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Value Chain Development for Hydrogen Refuelling in Road Transports

In collaboration with Vätgas Sverige, as part of the Nordic Hydrogen Corridor

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ABSTRACT

The events involving the Russian invasion acted as a catalyst for Europe to acknowledge the critical importance of diversifying its energy sources and diminishing its dependence on fossil fuels. This occurrence directly supports the continent's objective of decarbonization by facilitating the implementation of renewable energy systems, saving energy, and advancing on the establishment of modern regulatory frameworks that support different technologies. The most energy intensive sectors should the first to be addressed, such as industry and transportation in Europe. Considering that the last is mainly fuelled by fossil fuels with significant emissions, it is imperative to transition its energy supply to low-emission alternatives.

Over the past few years, the transportation industry has primarily centered its efforts on electrification as the top-notch approach to overhaul its operations. However, the adoption of batteries and plug-in hybrids as the primary technologies has been minor, capturing only a meager market share of 18% in 2021. Consequently, an equal deployment of complementary low-emission technologies is necessary to make a greater impact on the market and effectively tackle specific requirements, conditions, and tasks. Low-emissions hydrogen is one of the feasible technologies that can help achieve the decarbonization objectives in this sector, due to its energy density and versatility. Acknowledging such an alternative, the EU is recently backing its deployment under several strategies and regulatory frameworks, but still the development of a hydrogen market and ecosystem is at an early stage.

Sweden, a country with strict emission regulations currently holds one of the cleanest grids in Europe, giving it great potential for low-emission hydrogen production through electrolysis, which is being exploited by the industry. As one of the member states of the EU, this Nordic country must adopt the guidelines regarding hydrogen development, which includes the deployment of a refuelling infrastructure across the territory. Nevertheless, it is essential to construct a strong business model for hydrogen mobility that will enable its long-term deployment, entice a greater number of stakeholders, mitigate financial risks, and accelerate market development. Naturally, various aspects of its value chain can influence the desired outcome, and it is these aspects that this project aimed to investigate and evaluate.

On one hand, by incorporating perspectives from various industrial stakeholders and literature research, the development of a value chain cost model helped identifying key factors that could make competitive the hydrogen technologies for mobility, such as electricity procurement and subsidies for CAPEX and OPEX. On the other hand, under the same perspectives a regulatory framework assessment brought light to important gaps along the chain, such as the transmission of H_2, and the lack of coordination in the promotion and support of the hydrogen ecosystem and market guidelines. One clear advantage is the momentum and knowledge that the industry is building up for H_2, which the country must capitalise on by investing in technologies and developing policies that accelerate the development phase.

On the concluding remarks shaped as a 10-points checklist for a robust business model, the highlights encompass the need to secure revenue streams along the chain, cost parity with current technologies, acceleration and certainty of permitting processes, standardisation, and a stronger HRS infrastructure and offtakers that match supply with demand, among the previously mentioned.

ABSTRAKT

Händelserna som involverade den ryska invasionen fungerade som en katalysator för Europa att erkänna den avgörande betydelsen av att diversifiera sina energikällor och minska sitt beroende av fossila bränslen. Denna händelse stöder direkt kontinentens mål om koldioxidutsläpp genom att underlätta implementeringen av förnybara energisystem, spara energi och gå vidare med etableringen av moderna regelverk som stöder olika tekniker. De mest energiintensiva sektorerna bör åtgärdas först, såsom industri och transport i Europa. Med tanke på att den sistnämnda huvudsakligen drivs av fossila bränslen med betydande utsläpp, är det absolut nödvändigt att ställa om sin energiförsörjning till alternativ med låga utsläpp.

Under de senaste åren har transportindustrin i första hand fokuserat sina ansträngningar på elektrifiering som det förstklassiga sättet att se över sin verksamhet. Antagandet av batterier och plug-in-hybrider som de primära teknologierna har dock varit mindre och tagit bara en mager marknadsandel på 18 %. Följaktligen är en likvärdig användning av kompletterande lågemissionstekniker nödvändig för att få ett större genomslag på marknaden och effektivt hantera specifika krav, villkor och uppgifter. Vätgas med låga utsläpp är en av de möjliga teknikerna som kan bidra till att uppnå avkolningsmålen i denna sektor, på grund av dess energitäthet och mångsidighet. Genom att erkänna ett sådant alternativ stöder EU nyligen dess utbyggnad under flera strategier och regelverk, men utvecklingen av en vätemarknad och ett ekosystem är fortfarande i ett tidigt skede.

Sverige, ett land med stränga utsläppsregler, har för närvarande ett av de renaste näten i Europa, vilket ger det stor potential för lågutsläppsproduktion av väte genom elektrolys, vilket utnyttjas av industrin. Som ett av EU:s medlemsländer måste detta nordiska land anta riktlinjerna för vätgasutveckling, vilket inkluderar utbyggnad av en infrastruktur för tankning över hela territoriet. Ändå är det viktigt att konstruera en stark affärsmodell för vätgasrörlighet som kommer att möjliggöra dess långsiktiga utbyggnad, locka ett större antal intressenter, mildra finansiella risker och påskynda marknadsutvecklingen. Naturligtvis kan olika aspekter av dess värdekedja påverka det önskade resultatet, och det är dessa aspekter som detta projekt syftade till att undersöka och utvärdera.

Å ena sidan, genom att införliva perspektiv från olika industriella intressenter och litteraturforskning, hjälpte utvecklingen av en kostnadsmodell för värdekedjan att identifiera nyckelfaktorer som skulle kunna göra vätgasteknologierna konkurrenskraftiga för mobilitet, såsom elanskaffning och subventioner för CAPEX och OPEX. Å andra sidan, under samma perspektiv, ledde en regelverksbedömning till viktiga luckor längs kedjan, såsom överföring av H2, och bristen på samordning i främjandet och stödet av väteekosystemet och marknadsriktlinjer. En tydlig fördel är det momentum och kunskap som branschen bygger upp för H2, vilket landet måste dra nytta av genom att investera i teknologier och utveckla policyer som påskyndar utvecklingsfasen.

På de avslutande kommentarerna utformade som en 10-punkters checklista för en robust affärsmodell, omfattar höjdpunkterna behovet av att säkra intäktsströmmar längs kedjan, kostnadsparitet med nuvarande teknologier, acceleration och säkerhet för tillståndsprocesser, standardisering och en starkare HRS-infrastruktur och avhandlare som matchar utbud med efterfrågan, bland de tidigare nämnda.

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ABBREVIATIONS

AEM	Anion Exchange Membrane
AFIR	Alternative Fuels Infrastructure Regulations
BEV	Battery Electric Vehicle
CCfDs	Carbon Contracts for Difference
CCS	Carbon Capture Storage
CEF	Connecting Europe Facility
CF	Capacity Factor
DSO	Distribution System Operators
DSO	Distribution System Operators
EC	Environmental Code
ETS	Emissions Trading System
EUA	European Union Allowance
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FOM	Fixed Operation and Maintenance
GHG	Green House Gases
GJ	Gigajoules
GW	Gigawatt
HRS	Hydrogen Refuelling Station
IRA	Inflation Reduction Act
LCOD	Levelized Cost of Distribution
LCOE	Levelized Cost of Electricity
LCofHRS	Levelized Cost of dispensing at a Hydrogen Refuelling Station
LCOH	Levelized Cost of Hydrogen
LCOT	Levelized Cost of Transmission
Mt	Million Tonnes
MWel	Megawatt electric
MWh	Megawatt hour
NHC	Nordic Hydrogen Corridor
NZE	Net Zero Emissions
NZIA	Net Zero Industry Act
OM	Operation and Maintenance
PC	Passenger Car
PEM	Proton Exchange Membrane
PHEV	Plug-in Hybrid Electric Vehicle
PPA	Power Purchase Agreement
PtX	Power-to-X
PV	Photovoltaic
RES	Renewable Energy System
RFNBOs	Renewable Fuels of Non-Biological Origin
RQ	Research Questions
SMR	Steam Methane Reformation
SOEC	Solid Oxide Electrolyser Cell
tCO_2e	Tonnes of carbon dioxide equivalent
TEN-T	Trans-European Transport Network
TSO	Transmission System Operators
TWh	Terawatt hour
UnCAPEX	Unitary CAPEX

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1 INTRODUCTION

The world has experienced critical events during the past few years that affected the economy and the energy sector. While the two were recovering from the pandemic of COVID-19, the Russian invasion to Ukraine created significant impacts in the global energy markets [1]. The uncertainty around natural gas supply shook the energy security foundations of most of the EU countries that deeply depended on fossil fuel imports, and most of the planet, affecting the affordability, the cost of living, and the emissions [2]. Despite the circumstances, several countries reaffirmed their pledge of avoiding a global temperature increase above 1.5°C during COP27, by delivering a package of decisions to reduce Greenhouse Gas (GHG) emissions and financially assist developing countries with climate change adverse effects [3].

Decarbonisation of economy sectors can be addressed, among others, through increasing electrification by the hand of renewables, which can be the most efficient and cost-competitive solution for many cases, and low emissions hydrogen for the hard-to-abate ones [4]. In line with COP27, for the Net Zero Emissions (NZE) scenario, by 2050 electricity would be the backbone of global energy systems, by providing more than 50% of the total final consumption, with an increase of 3.3% per year from now on. This electricity, harnessed mainly from solar and wind, will also be used to produce low-carbon hydrogen. It can be expected that this gas, together with hydrogen-based fuels, to reach even more than 10% of the total final consumption by that year, depending on the market development and economic feasibility [5].

To attain the challenging goals of this scenario, GHG emission reduction efforts must address firstly the most emitting sources. The power sector including electricity and heat generation accounted for 40% of global emissions in 2020 and increased even more during 2021 (6.9%). Transportation and industry came afterwards with 23% each, with a rebound in transportation in 2021 after the pandemic mobility restrictions in the world [5]. Considering the fact that hydrogen can create direct impact over the two sectors, that it can be produced via water electrolysis and renewable energy, and that it has a higher energetic yield compared to hydrocarbon fuels [6], the deployment of this energy carrier should also be fostered.

Nonetheless, to unfold low-carbon hydrogen utilisation, demand must meet supply in an economically feasible way. In 2021, the world demand for hydrogen was approximately 94 Mt, with a 50% increase over since 2000, driven mainly by the chemical industry, with 48 Mt/year, and oil refining processes, with 40 Mt. However, only 0.7% of hydrogen corresponded to low-emission production, supplied mostly from fossil fuels with carbon capture technologies and, of that, a smaller 28% via electrolysis [7]. To successfully deploy this energy vector, the industry and transportation markets should switch their fossils fuel usage, regulatory frameworks should be developed, infrastructure and knowledge should grow, and finances should add up, of course with a shift in H_2 production to avoid emissions growth. Opportunely, many different projects in both sectors are being demonstrated, policies are developing, grants given, and technology readiness level is rising, paving the way for the demand surge that is forecasted.

