, many of which are assumed, which is why the costs in absolute terms should not be interpreted as an estimation of what the future price of hydrogen will be. Rather, they give an indication of the magnitude of the costs, what influences the cost and how the costs in the different cases relate to each other. When comparing the costs of the different cases it can be seen that the costs are more or less the same, for why it is not possible to make a recommendation for any certain case due to the assumptions made. Each construction of an electrolyzer is case specific and will have its own costs, distribution needs and challenges. For example, constructing a large electrolyzer in the southern parts of Sweden could require that the electricity distribution grid is expanded, which in turn is a very costly investment that takes a long time to realize. Moreover, it is clear that the cost of distribution rises sharply and becomes a large part of the total cost when the amount of hydrogen and distances increase.

The larger the electrolyzer size, the larger is the share of electricity on the hydrogen production cost. This means that the electricity will to a larger extent affect the hydrogen price in the large case compared to the small case. For example, if the electricity price would be halved, the production cost would decrease with with 29% in the small case but with 39% in the large case. As the wind energy capacity is expected to increase in the future (Energimyndigheten, 2021b; IEA, 2020b), the electricity price will become more volatile. Consequently, the electricity will have a larger range between when it is cheap and when it is expensive, but it could at times reach a negative price (Svenska Kraftnät, 2015). This leads to different opportunities for different actors. Electrolyzer sites with large storage capacity could utilize the times when electricity is this cheap for hydrogen production and thereby produce hydrogen at a much lower cost. This does however pose a contradiction. The effect of this will be big for medium or large electrolyzers, but those electrolyzers are assumed to have a higher load factor since they supply a great demand with lower variations, for instance an industrial process. They might therefore not have any free capacity to chose when to produce hydrogen. Another aspect of the electricity price regards if electrolyzer production units were to be constructed and operated by wind power operators. In theory, these operators could then choose whether to use the electricity they produce for hydrogen production or to sell it to the grid, and in times of low or negative electricity prices, they could use the electricity to produce hydrogen with an electricity price that is basically zero. If the electrolyzer is connected directly to an off-grid electricity provider, such as a wind power park, the electricity price would also be different and lower than assumed in the cases. However, this would also require storage capacity at the refueling station to make sure that hydrogen can be supplied at times when electricity production is not possible.

As stated by Mayyas et al. (2019), Reddi et al. (2017), Saba et al. (2018), and Schmidt et al. (2017), the costs of electrolyzers are expected to fall rapidly when the production of electrolyzers increases and the manufacturing is industrialized. This would lead to a larger relative cost reduction of electrolyzers in the small case, as the investment cost of the electrolyzer is a larger share of the production cost. However in absolute terms, the investment cost is much larger for a large electrolyzer and such an investment might not be possible with the current costs of electrolyzers.

Another factor that influences the LCOH of hydrogen is the utilization rate of the electrolyzer. An increased capacity factor means that the electrolyzer runs for a longer time, and economies of scale then lower the LCOH. In an initial phase, it is likely that the demand for hydrogen will be rather low, especially for the transportation sector. Therefore, it is likely that the demand will not be high enough to motivate a high capacity factor and a large production of hydrogen, especially in the medium and large cases. For example, if the capacity factor is assumed to be the same in the large case as it is in the small case, 40%, the LCOH for the large production increases with 11%. It is thereby important that the capacity of the electrolyzer is set accordingly to the demand of hydrogen to ensure that a low cost can be achieved. Because of this Ulleberg and Hancke (2020) elaborates that smaller electrolyzers might be more viable from an economical perspective in the early phase of the hydrogen transition, since it will be easier to achieve a high capacity factor in that case. However, the industries that use hydrogen as input to their industrial process will have a large and reliable demand for hydrogen, which would justify a high capacity factor of a large electrolyzer. The transportation sector could thereby seek to engage in partnerships with such industries, as this would lead to a lower production cost of hydrogen.

The main takeaway from the LCOH calculations is however the relation between the cost of hydrogen production and distribution. In both the cases when the hydrogen has to be distributed, the distribution accounts for a rather large part of the total cost. In the medium case, the distribution contributes to a cost increase with a fourth of the production cost. The main objective when planning for a hydrogen scenario should therefore be to minimize the distribution. The cheapest alternative to distribute hydrogen is to use pipelines. According to BloombergNEF (2020a), the cost of distributing hydrogen in pipelines could be as low as SEK 0,42/kg. This does however assume that the pipeline network already exists, which is not the case in Sweden. The investment cost of constructing a new and nation spanning pipeline network for hydrogen distribution is extremely high, especially given the large geographical size of Sweden. For such an investment to be justified, the flow of hydrogen would need to be very large, something that is not expected, especially not initially. Instead, the amount of hydrogen distributed will be rather small, thus making it less reasonable for establishing pipelines. Another aspect of the problem is that even if a pipeline network was to be built, it would most probably only be connected between the largest users of hydrogen and not reach all the hydrogen refueling stations, meaning that there would still exist a need for transportation on trucks for the last-mile delivery. Lastly, unlike the case of electrolyzers, the technology of distribution is not expected to experience decreased costs when the demand and production of hydrogen increases. This means that while the production can be expected fall when the installed capacity of electrolyzers increase, the distribution costs can be expected to be rather constant in the future.

5

Discussion

This chapter presents and discusses the empirical findings in relation to theory and the scenarios derived from the design space. First, the scenarios and the factors affecting their development are discussed, showing that both a decentralized or centralized production can be suitable, depending on the purpose and location of the electrolyzer. It is also shown that the need for collaboration leads to that neither fully nor non-dedicated production is preferable. Secondly, the empirical findings are discussed in relation to the theory presented in Chapter 2, and finally these discussions are summarized into a recommendation for how a hydrogen infrastructure can develop in Sweden.