Hydrogen demand is expected to be between 150 and 600 Mt by 2050. The broad range depends on the scenario that the world follows, aligned with the global temperature increase. To achieve the 1.5 - 1.8°C increase, demand would grow from 220 Mt in the announced pledge scenario to 600 Mt in the NZE scenario. Therefore, policies and low emissions hydrogen cost would be important gamechangers for a higher upsurge of H_2, together with industry development [8].

From the global policies perspective, 26 countries have pledged to accept low emissions hydrogen in their energy systems, reflected in an accumulated electrolysis national targets capacity increase more than 50% from 2021 to 2022, projecting 145-190 GW of deployment. Up to 15 new bilateral international agreements were developed, centred in hydrogen trade, adding private sector agreements to develop technologies and supply chains [7].

In a NZE, the cheapest method to produce hydrogen is by reforming natural gas without storing the process emissions (grey hydrogen), having an average Levelized Cost of Hydrogen (LCOH) of 1.5 USD/kg in 2020. According to McKinsey, the average LCOH of same process and year with Carbon Capture and Storage (CCS), would be 2 USD/kg. For electrolysis produced hydrogen, sometimes called clean or green H_2, the average LCOH corresponds to 5.3 USD/kg [9]. With technology development, clean hydrogen production could decrease to 2 USD/kg in the next 10 years, becoming cost-competitive [9]. Also, with carbon pricing policies booming 100 USD/tCO_2, grey hydrogen is expected to lose its competitive advantage in the near future [10]. The so called green, electrolytic, renewable, or clean hydrogen, will be called low-carbon hydrogen through the extent of the report, or simply hydrogen, as some CO_2 emissions throughout its lifecycle are inevitable.

Despite emissions tax increase and hydrogen policy improvements, few efforts have focused on industrial applications. Instead, it is the transport sector that has the most development and policies focused on demand creation, primarily through subsidies. From 2020 to 2021, H_2 demand grew 60% driven mostly by road transportation [7]. Within the framework of the European Green Deal target to reduce GHG emissions from transport by 90% by 2050, further deployment in the EU can be expected in the coming years, driven by the European Commission's policy priorities [11]. State guidelines have proven effective in countries such as the United States, Japan, Norway, among others, where purchase and/or fuel subsidies, tax reductions and infrastructure benefits have contributed to the deployment of this technology.

Sweden, a country with more than 50% of its total energy consumption coming from renewable energies and its derivates, could follow in the footsteps of its neighbouring country, Norway, in the implementation of low-carbon hydrogen for transportation and abating emissions that account for nearly 45% [12]. Aligned with the Trans-European Transport Network (TEN-T) policy, backed by AFIR, the country is starting to develop the Nordic Hydrogen Corridor (NHC) that will connect the capitals of the Nordic countries, accounting for 8 HRS and over 100 FCEVs. This corridor called Scandinavian-Mediterranean, is part of one of the nine TEN-T corridors.

Presently, the country has industries pushing the transition; the government is not fully aligned in the opportunity of hydrogen and the EU directives are guiding political developments. As the first pilot already started, the scope of this work is to assess how can low-carbon hydrogen in road-transportation thrive, by addressing a multidimensional perspective of the value chain that helps to build a strong business model.

2 PURPOSE OF THE PROJECT - UNDERSTANDING THE CASE

2.1 Scope & Objectives

Low-carbon hydrogen could become a turnkey solution to decarbonise hard-to-abate sectors such as transportation. In Sweden, some hydrogen refuelling stations (HRS) are being deployed as a demonstration project to evaluate the necessary factors for wider market acceptance of road-transportation. By assessing each link in the low-carbon hydrogen value chain with its stakeholders, under a holistic approach encompassing techno-economic, political, and end-user social dimensions, the characteristics of a solid business model will be identified. The work will be divided into the following sections:

- Model the hydrogen refuelling stations value chain in the Swedish context with literature inputs, and stakeholders' validation, demonstrating key aspects that could influence its deployment.
- Understand how the synergy between hydrogen refuelling stations value chain, automakers and end users can be influenced by policy, technology adoption and incentives to encourage market deployment.
- Determine the success factors, risks, opportunities, and challenges involved in the development of low-carbon hydrogen infrastructure.

The specific Research Questions (RQ) to be answered are:

1. What needs to be achieved with regards to hydrogen offtake in relation to refuelling stations investments cost and operating expenses, to make a robust business case?
2. Through qualitative analysis, establish to what extent user experience along with additional factors like public financing, transport policy measures and market incentives will affect market rollout for fuel cell vehicles and refuelling infrastructure.
3. Develop a checklist for robust business model along the entire hydrogen refuelling value chain, taking into account financial risk mitigation, availability of public finance instruments, role of market incentives and variety of revenue models.

2.2 Methodology & Boundaries

The methodology of this project was mainly focused on the development of the research questions (RQ), focusing the first on the techno-economic aspects and the second on policies, subsidies, and end-user experience, all over a 5-year probable scenario – 2023 to 2028. Value-chain cost model, interviews, and regulatory framework analysis are the three chapters where the data acquisition and preliminary outcomes were explained. The validation of the techno-economic assessment and comprehension of the regulatory framework across the value chain were achieved through literature research, and some interviews. The stakeholders, who possessed extensive knowledge of the subject, provided us with feedback and helped validate our findings. Indeed, end users give the extra information of their experience as hydrogen vehicles users. As is shown in Figure 1, each research question has different outcomes that contribute to the creation of a SWOT analysis, a risk assessment, and understanding of the bottlenecks through the value chain specially in mobility. As a conclusion, a checklist for a strong business model for hydrogen mobility in Sweden was proposed.

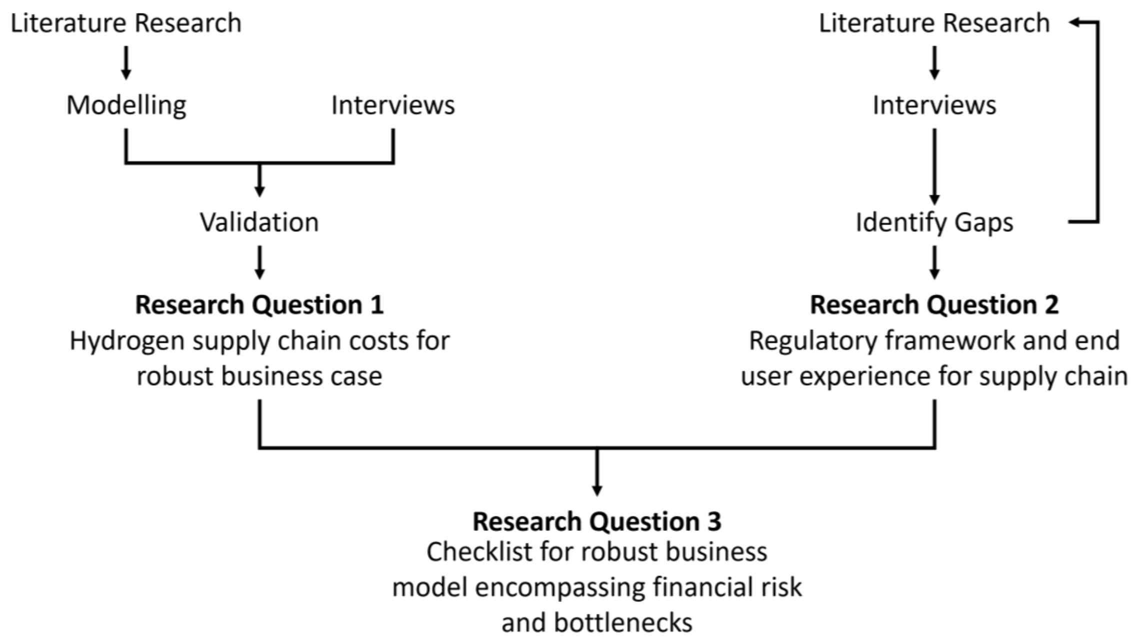

Figure 1. Flow diagram for methodology.

The starting point for the RQ1 and RQ2 was an extensive literature research, to understand the context and the development that Sweden has had in the low-carbon hydrogen value chain with emphasis on mobility. For RQ1, said research worked as an input for the development of a MATLAB model. The model's objective was to show the possible costs along every step of the value chain under certain assumptions and give a broad understanding of the Swedish costs.

For both RQs, the validation of the information was done through interviews with different stakeholders along the value chain. Naturally, key points, broader insights, and new information were gathered to research further, using a feedback loop methodology to identify any gaps in the process. By developing this practice, the authors were better prepared and informed before the next interview was scheduled. As the nature of RQ2 involved policies that could impact the development of H_2 in Sweden, such information also was used as an input for RQ1.

The data of each RQ and acquired outcomes was used to develop a holistic analysis, that translated into the development of a SWOT analysis and a financial risk overview as a prelude to the final conclusions. Figure 2 shows the boundaries of analysis for the research questions, considering that the analysis was from 2023 until 2028.

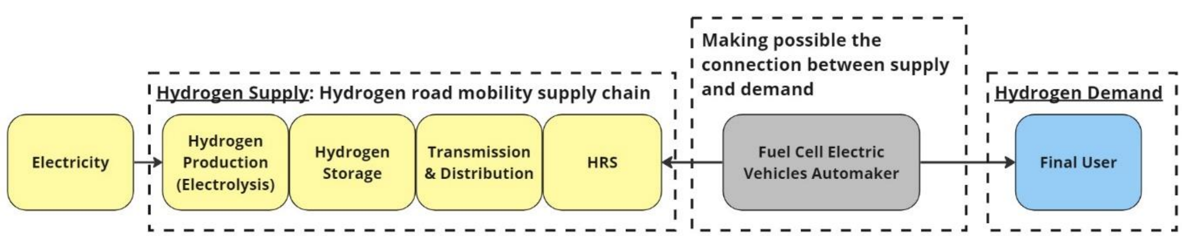

Figure 2. Methodology boundaries.

The cost model for RQ1 used the hydrogen supply boundaries for analysis. Electricity was just considered as an input for the system and not analysed in detail for the cost model. The RQ2 on the other hand, took into account hydrogen supply and demand, with the connecting link being the automakers with its FC vehicles, reaching out the end users.

2.3 Political guidelines

The European commission develops several directives (goals) and regulations (legal obligations) that all the EU member states, including Sweden, should follow by developing its own policies. The European Green Deal is the strategy seeking to reduce emissions of all EU economy sectors by 55% in 2030, compared to 1990. To accomplish such goal, the Fit-for-55 package intends to review and modify the regulations to put into a concrete policy framework several directives. Some of the policies being reviewed that impact the way hydrogen economy and infrastructure can be developed in the EU countries are the Emissions Trading System, the Gas Directive, and the Renewable Energy Directive. Regarding mobility, regulations such as the Clean Vehicles Directive, the Alternative Fuels Infrastructure Regulation, Sustainability and Smart Mobility Strategy encompassing the Trans European Transport Network, are driving the change. Is worth mentioning that the REPowerEU plan is boosting many of the previous regulations in favour of the energy security of Europe.

2.4 Supply chain overview

To be able to deliver the hydrogen to the FCEVs, hydrogen must go through different steps, which together build up the low-carbon hydrogen supply chain for road mobility. Hydrogen must be first produced, further distributed, stored, and finally dispensed to the FCEVs, as in the following image.

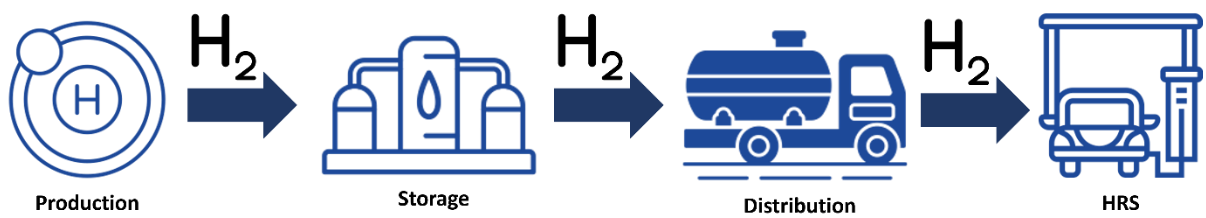

Figure 3. Hydrogen road mobility supply chain.

In this subchapter, an overview of the hydrogen supply chain for road mobility is given.

2.4.1 Hydrogen Production

Hydrogen is a common input for the chemical and oil refining industries, where the latter consumes 40 million tons (Mt) of hydrogen by 2020 [13]. However, the predominant production method is steam methane reformation (SMR), accounting for 90 Mt of hydrogen, or 95% of the annual global hydrogen production, a fossil resource-based process. Therefore, it is relevant to decarbonize the production of hydrogen, useful for these industries, and highly relevant for the decarbonization of other sectors. To be able then to obtain hydrogen from renewable sources, many different processes exist. The following diagram shows the different processes used to obtaining hydrogen, ranging from fossil resources, biomass, and water splitting technologies.

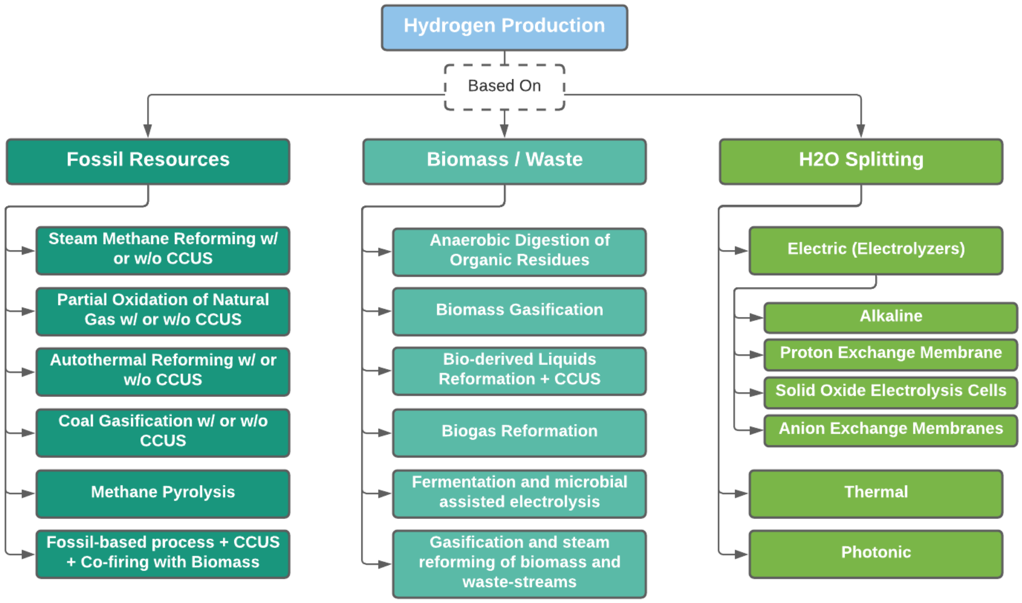

Figure 4. Hydrogen production technologies summary. Data has been obtained from the United States Department of Energy Hydrogen Program Plan [14] and the International Energy Agency Global Hydrogen Review [13].

Water splitting technologies offer the opportunity to reduce the reliance on hydrogen production based on fossil resources, and fully decarbonise this sector. Biomass emerges as an option in between to take advantage of resources with biological origin. On the left side of the chart, processes such as SMR emits 7 kg of CO_2, per 1 kg of hydrogen produced [15], which translates approximately into 590 Mt of CO_2 in 2020. However, this process, coupled with carbon capture, usage, and/or storage (CCU, CCS, CCUS), is able to reduce its emissions.

Water splitting technologies, especially water electrolysis, are predicted to become the predominant technology for hydrogen production. Many organisations, such as the IEA, BP, and IRENA, predict different levels of hydrogen production by 2050, with predictions between 500 and 660 Mt of clean hydrogen [16]. This trend towards water splitting technologies is becoming relevant, especially electrolysis, as the energy necessary to obtain this molecule could be sourced from renewable sources.

For electrolysis to occur, water and electricity are the most relevant inputs of the system. Water needs a demineralization process before entering the electrolyser stack, otherwise its components like membrane and catalyst could degrade faster and the OPEX would increase. Usually, the need of water would depend on the source, with e.g., lake water needing a rate of 1.5:1 for a Reverse Osmosis process and an electricity consumption for the treatment process of 2.2 kWh. Overall, between 9 and 10 litters of ultrapure water are needed to produce 1 kg of H_2 [17].

On the other hand, most of the emissions related to this process are dependent on the electrical grid mix. Added to this, many authors have already stated that electricity has large impact on the levelized cost of hydrogen (LCOH). For this reason, electricity is a major component to consider when analysing low-carbon hydrogen production. The impact however will further vary according to the technology and its operational parameters. Parameters such as electrical efficiency, pressure, and temperature of electrolysis, play a major role on the electrical consumption. The capacity factor, also relevant, allows to maximise fix costs. For high-temperature and high-pressure electrolysers, the electricity costs could represent as low as 36.9%

of the total costs, however this was obtained through electrochemical models and simulations [18]. Nevertheless, the Oxford Institute for Energy Studies, states that the main cost is electricity with 73%, which follows data gathered from operational and developed electrolysers [19]. The following table shows the KPI's for different electrolysis technologies relevant today such as PEM and AEM, and in the following years such as SOEC, relevant for the supply chain model.

Table 1. Summary of electrolysis technologies KPIs [19] [20] [21] [22] [23] [24].

KPI	PEM	SOEC	AEM
Temperature	50 – 80°C	700 – 850°C	40-60°C
Pressure	< 70 bar	1 bar	35 bar
Nominal System Efficiency (LHV)	70 – 80%	76 – 81%	< 74%
H_2 Production	400 Nm^3/h per stack	10 Nm^3/h per stack	925 Nm^3/h
Lifetime	50,000-90,000 h	8,000- 20,000 h	~30,000 h
CAPEX	1400 – 2100 EUR/kW	> 2000 EUR/kW	n/a
OPEX (% of CAPEX per year)	3 – 5%	n.a.	3 – 5%
Technology Readiness Level	9	7	6

Moreover, water electrolysis has different byproducts. As hydrogen is produced out of the splitting of water molecules (H_2O), oxygen is also obtained, a desired molecule for many industries. Additionally, electrolysis works at high grade temperatures, useful for different industrial processes and for district heating. Lastly, as there are targets to produce 7 TWh of hydrogen, equivalent to 1,280 MWel [25], there will be an increasing need for demand flexibility. Therefore, the right utilisation of byproducts could lead to extra revenues for hydrogen production, with further reduction of the cost of hydrogen produced.

Nevertheless, Sweden offers the possibility for cheap and low-carbon energy sources, such as hydropower, wind, biomass, and nuclear energy. This has created an environment in Sweden to invest and develop hydrogen production projects with immediate offtakers. This is represented in Figure 5, where it shows the geographical distribution of future projects concerning "fossil-free" hydrogen production on the left, and on the right, the potential for hydrogen hubs in different regions of the country.

The location of these hydrogen production projects is closely linked to the development of industrial hubs and municipalities, allowing to link the possible extra revenues mentioned above with immediate offtakers during the project development. However, the access to electricity for these projects is a topic to be analysed. Therefore, and even though electricity is not showed in the boundaries analysed, it is relevant to understand the electrical grid in Sweden, its future development, and the impact of hydrogen production.

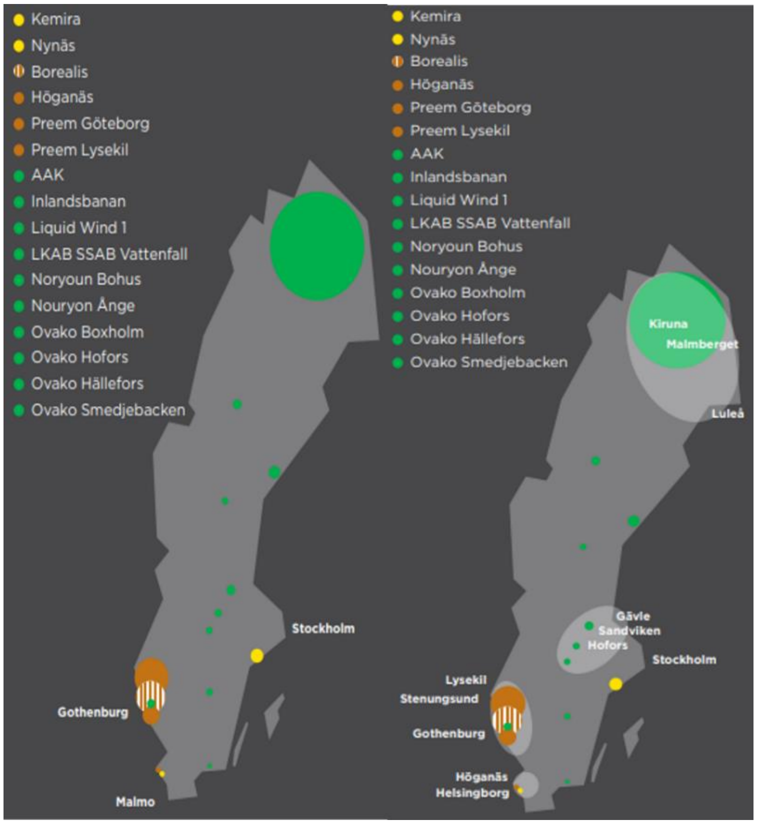

Figure 5. Hydrogen production projects in Sweden (left) and potential hydrogen hubs in Sweden (right) [25]

2.4.2 Electricity

Recognised for its abundant renewable energy sources, such as biomass and moving water, Sweden has crafted policies to develop its economy trying to prioritise ecological sustainability, competitiveness, and energy security. The reduction in fossil fuels and diversification of energy sources from 1970 is a clear accomplishment of the policies and technologies, as shown in the Figure 6. The country surpassed its 2020 goal of achieving a 50% renewable energy share in its energy mix as early as 2012, by promoting more biofuel utilization (consumption have tripled since 1980) and decreasing oil and petroleum usage (half consumption over the last 40 years). From the 508 TWh supplied, its final energy consumption in 2020 after losses and non-energy consumption was of 355 TWh, with higher shares of industry and buildings with 38.3% and 39.4% respectively, and transportation having the remaining share of 22.25% (79 TWh). Also, out of the 328 TWh of fossil fuels entering the country, 159 TWh are exported and 95 TWh are used. Electricity exports accounted for 37 TWh in 2020 [26].