5.1 The Four Scenarios

The four scenarios presented and analyzed in the previous chapter were derived from the design space, meaning that they portray the theoretical possibilities of how a hydrogen infrastructure might develop. The scenarios are speculative and need to be discussed in terms of whether they are reasonable or not. However, theory does not always correspond to reality which is why the scenarios need to be discussed in order to understand the factors that influence the development of each scenario, such as the size of the electrolyzer and distribution, as shown in the previous chapter.

The analysis of the LCOH for the different cases of electrolyzer sizes showed that there is a clear trade-off present, between distributing the hydrogen to where it is needed which adds a significant cost to the total cost of hydrogen, or eliminating the need for distribution but thereby getting a higher production cost. In the centralized scenarios, it can be assumed that hydrogen production will be higher and more consistent compared to the decentralized scenarios, leading to a more secure supply of hydrogen for the transportation sector. FCEVs will compete with an established system of conventional trucks for market share, meaning that shortages of hydrogen at tank stations will not be accepted and would greatly harm the adoption of the technology. On the other hand, a large electrolyzer must be highly utilized in order to achieve economies of scale, meaning that the demand for hydrogen must be large. Since the transition towards FCEVs is expected to happen gradually and mostly take place for a sub section of the transportation sector, heavy-duty long haul trucks, the demand will initially be rather small. Therefore, a dedicated centralized scenario does not seem reasonable, since the demand will not be large enough to achieve a high load factor of the electrolyzer. However, an industrial user can be assumed to have a large and consistent need for hydrogen, meaning that they can achieve a high utilization rate of a large electrolyzer. For industries that can ensure a large and consistent demand of hydrogen, it thereby seems more promising to invest in a large electrolyzer. The transportation sector could support such development, for instance with investments in the electrolyzer and in return get access to the hydrogen production. In that case, it could be suitable for the transportation actors to participate in the project and collaborate to utilize the centralized production.

If the trade-off recently described is present, there is another important aspect that follows which concerns the amount of hydrogen. In a centralized scenario, large amounts of hydrogen are produced at a lower cost compared to a decentralized scenario. When the hydrogen is dedicated for transportation, the supply of hydrogen can be assumed to always be enough and never experience shortages. For the decentralized case, this is far more insecure. Hydrogen production can differ between hydrogen refueling stations depending on where they are located, but it could also result in problems. They need to have extra capacity and production to be sure to always be able to provide hydrogen, for instance in the case of unexpected events. Although, due to the early phase of this development and all available data, it might be possible to do very accurate estimations and thereby avoid shortages of hydrogen. A further benefit of a dedicated system is the increased control to the transportation actors.

For the scenarios that are non-dedicated to be used by the transportation sector there is one main issue. As the production primarily will be dedicated for other sectors than the transportation sector, the system will not be developed to be optimal for transportation. The transportation sector's power over the value chain would be smaller and it would be more difficult to influence the development in order to benefit for the adoption of FCEVs. Actors that invest in electrolyzers for their own use are mainly interested in fulfilling their own needs and do not want to make too many adjustments only to let the transportation sector benefit from them.

Regarding the cost of hydrogen production from electrolyzers, it should be noted that there is a wide range of estimations presented in the current literature. This makes it very difficult and uncertain to estimate a future cost of hydrogen and when it can become competitive with the conventional fossil alternatives of today. Especially regarding estimations of costs for hydrogen distribution, data is scarce. It will however be important for actors to know the future cost of hydrogen production and distribution, in order to decide whether to use a centralized or decentralized approach, which is why that costs of hydrogen distribution is recommended as an area for future research.

Many of the roles of the fossil fuel value chain are transferable into a hydrogen value chain as similar activities are performed today. It is possible for many of the actors of today's value chain for fuels to continue to perform the activities that they do today. What will change is rather the increased need for collaboration and new relationships that will need to be formed. The interviewees were both optimistic and pessimistic depending on perspective to this development, as many stated that Swedish companies have experiences of collaborating in the development of technology transitions in the past, but none have any experience of doing this with hydrogen. Given that the activities in the new value chain will likely be similar to what they are today for conventional fuels, it can be assumed that the collaboration will be easier since the relationships might already exists and each actor knows what activity they can or will perform. Despite the development being in a very early phase, actors know which actors they can collaborate with and what their roles will be, something that should increase the chances of finding ways to collaborate and create a new value chain.

Advantages and drawbacks of the scenarios have been presented and there are some key takeaways. Regarding a centralized or decentralized infrastructure, they differ in terms of secure supply, investment costs and distribution. All of these aspects can be seen as trade-offs. The dimension regarding dedication to the transportation sector differs when it comes to control, power and investment costs. Since all of these aspects in both dimensions can be seen as trade-offs, one can argue that there are different situations in where different aspects are more important. Although, the level of dedication provides for no clear benefits when it is either maximized or minimized. Maximum dedication to the transportation sector provides a secure supply of hydrogen, but will require very large investment costs and at the same time have a small demand, especially in the early stages of the development. On the other hand, with minimal dedication of hydrogen to transportation, the power and control is close to zero, which also means it might result in that no hydrogen refueling stations are established. Further, it might result in refueling opportunities that is not optimal, resulting in increased distances and thus costs for the truck owners and operators. A non-dedicated system would also require that partnerships and collaborations with new actors are formed and that several industrial actors decide to make investments into renewable hydrogen solutions. The time and resources to first form such close relationships, and then get everyone to make decisions whether to invest in electrolyzers is likely to be too long to ensure that a hydrogen refueling infrastructure is developed when FCEVs are commercialized. This argues for a system to neither be maximized nor minimized regarding dedication to transportation. Regarding the centralized and decentralized scenarios it has been clear that the difference is not as big as for the dedication dimension. The cost of production is decreased the more centralized the system becomes, but at the same time the distribution cost is also increased. The more decentralized a system is, the less distribution cost but higher production cost. This means that, as discussed, a trade-off is present and what level of centralization is something that should be decided depending on the context.