Electricity generation in 2020 accounted for 161 TWh (135 TWh utilisation), and was mainly provided by hydropower, nuclear energy, and wind power with 45%, 29% and 17% respectively. The residential sector also used the most electricity with 70 TWh, followed by the industry with 47 TW and a low value for the transportation sector with 3 TWh [12]. It is expected that electrification keeps pushing back fossil fuels consumption, creating a possible scenario of electricity need of 286 TWh by 2045, which is more than double of today's utilisation [12].

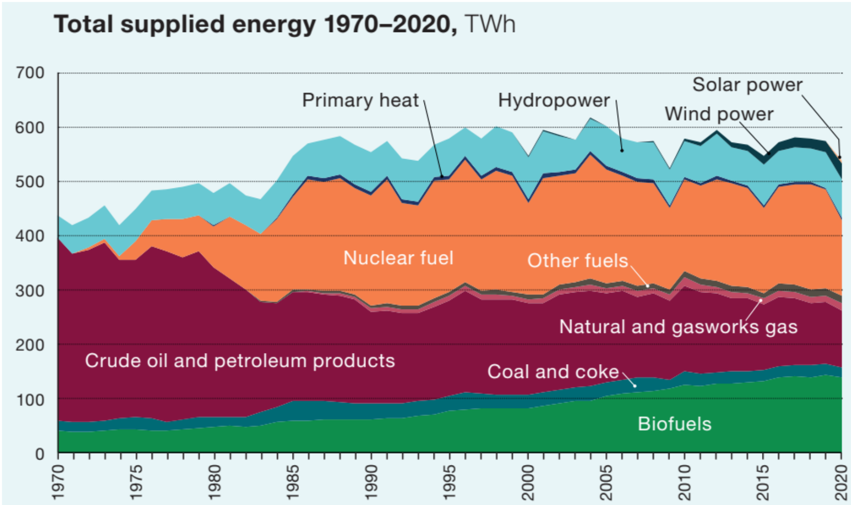

Figure 6. Energy mix of the total energy supplied yearly in Sweden [12].

Sweden is partitioned into four bidding areas, with SE1 located in the northern region and SE4 positioned in the southern region. The price of electricity in these areas is influenced by factors such as the supply-demand dynamics of electricity and the transmission capacity connecting the bidding areas. Northern Sweden can experience surplus electricity production relative to demand, while southern Sweden faces the opposite scenario. Consequently, there is a substantial transfer of electricity from the north to the south of the country with variation in prices across the bidding areas as a result of the physical limitations of the national grid [27]. The electricity prices are currently under a volatility period, with electricity price peaks as high as 600 €/MWh, showing the vulnerability of Sweden to natural gas prices instability after the shortage of natural gas flows from Russia to Europe, and the further invasion of Russia to Ukraine. This is represented in the following image, showing the electricity prices evolution since 2015, where prices maintain seemingly constant, until the natural gas shortages in 2021.

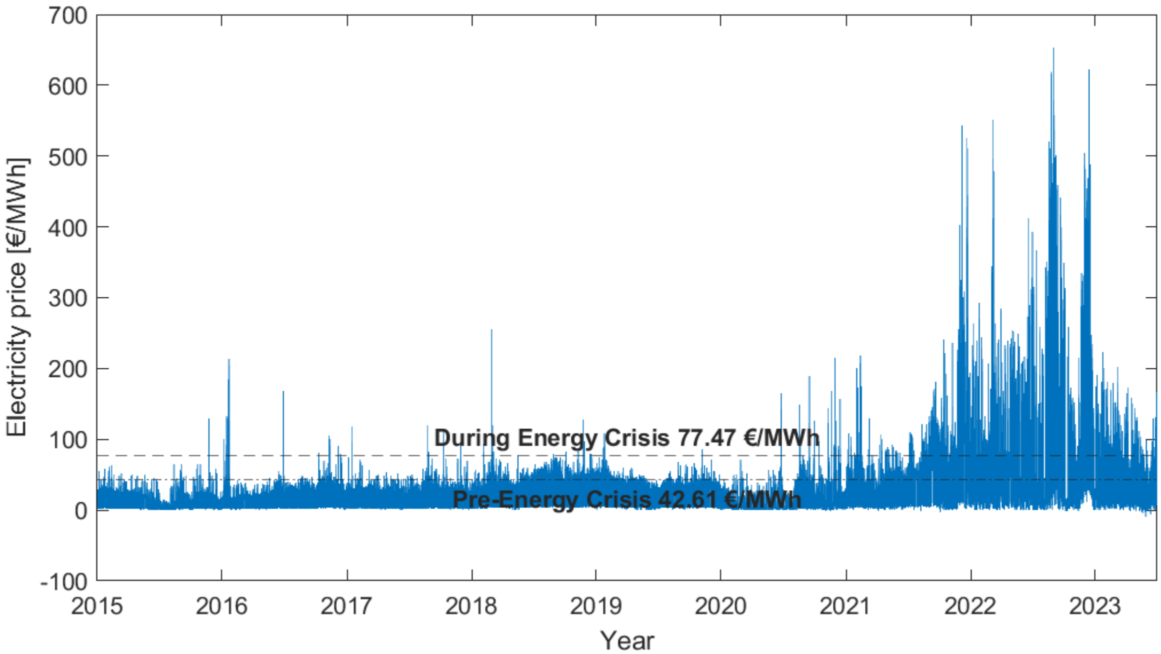

Figure 7. Historic electricity prices 2015-2023. Data retrieved from Ember Climate [28].

As a consequence, the average electricity price jumped almost 35 €/MWh, from 42.61 €/MWh to 77.47 €/MWh. Now, with the increased normalisation of the natural gas market, the electricity prices are coming out of a period of extreme volatility, however, there are uncertainties on how the market is going to develop on the following years. Additionally, the crisis has also affected the prices of fossil fuels such as petrol and diesel prices. Therefore, the development of more distributed renewable energy projects in Sweden is imperative to reduce the reliance on external electrical grids, further de-linking the natural gas with the power market. However, negative electricity prices, a new frequent phenomenon, is highlighting an issue with power markets, interconnections between countries, and the need for demand flexibility [29] [30] [31]. This new electricity prices scenario imposes a challenge for hydrogen producers and increase the uncertainty in hydrogen costs for the future.

2.4.3 Storage, transmission, and distribution

In this section, the management of low-carbon hydrogen through the entire transport process is assessed – from production site, until the HRS gate. The focus lies on the transport and storage of the low-carbon hydrogen for the road mobility supply chain in Sweden. As natural gas, hydrogen gas can be transported via pipelines, liquefied, and/or compressed in trucks. Moreover, it could be stored in similar conditions as natural gas in caverns, rock formations, and containers, however, with considerable differences due to the properties of the gas. Transmission and distribution differentiate on the pressure, distances, and quantity of hydrogen transported. While transmission focuses on transporting for long distances from production to consumption areas at high pressures and large quantities, distribution takes from the transmission grid and delivers the gas to the final user with smaller demand. The exact numbers to differentiate between both, mostly depends on national regulations for these sectors.

Table 2. LCOT according to the European Commission report on overview of costs and key benefits from hydrogen generation in Europe [32].

LCOT				CONDITIONS
3.70	€/MWh	0.12	€/kg	Retrofitting NG to H_2 pipeline
4.60	€/MWh	0.15	€/kg	48-inch pipeline. Includes pipeline and compressor CAPEX and OPEX and compression fuel-related costs.
9.60	€/MWh	0.32	€/kg	34-inch pipeline. Utilization of 75% and 50 km distance
11.40	€/MWh	0.38	€/kg	1,500 km distance, considering all capital and operating costs.
45.00	€/MWh	1.50	€/kg	7 - 10-inch pipeline over 100 km
16.1 - 49.8	€/MWh	0.54 - 1.66	€/kg	Capacity of >100 tons/day; 100 km pipeline

Stakeholders today are studying the different technologies to transport and store hydrogen, mostly according to the pressure levels, quantities, and distances. For hydrogen transmission and distribution, using pipelines has been highlighted for inland transportation due to the capacity and low costs in the long term. Refurbishing natural gas pipelines has emerged as an option to avoid stranded assets for many countries. In 2020 and 2021, the European Commission released a report, where information for hydrogen infrastructure cost is being compiled, showing that as the capital expenditures for new hydrogen pipelines ranges between €0.93 and €3.28 M per kilometre, repurposing natural gas pipelines cost €0.37 M per kilometre [32]. This highly depends on the pipeline diameter and pressure, translating into more compression stations. On the other hand, as capital expenditures increase for pipelines with larger capacity, the levelized cost of transmission (LCOT), reduces. The LCOT in this same report ranges between 4.6 and 45 €/MWh for a 48-inch new pipeline and a 10-inch new pipeline respectively, as shown in Table 2. For a refurbished natural gas pipeline, the LCOT will in fact be lower, with a value of 3.7 €/MWh, as calculated by Guidehouse [33].

As the described conditions apply to hydrogen transmission, the European Commission has a different section for hydrogen distribution, which consider pipelines and trucks [32]. As distribution pipelines are mostly located inside cities, buildings, and under main roads, it is vital to repurpose and minimize the costs when shifting to low-carbon hydrogen from natural gas. Therefore, the European Commission reports CAPEX of pipeline refurbishing, with a CAPEX ranging between 0.23 and 0.47 €/MWh for pipelines between 5 and 10.5-inch, respectively [32]. On the other hand, for the Levelized cost of Distribution (LCOD), the report shows refurbishment of pipelines, and trucks with compressed and liquified hydrogen. Table 3 summarizes the conditions at which different LCOD could be obtained.

Table 3. LCOD according to the European Commission report on overview of costs and key benefits from hydrogen generation in Europe [32].

LCOD				**CONDITIONS**
				New Infrastructure
0.05	€/MWh	0.0017	€/kg	LCOD for 1000 km pipeline network, including storage and compression
0.06	€/MWh	0.0020	€/kg	LCOD for 100 km pipeline network, including storage and compression
0.16	€/MWh	0.0053	€/kg	LCOD for 10 km pipeline network, including storage and compression
1.61	€/MWh	0.0537	€/kg	LCOD for 1 km pipeline network, including storage and compression
				Refurbishment of Natural Gas Pipelines
0.11	€/MWh	0.0037	€/kg	Based on current natural gas distribution costs in the UK.
				Distribution by Truck
0.54	€/MWh	0.0180	€/kg	LCOD of a 50 km pressurized H_2 truck, including compression and storage
2.52	€/MWh	0.0840	€/kg	LCOD of a 50 km liquid hydrogen truck

As pipelines are an economical option compared to transporting hydrogen by trucks, other factors, such as quantity of hydrogen transported, in logistic terms, and risk assumed for infrastructure development, have not been considered at this stage. For this purpose, BloombergNEF, in its Hydrogen Economy Outlook released in 2020, developed recommendations on the different transportation modes considering the distance and the amount of hydrogen, showing also the LCOT/LCOD cost range.

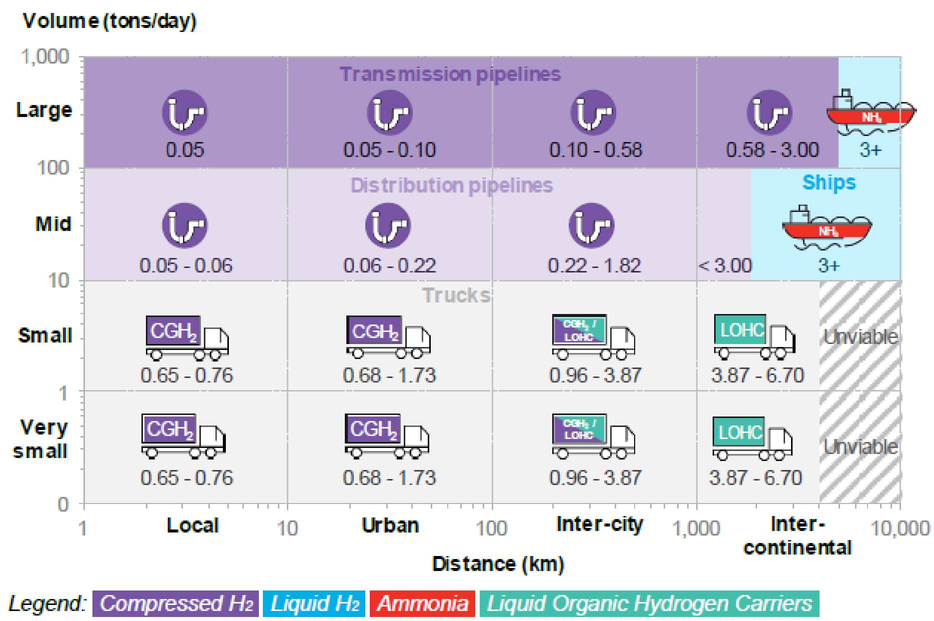

Figure 8. BloombergNEF hydrogen transport costs based on distance and volume USD/kg [34].

When following BloombergNEF recommendations on hydrogen distribution, it is possible to determine that hydrogen should be distributed, in early stages of infrastructure development, as a compressed gas in hydrogen trucks. Therefore, in the early stage of infrastructure development that Sweden is for hydrogen refuelling stations, hydrogen should be transported in compressed gaseous form via trucks with a LCOD between 0.68 and 1.73 €/kg.

Table 4. Hydrogen storage costs [32].

	DEPLETED GAS FIELDS	SALT CAVERNS	ROCK CAVERNS
CAPEX [€/MWh STORED]	280 – 424	334	1232
LCOS [€/MWhH_2]	51 – 761 [1]	19 – 1042 [2]	6 – 262 [2]

However, as the goal is to obtain lower cost of hydrogen, optimization of logistics must be accomplished. This is possible with storage, as it works as buffers for longer periods of time,

[1] One cycle per year

[2] Lower boundary: monthly cycling; Upper boundary: bi-annual cycling.

ensures a smooth operation of the supply chain and compensate for supply deficits during periods of higher demand. Large scale storage can be conceived in salt caverns, depleted gas fields, and rock caverns. However, rock caverns are the only possible technology to develop in Sweden, as the other two are not available.

As depleted gas fields and salt caverns offer the lowest CAPEX, the contrary is in the levelized cost of storage (LCOS), as shown in Table 4, where rock caverns are a strong option when having more cycling throughout the year. The Swedish industry, more specifically HYBRIT, has started a low-carbon hydrogen storage pilot project, where a rock cavern storage facility will be inaugurated in 2024 for a two-year test period, supporting the development of hydrogen infrastructure and developing know-how and expertise. The pilot plant will have 100 cubic meters, while the full-scale storage facility might require between 100,000 and 120,000 cubic meters, able to store up to 100 GWh of electricity converted to low-carbon hydrogen, equivalent to approximately 2.1 kt of H_2[3], enough to supply a full-sized sponge iron factory for three to four days [35].

Such large volume has the scale for an entire region usage or even seasonal storage, but having smaller storage capacity becomes also important to provide smooth operation of the supply chain and balance the demand. Line packing, a technique to store gases in the transmission system by isolating pipeline sections, and above the ground vessels such as compressed and liquified tanks, are most likely to offer intra-day flexibility, also close to high demand locations [36]. The technologies mentioned offer different operational conditions and costs, which become more suitable in specific conditions. The following table shows the CAPEX and OPEX of above the ground compressed gas and liquified hydrogen storage technologies.

Table 5. Hydrogen storage costs in tanks according to Element Energy [36].

	CAPEX [€/GJ]	**OPEX [% OF CAPEX]**	**Efficiency [%]**	**Lifetime [years]**
Compressed Hydrogen Tank	5,320	1	97	30
Liquified Hydrogen Tank	1,550	4	95	25

The main advantage of liquified hydrogen tanks is the density of storage, as it allows to store more hydrogen in the same space, with considerable extra operational costs for this solution. Hydrogen refuelling station developers will choose the technology considering the daily demand of hydrogen and the space available.

2.4.4 Hydrogen refuelling stations

As the final step of the hydrogen supply chain for road mobility, the HRS are a key component in the infrastructure for the development of the hydrogen transport sector. Different types of HRS are available in the market or in pilot phase, with two main classifications by the storage

[3] Based on 70% nominal system efficiency.

medium: liquid HRS (LH_2) and gaseous HRS (GH_2) [37]. The last and more used nowadays, could be classified in two, according to the pressure they handle. 350 bars and 700 bars are the internationally agreed refuelling and storage pressures, also followed by the TEN-T regulations. The TEN-T requires after 2030 a 1 ton/day HRS every 200 km in the core network and in all urban nodes serving both cars and lorries [38].

In this order of ideas, Sweden has a TEN-T network of 6,417.7 km, where 52% is comprehensive network, and 48% is core network, and a total of 18 urban nodes. As the HRS are required by AFIR in the core network, this translates into a minimum of 15 HRS at the network, additional to the 18 HRS in the urban nodes, with a global minimum of 33 HRS. Sweden today, with 5 HRS working, is far from reaching the 33 HRS requirements. However, with data compiled from news and different webpages, it was possible to identify 53 HRS projects announced, in development, or already working. This allows to overcome the total HRS required, however, not fulfilling the urban nodes requirements, as seen in the following picture.

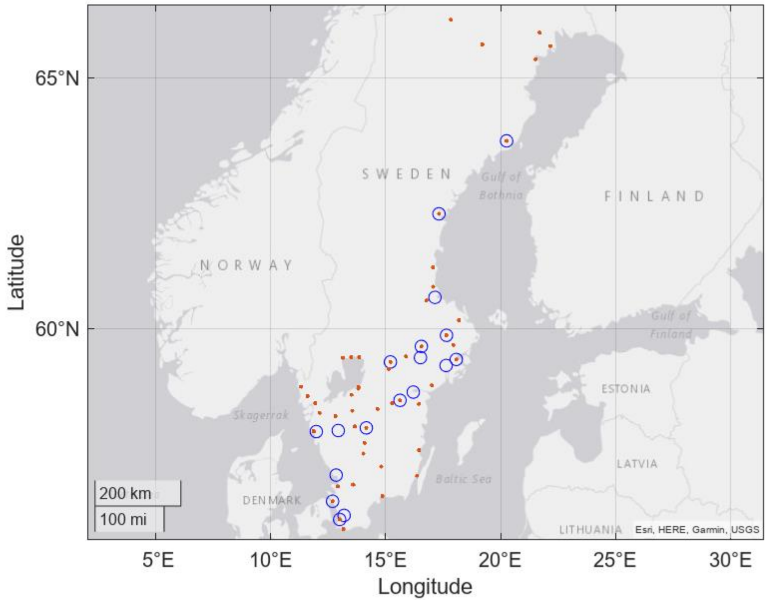

Figure 9. Hydrogen refuelling stations announced (dots) and TEN-T urban nodes (circles) overlapped. The exact data of locations and sources can be found in Table 19 on Appendix A.

When overlapping the HRS projects announced or already deployed, and the TEN-T Swedish urban nodes, it is possible to see that 6 urban nodes are still missing HRS announcement. Regarding the distance between refuelling stations in the core network, the following image shows the location of the HRS (same dots), and an ellipse representing a radius of 200 km, where it is possible to determine if the HRS are located within the required distance.

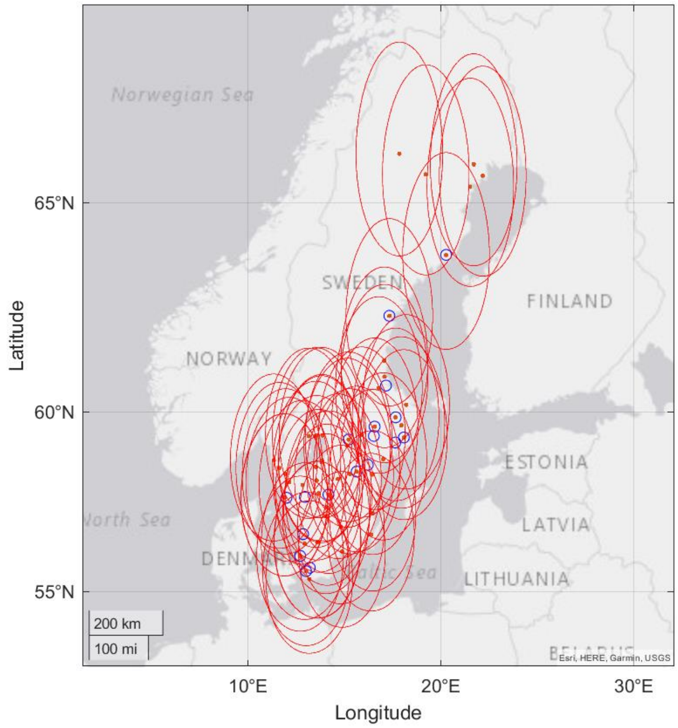

Figure 10. 200 km radius (ellipse) from each HRS project announced (dot).