5.2 Empirical Impressions

In the interviews conducted in the study, a lot of different perspectives and aspects of the hydrogen infrastructure development were brought up. These empirical findings can guide how a hydrogen refueling infrastructure can develop in Sweden and what different actors believe about the hydrogen development. Some aspects were brought up and discussed more than others, and these will be discussed further along with how they can affect the hydrogen infrastructure development. One such aspect is the need for a system perspective. The focus of this study is on hydrogen infrastructure development in Sweden, but some interviewees argued for a global perspective because Sweden alone will not create a system that is unique. Sweden will need interfaces, regulations and standardization that is aligned with the rest of the world. Moreover, with many actors engaging in hydrogen projects, there is a risk of them focusing on their own internal processes. The actors that are able to step back and take a system perspective could benefit a lot from this, by collaborating with others. By taking a system perspective and looking at which applications hydrogen solutions can make the largest impact, it is possible to find collaborations and with others. An example of where this is suitable is in the case of excess hydrogen from industries that could be used in FCEVs. An arrangement like this where both parties assure supply and demand would lower the barriers and thus move the development forward, and it is not possible to find these collaboration unless a system perspective is taken. Adner (2006) states that the performance and the dependencies within a system greatly affects the success of an innovation, indicating the need to have a system perspective and for each actor to look further than just their own needs and role. Further, Walters et al. (2008) emphasize the importance of having the entire value chain in focus, instead of one part, as they become more complex the more actors that become involved. Many interviewees also stated the importance for each actor to have a system perspective of the development and look further than just their own purposes.

The most discussed and brought up topic during the interviews was the need for a system perspective and collaboration between different actors. As hydrogen production from electrolysis still is more expensive than SMR for production of hydrogen and conventional truck fuels, all interviewees stressed the need for initiatives to decrease the costs. Collaborations were seen as a key to reduce costs and make a more complete system, since it will be too expensive for one single actor to make the transition on their own. As several industries will have a need, and make use of renewable hydrogen, there are several actors that are in the same situation of wanting to make the transition but are being held back because it is not economically viable. Actors could then instead collaborate or create a consortium to invest in an electrolyzer. Such collaborations could also spillover and lead to that further synergies are created. For example, if Volvo collaborates with a steel manufacturer for hydrogen production, they would not only get the possibility to obtain renewable hydrogen as fuel. The steel produced would use the hydrogen to make renewable steel which could be used to build trucks, leading to a more sustainable truck. A majority of the interviewees mentioned synergies to be something that could be achieved, which would favor for collaborations. The main reason for the collaborations however is to share the costs and risks, since the hydrogen projects initially require large investments. Further, some respondents argued that the knowledge level is increased when collaborations take place, and at the same time the production of electrolyzers is increased, which leads to a lower CAPEX. All of these beliefs are supported by literature. Rese (2006) argues for lowered coordination costs when collaborations are present as well as increased productivity, which in turn leads to increased value. Powell (1990) argues that it is better to work in networks when working with new technologies and Majava et al. (2013) also discusses the increased utilization of resources and that economies of scale can be achieved in collaborations.

One challenge regarding collaboration between actors is the coordination, which was mentioned by a majority of the interviewees. Collaborations and networks are not created out of nothing but need to be initiated by some actors. Since different actors can have different roles in the collaboration, there is also a need for coordination. Organizing in networks with no clear coordination, can according to Glasmeier (1991) lead to a collective action problem, where the absence of a clear coordinator in the network results in problems to deal with change and staking out the path forward. The interviewees had different ideas on how this could be solved. Some argue for having an actor with a dedicated coordinating role, without having a hydrogen use. On the other hand some argue for an actor that is more operative in the network, and produces or uses hydrogen, to take on the coordinating role. This also comes in various levels where one actor might need to take a coordinating role in Sweden, and other actors need to take this role lower in the system in various projects. During one interview it was mentioned that it is important to try to avoid power imbalance in these collaborations. Having a third party actor undertaking the coordinating role would manage this coordination and in that way, all involved actors in the project has equal power and the coordinating actor can operate without risking conflict of interest. There are some actors that could have a more obvious coordinating role, for instance if they interact with different industries and sectors today and do not need hydrogen for own use. This could be universities, ports or municipalities, to mention some examples. However, this is yet to be discovered since there are no clear answers to the question and no aligned view among different actors. Further research on the coordination in these projects is therefore recommended.

The early phase of the hydrogen development is another challenging factor for collaborations. One respondent exemplified this by describing that it was difficult to know if conversations were held with a future supplier, customer or competitor when having meetings with other actors about hydrogen projects. If this is unknown and it is not clear which roles that will be needed and what roles other actors will take, it is difficult to develop trust, which is important when forming successful partnerships according to Majava et al. (2013). This is only one reason why there are rather few examples of practical hydrogen projects in Sweden. As actors still do not know what can be achieved with the technology and how it might develop, many would rather wait to engage in projects. Many interviewees expressed frustration that there was a lot of talk, but no real action and that the development had become similar to the concept of waiting game from Robinson et al. (2012).