The ellipses in the image represents 200 km in all directions of each HRS. South, and middle of Sweden is where most HRS are concentrated, also following the population density. On the other hand, the north of Sweden is covered by HRS located in industrial nodes, such as Luleå, Boden, Piteå and Umeå, and in remote locations such as Arvidsjaur and Arjeplog. As the core TEN-T roads are mostly located on the south, starting in Malmö, and dividing in two main roads, one heading north towards Oslo passing by Gothenburg, and the other reaching Stockholm as central point. In Gothenburg, the road also divides, heading towards Stockholm through Jönköping and Borås. At Stockholm, a road heads east towards Oslo, and one north towards Luleå, passing by Umeå, Gävle, and Sundsvall. At Luleå, the road divides in two, heading towards Tornio, Finland, and towards Norway, going through Kiruna. After Kiruna, the HRS coverage is still to be announced by developers.

Also is to be considered the security requirements that an HRS must fulfil to be able to operate and being approved by the different entities, such as fire departments. The technical specifications guidelines, under the Directive 2014/94/EU, are the ISO/TS 20100, the purity specifications (ISO 14687-2) and connectors (ISO 17268 (SAE J2600)) among others [39], but this project will not delve further into safety regulations or extra details.

When dispensing hydrogen at an HRS, a series of consecutive steps must be followed to comply with the regulatory guidelines and operational protocols. At this step of the supply chain, the hydrogen is already stored in pressurized tanks at the dispensing pressure. When the hydrogen is dispensed, the pressure must be guaranteed to be delivered at 350 and 700 bars, depending on the case. For this, a buffer tank, called hydrogen storage bank, is located between the bulk storage and the dispenser. A compressor is used to increase the pressure from the bulk storage to the buffer tank. Finally, hydrogen is dispensed at -40 °C. Metering technology is used and is highly relevant, since it allows for a correct measurement of variables, guaranteeing safety. The same process is possible for liquid hydrogen with a cryopump instead of a compressor, and an evaporator to dispense compressed H_2. The following images shows a schematic for the dispensing process.

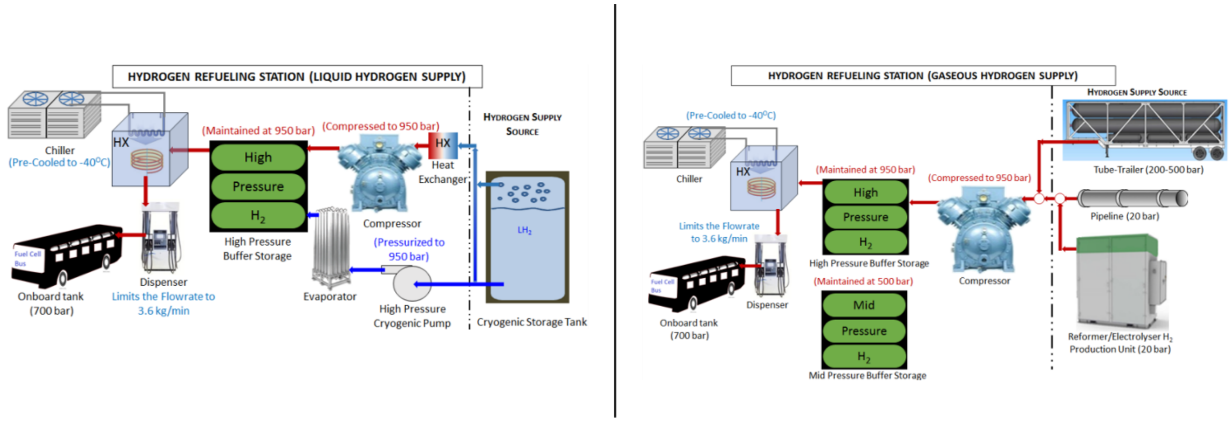

Figure 11. HRS configurations for gaseous and liquid hydrogen supply [40].

Costs for these two types of HRS vary according to the dispensing capacity. Capacities today vary from 100 kgH$_2$/day to 520 kgH$_2$/day for compressed hydrogen, and more than 1,000 kgH$_2$/day for liquid hydrogen. However, as the HRS size increases, the specific CAPEX tends to decrease.

Table 6. HRS CAPEX according to the European Commission report on overview of costs and key benefits from hydrogen generation in Europe [32].

CAPEX		SPECIFIC CAPEX		CONDITIONS
850.00	k€	4.25	k€/kg	For cars, 200 kgH$_2$/day, 10% utilization
890.00	k€	4.20	k€/kg	212 kgH$_2$/day
2,440.00	k€	4.07	k€/kg	600 kgH$_2$/day, 76% utilization
1,710.00	k€	1.71	k€/kg	For trucks, 1,000 kgH$_2$/day, 40% utilization
2,000.00	k€	2.00	k€/kg	1,000 kgH$_2$/day
3,990.00	k€	2.66	k€/kg	1,500 kgH$_2$/day, 80% utilization

As the specific CAPEX, the Levelized Cost of a Hydrogen Refuelling Station (LCofHRS) reduces as there is a larger dispensing capacity.

Table 7. HRS levelized cost according to European Commission report on overview of costs and key benefits from hydrogen generation in Europe [32].

LCofHRS				CONDITIONS
63	€/MWh	2.1	€/kg	300 kg/day, utilization rate of 60%
32	€/MWh	1.07	€/kg	1050 kg/day, utilization rate of 60%

Logistic wise, having smaller refuelling stations is beneficial for infrastructure development, reduced financial risk, and easiness of operation. On the other hand, having larger HRS allows a faster deployment of vehicles as the final cost of refuelling is lower. Nevertheless, the costs are also dependent on the utilization rate of the HRS, therefore, having a low utilization rate on the HRS, would then induce higher LCofHRS, which is counterproductive for the supply chain development. These costs will be analysed further in the supply chain cost model, where countermeasures on how to avoid larger LCofHRS with low utilization rates are determined.

2.5 Need of hydrogen in mobility

As a key contributor to Sweden's Hydrogen Strategy, Vätgas Sverige, an NGO committed to sharing and coordinating hydrogen-related knowledge nationwide, collaborated with a broad range of stakeholders, including representatives from over 150 industry, academic, and municipal organisations. In this proposal, goals, upcoming projects, and suggestions can be found, to make hydrogen thrive, especially when is expected to take a bigger role in the upcoming years. Currently, the production and utilisation of hydrogen is approximately 180 kt, generated mostly from natural gas (120 kt), and used mostly in refineries (72%) and the chemical industry (27%). Only an approximately of 0.2% (3,600kg) were used in HRSs along the country [25], which could be translated approximately into 200 MWh over a year.

Petroleum products were responsible of fuelling 59 TWh (75%) of the 79 TWh transportation needs in 2020, percentage that also has been declining over the last years. Road transportation accounted for 94% of such energy consumption [12], which translate into 14.02 $MtCO_2e$ for the country, as shown in Figure 12. Since 2005, the main emitters have been heavy duty trucks and passenger cars (PCs) accounting for a 20.32% and 62.62% of the total transportation emissions respectively [26].

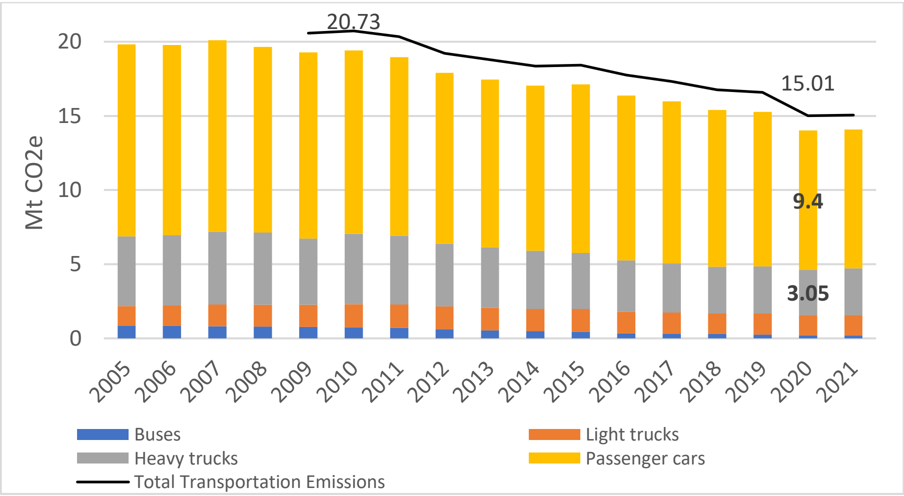

Figure 12. Historic transportation emissions in Sweden [26].

In the EU alone, 9.7 million new PCs were registered in 2021 [41], and only 1.74 million (18% of the total) were low emissions vehicles (BEV and PHEV) [42]. In the upcoming years, it's expected that the number of new low emissions vehicles sharply increases to achieve the climate goals (by 2035 no new vehicles should emit GHG [43]). Then, to avoid future bottlenecks of tight supply-chains and scarce raw materials, diversification of all the technologies that can support the change should be developed, and its TRL be mature enough to respond to the transition. Moreover, end-user's utilisation could be key to foster the ramp-up of some technologies above others and their choosing subject to specific aspects, e.g., heavy-duty trucks needing a fast fuel refill for optimising its operational cost.

When used to power vehicles, trucks and working machines with fuel cells (FC), hydrogen proves to be a favourable alternative in terms of emissions, as it produces zero pollutants after undergoing an electrochemical process for electricity generation. Some other advantages can be a similar refill time compared to petrol, and the low emissions lifecycle of producing hydrogen with renewable energies. The last can also be a concern because nowadays most of the hydrogen comes from fossils fuels and only below 1% of the hydrogen production in the world comes from renewables and in Sweden this percentage is below 3%. Still, all of the H_2 used nowadays in the country's HRSs is electrolytically produced [7]. The availability and competitive cost of low emissions hydrogen is mandatory if this technology is to thrive.

3 VALUE CHAIN COST MODEL

3.1 Assessment Description

This chapter aims to identify the quantitative conditions for a strong business model around hydrogen refuelling stations' supply chain costs. To start, a relevant indicator for the success of the hydrogen supply chain was recognised, which is the cost of hydrogen for the final user. Different experts have expressed concern about how low-carbon hydrogen's cost can reduce its competitiveness against other solutions. Such statement is supported by the lack of expertise in producing, managing, and using low-carbon hydrogen in large scale, making it a non-competitive solution when compared to hydrogen produced through steam methane reforming, a broadly used technique along the world.

Consequently, the learning curve regarding low-carbon hydrogen technology will pave the way for cost reduction opportunities, which can grant the possibility of making tomorrow’s strong business today. Hence, the following are the desired outcomes for this analysis:

1. Identify opportunities where subsidies and other factors could further reduce the cost of hydrogen throughout the supply chain.
2. Have a final overview of the supply chain and the impact of the different steps on the cost of hydrogen dispensed on 2023 and 2028.