The public sector is believed to have a large role in order to overcome the waiting game and get the hydrogen development going. Green hydrogen is still more expensive than the fossil alternatives, meaning that companies will chose the fossil alternative if no public interventions are made. Many interviewees talked about how green investments must be competitive with the current alternatives, and that it is the role of the public sector to create the market conditions for this. This can, according to the interviews, be done in mainly two ways. Either requirements should be established to make it more expensive to release emissions, and thereby making the fossil alternatives more expensive, or provide for a financial framework that lower the costs of hydrogen. Regarding making fossil alternatives more expensive, interviewees discussed the possibility that it in the future could become illegal to approach a city or drive with a fossil fueled vehicle. Some respondents even assumed that this would become a reality and built their business case upon that assumption. To create financial preconditions for actors were something a majority of the interviewees believed to be important. As stated by Jacobsson and Bergek (2004), it is essential to get investment from governments for a technology in the era of ferment should to make a breakthrough. Furthermore, it could be even more difficult for green technologies to reach the market, thus leading to a waiting game since they according to Bakker and Budde (2012), might lack performance. Hydrogen is a green technology, and thus investment from the public sector could help overcome this barrier and potential waiting game. For example, one could argue hydrogen competes against conventional fuels, which excels hydrogen in performance and costs but have a worse impact to the environment. In line with the statement from Klijn and Teisman (2003) saying that public funding can lead to synergies both for the private and public actors, as the public actors are encouraged to develop innovative solutions while also promoting renewable alternatives and private actors are helped to overcome the high barriers. This is also supported by Un and Montoro-Sanchez (2010) who state that public funding have a positive outcome on innovations.

The financial support from the public sector could be both in forms of investment capital for electrolyzers or subsidizing hydrogen and the elements included in hydrogen production. Such support will rather come from the public sector organizations on a national level than on a regional or local level. The regional and local level of the public sector have a clear assignment to provide citizens with the alternatives that are best right now, and rarely budgets large enough to help to make the investments necessary. However, they could instead undertake a coordinating role, conduct research and support with knowledge and guidance to the hydrogen infrastrcture development. The possibility to apply for financial support via the initiatives IPCEI and Industriklivet was viewed positively by most respondents and seen as an opportunity to get started with hydrogen projects. Some did however state that it still was unclear how to apply and what type of projects that was promoted. Therefore, many interviews also stated that a clearer pathway of how Sweden should develop a hydrogen infrastructure and what the goal of such a development will be should be presented by government officials. The Swedish Energy Agency did during the spring of 2021 begin to develop a national hydrogen strategy from Sweden, which was welcomed by all interviewees. Some did however raise concerns that this action had been initiated too late and that Sweden risked of failing behind compared to other European countries. It is clear that the public sector will have to play a big role in the hydrogen development, both by staking out a pathway and a way forward but also by supporting financially in order for the development to take off.

To overcome the era of ferment and the situation where a lot of plans are made but no action takes place, it is important to perform tests and launch hydrogen projects. In line with the hypothesis-driven approach by Eisenmann et al. (2012), many interviewees stated that there currently are not enough projects undertaken where the hydrogen technology is tested. Several respondents talked about how the current knowledge is just theoretical and that practical projects will drive the development and show capabilities of the hydrogen technology, while at the same creating knowledge. Furthermore, Sweden is not familiar with an everyday use of gases. As a result, the knowledge level is very fluctuating where some actors have a lot of knowledge while others are very inexperienced. It was mentioned during one interview that no one has knowledge about renewable hydrogen solutions because it is so new in this setting. Instead, there is a collective learning taking place. This is an idea that further supports the need for projects in the field, but also the need for collaboration. Another aspect of testing and launching projects brought up in many interviews is the positive effect it will have on further development. Showcasing successful applications of hydrogen will encourage more to test the technology, which will accelerate the development. Almost all actors that were interviewed emphasized this need because that is how you learn and get experiences. Doing this in niche markets, which are the type of markets new technologies tend to enter before being further adopted (Griliches, 1957), are according to Eisenmann et al. (2012) suitable. This shows the need for demonstration projects in suitable niches that provide for learning opportunities.

To make these projects a reality it is important to get public support as presented earlier. If the public sector engages in this, there is a chance to align the activities, but also create a framework for the future development. This can cover many different aspects, from safety regulations regarding hydrogen to how much emissions it is allowed to release. Many actors also pointed at the importance to get a streamlined system for hydrogen and compared it to the system for conventional fuels. In one way is the development initiated by politics that demand for a more sustainable society. It can then be argued for the public actors to support the transition and provide for support or guarantees that reduce the risks for actors to make the change. It was also mentioned during the interviews that the sustainable actions taken by companies should be rewarded in some way, especially if one actor takes the lead. Some argued for an automatic reward in terms of increased market share combined with knowledge and increased sustainability for the pioneers. Some others argued for some kind of financial reward system, where the government initially supported the first-movers with large resources that eventually were reduced after time as more actors followed.

By initiating projects within hydrogen infrastructure development, it is possible to move it forward from where it is today. Some interviewees emphasized that many actors talk about their visions and plans, but it is even more important to show in practice. These actors also believed that what type of projects that are initiated is not important, it is more important to increase knowledge and development. For instance, there are many ideas proposing that hydrogen is a great way to balance the power grid in Sweden. However, it appears that this is mainly theoretical today and that no one really have tested it or know how such a solution would work in practice. Furthermore, these projects would potentially increase legitimacy for the actors engaged and in turn it is possible that more actors feel safe to also to the transition.

Distribution was discussed with many interviewees as a great challenge for the hydrogen infrastructure development. The ideas differ on what method that is most suitable, where some actors believe a decentralized approach without any distribution is best, while others believe that compressed gas on trucks is the way to go. Regarding liquid hydrogen, some benefits are brought up during the interviews, but the hydrogen flow is not deemed to be large enough now or in the nearest future to make it a reasonable solution. Over time, this might change, with further development and experiences. Independent of what method that will be used, the electricity supply will be of importance. The distribution grid will need to be upgraded to be able to provide for the planned electricity need and is a potential bottleneck. This issue argues for solutions that are off-grid and will not be limited by bottlenecks in the power distribution grid, as brought up earlier. Solutions that are small are easier to provide electricity for, and would result in a lower investment cost compared to a large system with associated electricity production, thus lowering the barriers for smaller actors.

The high costs of the construction of a renewable hydrogen infrastructure are a major barrier and the reason for why it has not occurred earlier. The investment costs are still very high, but they are expected to decrease as production of hydrogen equipment is increased. In combination with the reduced cost for renewable energy, it is these aspects that power the hydrogen development. IRENA (2020), Mayyas et al. (2019), and Saba et al. (2018) all mention that CAPEX will decrease in the future with increased activity. This does however require that someone is willing to buy electrolyzers today at a higher price. This is an action which the public sector could support, which is why public support to cover the investment cost of electrolyzers were proposed by many interviewees. OPEX mainly consists of the cost for electricity, and can largely influence the total cost for making a transition to renewable hydrogen solutions. The entire rise of renewable hydrogen solutions relies on a large supply of cheap renewable energy. If that is not the case, renewable hydrogen solutions are not viable. Although, the production of renewable electricity is not considered to be a challenge according to the interviewees, as more are concerned over the distribution grid capacity. This is another factor that could lead to a waiting game situation that has been discussed earlier. If the cost of electrolyzers and renewable energy is expected to decrease sharply in the future, some might consider waiting in order to reduce the financial investments and risks. It is more safe to wait five years to when the technology and applications are further developed. But, this would be a disadvantage to the development and would slow down the current innovation pace. It is now clear that projects need to be initiated to lower the costs and if all actors shared this mindset, the development would be slowed down.

5.3 How to Develop the Hydrogen Infrastructure in Sweden?

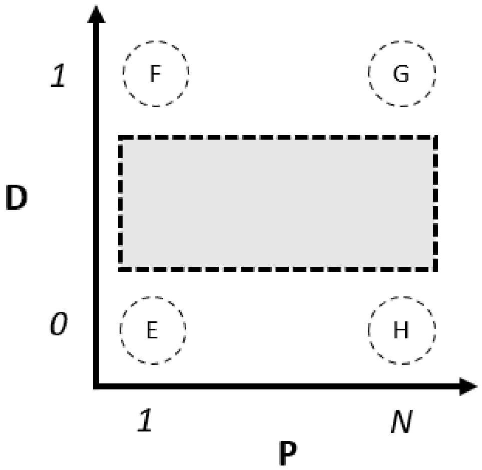
Regarding the first dimension in the design space, there is a trade-off between centralized and decentralized production. The different systems provide for various benefits and drawbacks, such as a low production cost but high distribution cost in the centralized scenarios. It has also been clear that more projects are needed, independent of size, in order to drive the development forward and further reduce the investment costs of electrolyzers, which today is a large barrier. However, as the LCOH calculations showed, it is difficult to determine and suggest whether a centralized or decentralized system should be adapted. Each hydrogen production unit will have to be evaluated based on the characteristics and conditions of the situation and purpose of the electrolyzer. If a large industrial actor that can ensure a large and consistent demand plans to make a hydrogen transition, a centralized system might be suitable to achieve greater scale. But if an actor with many different sites are planning a transition to hydrogen, a decentralized system could be reasonable to avoid the distribution cost. This was also a topic that the interviewees had shared views on, with no clear or aligned idea. Furthermore, the list of companies that applied for financial support via the IPCEI-initiative consisted of companies that will use both centralized and decentralized approaches, indicating that both types of systems are being developed in Sweden. These aspects imply that the production system will consist of both centralized and decentralized solutions that work together and complement each other in a hydrogen infrastructure system.

The second dimension in the design space, dedication of production to the transportation sector, is not as dependent on contextual factors as the earlier one. There are some benefits and drawbacks of having a completely dedicated or non-dedicated hydrogen production for transportation needs. For instance, the control over the value chain is expected to be higher for the transportation sector in a dedicated scenario, but with high costs and a low initial demand for hydrogen. In a non-dedicated scenario, the production cost of hydrogen will probably be lower for the transportation sector by utilizing excess hydrogen and capacity, but with the negative aspects of having less control and a slower development. If a non-dedicated approach is taken, the transportation sector would become dependent on industrial actors to make the hydrogen transition, leading to lower control of the development. This becomes more prominent as the transportation sector requires that a network of electrolyzers are constructed, rather than just a single one close to an industrial site. Therefore, it is very uncertain that a completely non-dedicated approach would lead to a hydrogen production setting that is sufficient to cover the demands of FCEVs. Furthermore, the interviews showed that the time frame of hydrogen projects differ among many of the large industrial actors, where some actors' plans are relatively long. This means that it would take long time to construct a hydrogen refueling network based on a non-dedicated approach. The development should therefore have a share of dedication for transport already from the beginning to ensure the development for a network of stations that are ready when FCEVs are commercialized. Furthermore, as close to all interviewees stated that a collaborative approach for a hydrogen infrastructure development was preferred and deemed a requirement for a hydrogen infrastructure to develop, it does not seem viable with a production unit that is dedicated for any sole purposes. Instead, the system should be developed with hydrogen production for several purposes where different actors could make use of an electrolyzer. This implies that the dedication factor will end up in the middle, indicating that hydrogen will be produced for several purposes.