Public data in literature and reports were gathered and used in the developed model to calculate the costs along the value chain. Additionally, interviews were carried out to validate the importance of specific regulations that support the value chain development. Similarly, the model results were validated through interviews and publicly available data. Finally, sensitivity analyses were carried out to fulfil outcome #1. Outcome #2 is assessed in the subchapter concluding remarks, where an overview of the aggregated supply chain cost is given, and main outcomes are enumerated, being the base for the risk assessment and conclusion chapters.

3.2 Hydrogen production

For the first step of the supply chain, hydrogen production via electrolysis, capital expenditures (CAPEX) of electrolyzer installations are considered, together with electricity expenditures, fixed operation and maintenance (FOM), and finally water consumption. As explained before, the cost of hydrogen would be the metric utilized throughout this chapter, along with the identification of cost reduction opportunities, and its impact assessment through a sensitivity analysis. Water consumption and FOM are aggregated to the operation and maintenance (OM) variable of the system. Electricity has been considered an independent variable from the OM due to the impact it has on the LCOH. The LCOH is determined using the following equation.

$$LCOH = \frac{Costs}{Hydrogen\ Produced}$$

Where costs are described above and determined with the following equations.

$$Costs = CAPEX + OM + Electricity_{costs}$$

Where OM is

$$OM = FOM + H2O_{costs}$$

H_2O_{costs} are the costs related to water usage, assumed to be 0.08 €/kg of hydrogen produced [21]. The FOM is assumed to be 3% of the installation CAPEX per year [44]. Nevertheless, the author describes that the OM costs are dependent on the size of the electrolyzer, a factor not considered for this assessment. The electricity expenditures (El_{exp}) are calculated using the following equation.

$$El_{exp} = El_{cost} * 8760 * CF * Lifetime * Electrolyser_{size}$$

Where El_{cost} is the cost of a MWh of electricity in the wholesale market, and the lifetime is 20 years for an electrolysis facility.

To determine the CAPEX of the installation, an exponential regression was done to obtain an equation describing the unitary CAPEX ($UnCAPEX$) of the system according to the size of the electrolyzer, following a capital cost scaling factor method [22]. For this, an initial CAPEX of 1,200 USD/kW (1,068 €/kW), at 1MW capacity installed is considered and further scaled with the method described. The following curve represents electrolyzer CAPEX according to the installation size.

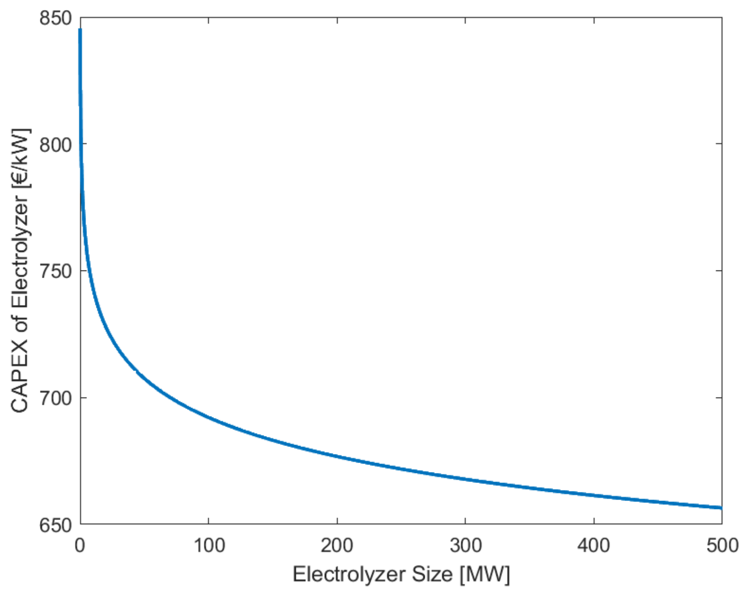

Figure 13. Electrolyser unitary capex vs electrolyser size regression curve with R^2=0.774.

The following equation describes the curve above.

$$UnCAPEX\left[\frac{€}{MW}\right] = -30{,}480 * \log(Electrolyser_{Size}[kW]) + 1.0911 * 10^6$$

The equation allows running a sensitivity analysis, understanding the impact of having bigger installations on the final cost of hydrogen. The CAPEX of the installation will be determined using the unitary CAPEX ($UnCAPEX$) determined above when multiplied by the installation size.

The hydrogen produced is determined with the capacity factor (CF) of the system, which is a number between 0 and 1 to translate the 8,760 hours of the year to a fraction of it, depending on the electricity sourcing. Finally, the hydrogen produced is determined by the following equation.

$$Hydrogen\ Produced = \frac{Electrolyser_{size} * \eta_{electrolyser} * 8760 * CF * Lifetime}{LHV_{H2}}$$

With the equations already stablished, the results are shown in the following section.

3.2.1 Results Hydrogen Production

The model described before was used to determine the LCOH for Sweden. First, the base case was obtained, which aims to represent the Swedish case by 2023, considering capital and operating costs for low-carbon hydrogen production obtained from the literature research. It must be acknowledged that the results are not totally accurate due to a lack of operational data publicly available, therefore, the chosen input values seek to represent and identify the base scenario for low-carbon hydrogen production via electrolysis. The base scenario considered is off grid production via electrolysis with a solar PV plant providing the electricity (CF = 24%) [22], with a capacity to supply four to five refuelling stations per day, and an electricity cost of 90 €/MWh. The following are the input variables for this scenario.

Table 8. Input variables for hydrogen production base scenario.

PARAMETER	UNIT	VALUE
Electrolyzer Size	MW	10
Unitary CAPEX	€/kW	1,068
Capacity Factor	%	24
Electricity Cost	€/MWh	90
Efficiency	%	65
Lifetime	Years	20
OPEX	% CAPEX/Year	3

The LCOH obtained is 6.72 €/kg of hydrogen produced in this scenario. When measuring the impact of the costs on the LCOH, it is noticed that electricity expenditures represent 69% of the cost of hydrogen produced, while CAPEX represents 19%, and OPEX represents 13% of the cost.

Having the base case, sensitivity analyses were carried out to identify the individual impact of variables previously identified as possible cost reduction possibilities. First, a sensitivity analysis of the electrolyzer size is carried out to identify the impact of CAPEX and electrolyzer size on the LCOH. The electrolyser size modelled is between 0.1 MW and 500 MW, representing distributed production of low-carbon hydrogen, and centralized production of hydrogen in hubs, respectively. Figure 14 shows the results from the sensitivity analysis.

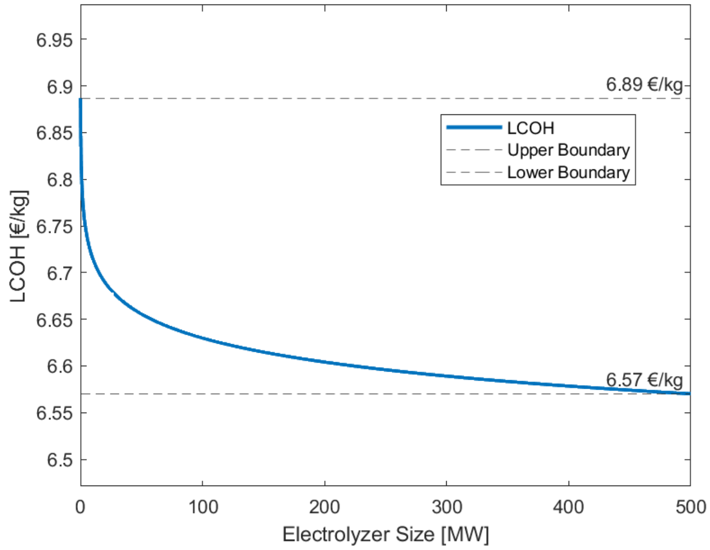

Figure 14. Electrolyser size vs levelized cost of hydrogen.

For a 0.1 MW electrolyzer, the LCOH is 6.89 €/kg, while for a bigger centralized electrolyzer, the LCOH is 6.57 €/kg. However, is important to mention that OPEX costs in this analysis are fixed as a percentage of the CAPEX, same as in the base case, and it does not include other revenues that reduce the LCOH. Other revenue streams, such as selling heat and oxygen byproducts, participating in the frequency regulation market, and hydrogen storage, are not considered in this analysis. However, these potential revenue streams would reduce the LCOH for MW-scale installations as they are located close to industrial offtakers which might benefit from the oxygen and heat. Participating in the frequency regulation market is becoming imperative due to grid constraints, as happening today in Sweden, being also a positive cash flow for the project. Finally, storage is important as it allows to optimize hydrogen production depending on hydrogen demand and electricity prices.

Other variables identified as possible cost reduction factors, are electricity price and capacity factor, two closely related variables as it relates to the most important cost factor which is electricity expenditures. The following are the boundaries for the sensitivity analysis.

Table 9. Input variables for sensitivity analysis.

PARAMETER	UNIT	NOMINAL	LOW	HIGH
Capacity Factor	%	24	5	100
Electricity Cost	€/MWh	90	20	120

With these input variables, a heat map was constructed showing the impact of both variables together.

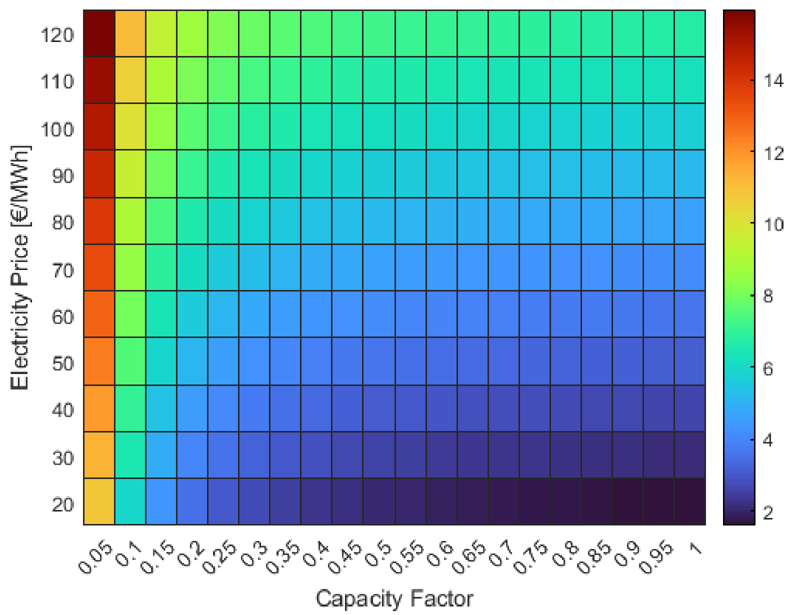

Figure 15. Heat map of sensitivity analysis of capacity factor and electricity price impact on the LCOH in €/kg (bar on the right).