5.4 Recommendations

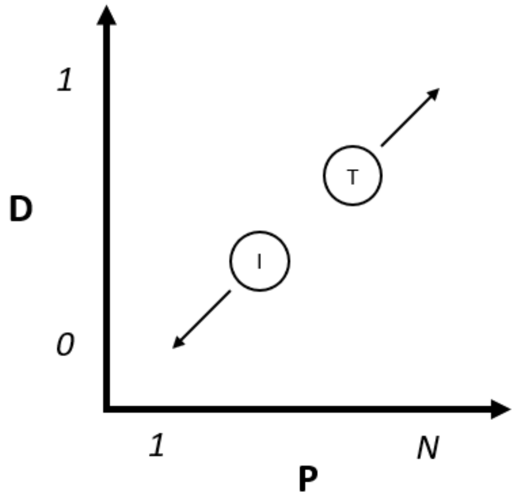
The presented aspects combined leads to a recommendation that is the design space in Figure 5.1. The square represents the area of the proposed hydrogen infrastructure development, with both centralized and decentralized approaches being suitable but with the need for collaboration leading to a system that is not dedicated to any certain actor.

Figure 5.1:
The design space marked with the area where it is recommended for actors to position themselves in for future development of a hydrogen refueling infrastructure.



From a cost perspective, the overall development of a hydrogen infrastructure system would benefit if the transition starts off using a centralized approach with larger industrial actors first. The capital expenditures of an electrolyzer are a main hinder for the hydrogen infrastructure development but by constructing large electrolyzers, the manufacturing scale and electrolyzer production will increase leading to that the costs for electrolyzer components will decrease. Thus, construction of large electrolyzers will spark the electrolyzer manufacturing industry, leading to lower electrolyzer costs which in turn will make it easier to establish decentralized projects. However, as it can be seen that there is also a high interest and already plans of decentralized projects, it is likely that a mixed system using both centralized and decentralized approaches will develop from the start. This could lead to that the early movers of decentralized projects will have problems in being profitable. Moreover, this increases the risks of a dispersed development and further emphasizes the requirement of close collaborations and clear framework with pronounced coordination. The collaboration and partnerships will be key to handle the high costs in the initial phase of the development. As the development moves on, knowledge increases and the technology matures. It is therefore likely that there will be a development where this requirement will decrease and that production becomes more and more dedicated over time, leading to several systems where each hydrogen purpose has its own system, based on its specific needs and characteristics. This development is illustrated in Figure 5.2, where the transportation sector's needs for a large number of tank stations and the large distribution costs are likely to lead to a system which is decentralized with production dedicated for transportation.

Figure 5.2:
The design space showing potential development over time.



Note. In the design space, the development for traditional industries (I) and the transportation sector (T) can be seen. It is believed that the systems initially will be positioned in the area showed in Figure 5.1, but over time the industrial use of hydrogen will lead to more centralized systems not dedicated to be used by the transportation sector, and the transportation sector will seek to develop dedicated systems in a decentralized setting.

It is believed that Volvo does not have a natural position in the value chain to take on any of the roles presented earlier since that is very far away from their core business today. Instead is recommended that Volvo should engage in projects that have the purpose of increasing hydrogen usage. On a general level, the projects could be in different sectors since all of these still would increase knowledge and at the same time decrease the investment costs. The projects could be managed alone, but it is recommended to collaborate with others, which provides for many benefits such as shared risks and reduced costs. This was the main takeaway from the interviews. Examples of how Volvo could engage in such partnerships could be to create consortia with actors that plan to invest in electrolyzers. In this way, real projects could be created quicker and the technology would be tested, which would lead to faster learning. The consortia could be created with industrial actors with a large-scale electrolyzer, like the earlier described example of Volvo and Ovako, new actors or energy providers constructing decentralized and small-scale electrolyzers, but also with large companies that have a great distribution need, such as retailers. Such initiatives would lead to an increased level of hydrogen production and a possible creation of hydrogen tank stations, but also lead to further synergies. Many actors, independent of industry, have large transportation needs and even if a manufacturing company uses renewable energy for all its processes, they still need to distribute their products which probably stands for a lot of emissions. By collaborating with other actors to construct electrolyzers, it is possible to conduct pilot projects where hydrogen trucks can be fueled with hydrogen produced at the industry and then is used for the industrial actor's distribution. This would serve as a suitable niche market to test and learn about the technology in real life cases, as argued by Eisenmann et al. (2012) and Griliches (1957). By retrieving fuel cell trucks from Volvo, a partner company can achieve even lower carbon footprint, which should be a driving force from their view. From Volvo's perspective, tank stations would be constructed and FCEVs will be tested and introduced in a smaller scale before being diffused. Although the main objective should, as pointed out in almost every interview, be to engage in real projects and test possible solutions to validate the technology and learn how it best could be utilized.

A framework needs to be established by the public actors regarding how this development should proceed in Sweden. After the proposed hydrogen strategy from Fossilfritt Sverige was presented in the beginning of 2021, the Swedish Energy Agency initiated the work to develop a national strategy for Sweden. This is an important step, as almost all interviews pointed at the need for a framework and financial support regarding hydrogen. It is important that this strategy has a global perspective as well, since it was clear from the interviews that Sweden will not manage this hydrogen development alone and that global arrangements and standards are important. It is also recommended to upgrade the power grid in Sweden. Production of renewable electricity will increase, but there might be challenges to distribute this electricity if the distribution grid is not expanded. Since this will take many years, it is further recommended for actors to investigate in the possibilities of creating off-grid systems. This would decrease demand for electricity from the national grid, but also provide benefits such as the possibility to locate production where it is optimal.

6

Conclusion

Hydrogen has the potential to greatly impact our society and the environmental challenges that we currently face. Many actors want to be a part of this development, but it will require great efforts and resources to make it a reality. In this study we have interviewed actors with different perspectives regarding the development of a hydrogen infrastructure and elaborated on potential scenarios that illustrate how a hydrogen refueling infrastructure can develop as hydrogen becomes a more frequently used element in the society.

It has been clear in this study that there are many possible paths for the development of a hydrogen refueling infrastructure in Sweden and that each path could be adapted to fit each situation. The study shows that in general, both a centralized or decentralized approach can be suitable and that the hydrogen production is recommended to be neither fully nor non-dedicated to be used by the transportation sector. Further, the main factor influencing the hydrogen development are the high costs, which need to be lowered in order for hydrogen solutions to reach widespread use. To lower the costs, actors are recommended to collaborate, have a system perspective on the development and initiate projects to increase the use of hydrogen and achieve synergies. Further, the public sector plays an important role and it is suggested to establish a framework regarding the development of hydrogen solutions as well as provide financial support or establishing regulations to make hydrogen more competitive against the current fossil alternatives.

Volvo Group can take an active role in the development by initiating and be involved in projects in the field. As collaboration and initiating projects are important to achieve progress, Volvo can accelerate the development and obtain knowledge about the technology which is crucial at this stage of the development. With the size and power of Volvo, the company has a great possibility to legitimize hydrogen solutions and make way for further development. Volvo is already involved in multiple projects of hydrogen development, such as the examples of cellcentric, H2Accelerate and Ovako and it is recommended to continue on this path. Since the development is in a very early phase, there are great opportunities to be involved and shape the future. To get there, it is suggested for Volvo to support and collaborate in projects as much as possible.

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A

Appendix A

Interview Guidelines

Start off by:

- OK to record?
- Present aim, who we are and give context to the study

Explain your role and how you and your organization work with hydrogen.

Could you start by explaining your take on hydrogen, and how you may work with it today?

How do you experience that other actors are investing in hydrogen projects?

What is your take on the knowledge regarding hydrogen today in Sweden?

What would be the main purpose for you and your organization if you were to invest in hydrogen?

What role do you plan to take in the future value chain for hydrogen, and what is your idea regarding this?

What potential do you see for hydrogen solution in the coming 15-20 years, both for your organization but also for society as a whole? In which industries do you believe it will have its main use areas?

What is your organization's role in hydrogen projects? To coordinate the work? Construct pilot projects and learn?

Distribution is a great issue when it comes to hydrogen. What does your organization think about this (in Europe and Sweden)? (As Sweden don't have a pipeline network.) Do you think it is reasonable to transport hydrogen on trucks, or better to produce it at the tank stations? Gaseous or liquid hydrogen?

Do you think the limitations of the power distribution grid will limit the development of a hydrogen production infrastructure?

What is your view on partnerships for hydrogen development? How should the roles be divided in such partnerships? Who coordinates? What actors, institutions and networks are most important in the development of hydrogen partnerships? Do you believe it is probable that such collaborations will succeed?

The EU has had a big role in legitimating hydrogen, what is your view on how authorities and institutions work with this toady, and what do you think they should do?

What do you believe are hindering the hydrogen development?

What is the most important part that you believe should be prioritized for a hydrogen infrastructure to develop as fast and smoothly as possible?

Do you have anything that you would like to add, that could be good for us to know?

Do you have any recommendations on people that could benefit this study?

Is it okay for us to mention you in our report, as input providers?

B

Appendix B

Presentation of Assumptions and Calculation of LCOH for Small Case

Equation to calculate LCOH:

$$LCOH = \frac{\sum_{n=1}^{t} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{n=1}^{t} \frac{m_t}{(1+r)^t}} \tag{B.1}$$

where *CAPEX* and *OPEX* are the capital and operating expenditures, r is the discount rate, m represents the kg of hydrogen produced, n is the lifetime of the system and t is the year in operation.

Small Case

CAPEX is according to IRENA (2020) \$ 750/kW.

Size of electrolyzer: 10 MW.

$$CAPEX = \$750/kW * 10MW = \$7500000 \tag{B.2}$$

CAPEX only occur in t=1.

OPEX is assumed to consist of O&M and electricity costs.

O&M is assumed to be 2% of CAPEX costs, according to Minutillo et al. (2021), and reoccurs for every t>0.

$$YearlyO\&M = 0,02 * \$7500000h = \$150000 \tag{B.3}$$

The electricity cost depends on electricity price and how much electricity is used.

An electricity price of SEK 0,34/kWh is assumed, which corresponds to \$0,04/kWh for a dollar rate of SEK 8,4/\$.

A capacity factor of 0,4 leads to that 3504h out of the possible 8760h will be used for production in a year.

$$YearlyElectricityCost = \$0,04/kWh * 3504h * 10MW = \$1418286 \tag{B.4}$$

$$OPEX = \$1418286 + 150000 = \$1568286 \tag{B.5}$$

OPEX occurs for t > 1.

Energy consumption in stack is 4,5 kWh/Nm^3 according to NEL Hydrogen (2021). 1 Nm^3 corresponds to 0,0899 kg of hydrogen. The yearly hydrogen output equals m.

$$m = \frac{10MW * 3504h * 0,0899kg/N\text{m}^3}{4,5kWh/N\text{m}^3} = 700000kg \tag{B.6}$$

m occurs for t > 1.

t ranges from 1-20 as a system lifetime of 20 years is assumed, as per Carmo et al. (2013).

r = 10%

Using Equation B.1 leads to LCOH = \$3,499 = SEK 29,4.

C

Appendix C

Presentation of Assumptions and Calculation of LCOH for Medium Case

Equation to calculate LCOH:

$$LCOH = \frac{\sum_{n=1}^{t} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{n=1}^{t} \frac{m_t}{(1+r)^t}} \tag{C.1}$$

where *CAPEX* and *OPEX* are the capital and operating expenditures, r is the discount rate, m represents the kg of hydrogen produced, n is the lifetime of the system and t is the year in operation.

CAPEX is according to IRENA (2020) $ 500/kW.

Size of electrolyzer: 100 MW.

$$CAPEX = \$500/kW * 100MW = \$50000000 \tag{C.2}$$

CAPEX only occur in t=1.

OPEX is assumed to consist of O&M and electricity costs.

O&M is assumed to be 2% of CAPEX costs, according to Minutillo et al. (2021), and reoccurs for every t>0.

$$YearlyO\&M = 0,02 * \$50000000h = \$1000000 \tag{C.3}$$

The electricity cost depends on electricity price and how much electricity is used.

An electricity price of SEK 0,33/kWh is assumed, which corresponds to $0,039/kWh for a dollar rate of SEK 8,4/$.

A capacity factor of 0,5 leads to that 4380 out of the possible 8760h will be used for production in a year.

$$YearlyElectricityCost = \$0,039/kWh * 4380h * 100MW = \$17207143 \tag{C.4}$$

$$OPEX = \$1000000 + 17207143 = \$18207143 \tag{C.5}$$

OPEX occurs for t > 1.

Energy consumption in stack is 4,5 kWh/Nm^3 according to NEL Hydrogen (2021). 1 Nm^3 corresponds to 0,0899 kg of hydrogen. The yearly hydrogen output is based on the capacity of the electrolyzer and for how many hours it is operated.

$$m = \frac{100MW * 4380h * 0,0899kg/N\mathrm{m}^3}{4,5kWh/N\mathrm{m}^3} = 8750000kg \tag{C.6}$$

m occurs for t > 1.

t ranges from 1-20 as a system lifetime of 20 years is assumed, as per Carmo et al. (2013).

r = 10%

Using Equation C.1 leads to production LCOH = $2,752 = SEK 23,12.

It is assumed that the distribution of hydrogen will be less than 10000 kg per load and that the distance will be less than 100 km. According to BloombergNEF (2020a), the cost of distribution will be $ 0,68/kg.

This gives

$$TotalCost = 23,12 + 0,68 * 8,4 = SEK28,8/kg \tag{C.7}$$

D

Appendix D

Presentation of Assumptions and Calculation of LCOH for Large Case

Equation to calculate LCOH:

$$LCOH = \frac{\sum_{n=1}^{t} \frac{CAPEX_t + OPEX_t}{(1+r)^t}}{\sum_{n=1}^{t} \frac{m_t}{(1+r)^t}} \tag{D.1}$$

where *CAPEX* and *OPEX* are the capital and operating expenditures, r is the discount rate, m represents the kg of hydrogen produced, n is the lifetime of the system and t is the year in operation.

CAPEX is according to IRENA (2020) \$ 400/kW.

Size of electrolyzer: 1 GW.

$$CAPEX = \$400/kW * 1GW = \$400000000 \tag{D.2}$$

CAPEX only occur in t=1.

OPEX is assumed to consist of O&M and electricity costs.

O&M is assumed to be 2% of CAPEX costs, according to Minutillo et al. (2021), and reoccurs for every t>0.

$$YearlyO\&M = 0,02 * \$400000000h = \$8000000 \tag{D.3}$$

The electricity cost depends on electricity price and how much electricity is used.

An electricity price of SEK 0,30/kWh is assumed, which corresponds to \$0,036/kWh for a dollar rate of SEK 8,4/\$.

A capacity factor of 0,6 leads to that 5256 out of the possible 8760h will be used for production in a year.

$$YearlyElectricityCost = \$0,036/kWh * 5256h * 1GW = \$187714286 \tag{D.4}$$

$$OPEX = \$8000000 + 187714286 = \$195714286 \tag{D.5}$$

OPEX occurs for t > 1.

Energy consumption in stack is 4,5 kWh/Nm^3 according to NEL Hydrogen (2021). 1 Nm^3 corresponds to 0,0899 kg of hydrogen. The yearly hydrogen output is based on the capacity of the electrolyzer and for how many hours it is operated.

$$m = \frac{1GW * 5256h * 0,0899kg/N\mathrm{m}^3}{4,5kWh/N\mathrm{m}^3} = 105003000kg \tag{D.6}$$

m occurs for t > 1.

t ranges from 1-20 as a system lifetime of 20 years is assumed, as per Carmo et al. (2013).

r = 10%

Using Equation D.1 leads to production LCOH = \$2,311 = SEK 19,42.

It is assumed that the distribution of hydrogen will be less than 10000 kg per load and that the distance will be less than 100 km. According to BloombergNEF (2020a), the cost of distribution will be at least \$ 3,00/kg.

This gives

$$TotalCost = 19,42 + 3,00 * 8,4 = SEK44,62/kg \tag{D.7}$$

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