The heat map allows to identify how the costs are distributed according to both variables. As expected, lower costs are obtained at higher capacity factors and lower electricity prices. Moreover, the impact of the capacity factor is higher than the electricity prices. While both variables have a large influence on the LCOH, the capacity factor has a higher influence as it allows maximizing fixed costs as CAPEX. Therefore, the cost reduction due to electricity price has a linear impact of 0.51 €/kg per 10 €/MWh, the capacity factor has a different behaviour as seen in the following graph.

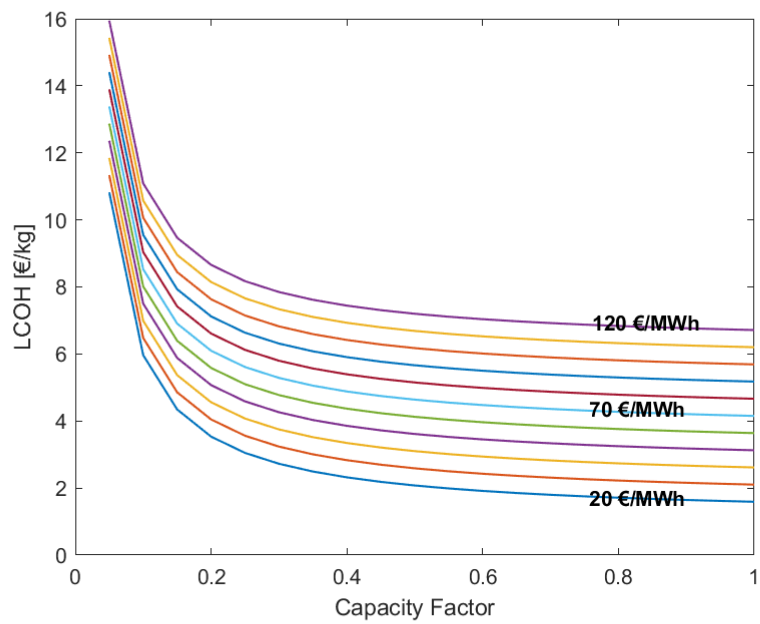

Figure 16. LCOH curves based on capacity factor for different costs of electricity.

Due to the exponential behaviour of the curves because of to the capacity factor, the marginal difference of the LCOH reduces as the capacity factor increases. This shows that fix costs, such as the CAPEX, are maximized, making it relevant to obtain higher capacity factors. Moreover, this allows flexibility in hydrogen production, as it is possible to obtain the same LCOH with different conditions of electricity procurement. As an example, to obtain an LCOH of 6 €/kg, it is possible to have an electricity cost of 20 €/MWh with a capacity factor of 0.1, and an electricity cost of 100 €/MWh with a capacity factor of 0.62. Thus, it becomes evident that adopting a well-planned electricity procurement strategy is crucial in order to enhance capacity factors, maximize fixed costs, optimize hydrogen production, and decrease the LCOH.

Now, it becomes relevant to have a more thorough understanding of the historic electricity prices already shown in Figure 7. For this, an analysis is done to identify the percentage of time a specific price range was obtained (price range of 20 €/MWh), in different timeframes. The timeframe analysed is January 1st, 2015, until July 22nd, 2023, equal to 3,124 days, further divided into the periods 2015-2020, and 2021-2023.

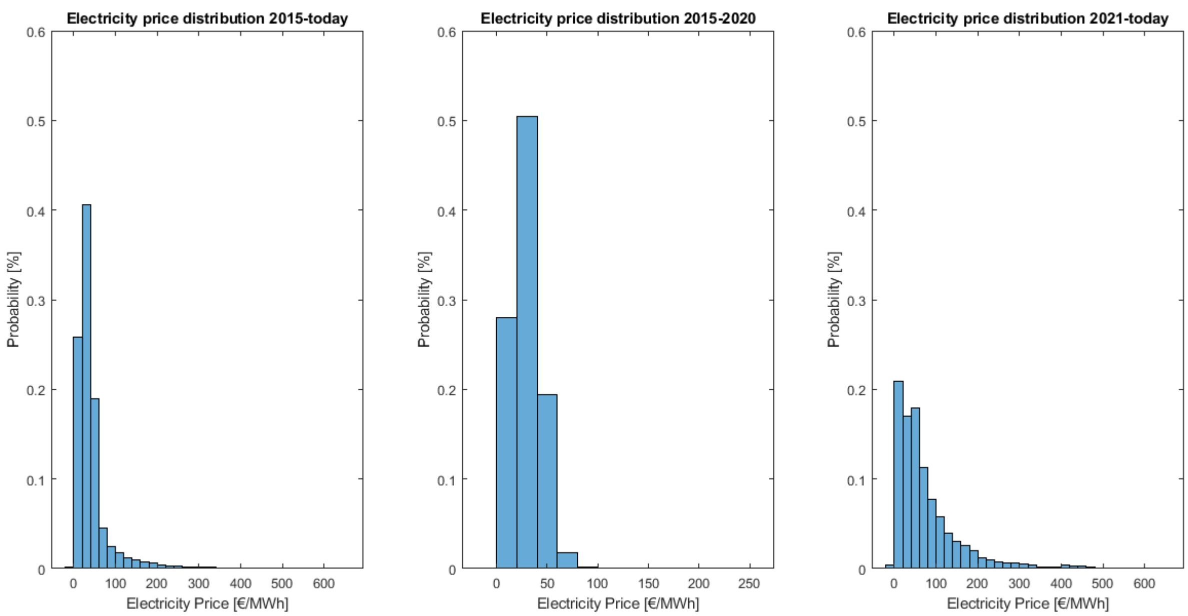

Figure 17. Electricity prices distribution for three analysed periods.

The first graph shows the price distribution from 2015 until today, where 66% of the time, the electricity price was below 40 €/MWh, where 0.1% (3.8 days) were negative electricity prices, and 90% of this time (2,818 days), the price was below 80 €/MWh. Nevertheless, during this period, the electricity prices trend varied after the energy crisis started in 2021 with the natural gas shortages from Russia to Europe. Therefore, it is relevant to divide this analysis into the pre-energy crisis, the period before 2021, and during the energy crisis, the period starting in 2021. In the second graph, or pre-energy crisis (2,192 days), the trend shows that the electricity prices before the crisis were 99.6% (2,183 days) of the time between 0 and 80 €/MWh. 78.4% (1,719 days) of the time were between 0 and 40 €/MWh, conditions vastly favourable for hydrogen production due to the possibility to obtain high-capacity factors with low electricity price. Nevertheless, during the energy crisis (932 days), the electricity prices show a larger price distribution, and negative conditions for hydrogen production, where 32.4% (302 days) of the time the electricity prices were above 80 €/MWh, and only 37.9% (353 days) where between 0 and 40 €/MWh.

The previous analysis is used for determining the electricity prices for the supply chain analysis, and the target electricity price by 2028. Even though the average electricity price during the energy crisis has been 83.16 €/MWh, the value used for the supply chain analysis is 90 €/MWh to have a conservative case. The target electricity price should consider a scenario between pre-energy crisis, and during the energy crisis, therefore, the average value since 2015 has been 43.85 €/MWh, and the target is 40 €/MWh.

3.3 Storage, transmission, and distribution of hydrogen

The next step in the hydrogen supply chain is the storage and transport of hydrogen to the refuelling stations, what is going to be considered the LCOD. The LCOD is calculated for two scenarios: off-site hydrogen production, and on-site hydrogen production. For the first, the supply chain described in Figure 18 is assessed, while for the last, distribution is not considered. Nevertheless, both require compressor systems to reach desired pressures, which are bulk storage pressure, and distribution pressure for the first case. Lastly, but not included in this step, hydrogen is delivered to the HRS, which further requires storage at 720 bar, this value is the target pressure for 2028 due to the demand from heavy-duty vehicles according to AFIR.

In this order of ideas, compressing OPEX and CAPEX, storage tank CAPEX, and transport costs are considered, and has been modelled in the following order.

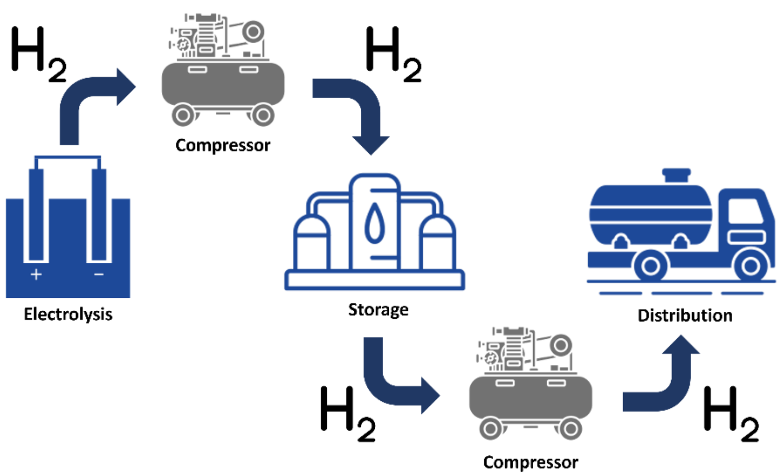

Figure 18. Supply chain in hydrogen storage, and transmission and distribution.

Several studies gather transmission and distribution costs (TD_{costs}) with storage costs ($LCOS$) in the same cost indicator, allowing to optimize logistics. The indicator used for the cost related to this supply chain step is the levelized cost of distribution ($LCOD$). The LCOD is the sum of the TD_{costs} and the $LCOS$, as in the following equation:

$$LCOD = LCOS + TD_{costs}$$

The compressing costs ($Comp_{costs}$) mentioned before, are present in both parameters. TD_{costs} are obtained with the cost of moving the hydrogen transporting truck ($Transp_{costs}$) added to the $Comp_{costs}$.

$$TD_{costs} = Comp_{costs} + Transp_{costs}$$

$Comp_{costs}$ considers the operational and capital expenditures related to compressing the hydrogen from electrolyser pressure to the bulk storage, and finally to the truck pressure.

$$Comp_{costs} = Comp_{OPEX} + Comp_{UnCapex}$$

The compressor operational costs ($Comp_{OPEX}$) are determined using the following equation in €/kg [18]:

$$Comp_{OPEX}\left[\frac{€}{kg}\right] = \frac{P_{comp}}{H2_{demand}} * \frac{60}{3.6}$$

Where the compressor power $\left(P_{comp}\right)$ is.

$$P_{comp}[kJ] = \frac{P_{shaft}}{\eta_{motor}} * Motor_{factor}$$

And the shaft power $\left(P_{shaft}\right)$ is.

$$P_{shaft}[kJ] = \frac{Comp_{factor} * H2_{Demand} * CF * R * T_{max} * N_{stages}}{\eta_{isentropic}} * \frac{k}{k-1} * \left(\frac{P2}{P1}\right)^{\left(\frac{k-1}{N_{stages}*k}-1\right)}$$

The compressor CAPEX ($Comp_{CAPEX}$) now is calculated with the compressor power as an input.

$$Comp_{CAPEX}[€] = UnCost_{comp}\left[\frac{€}{kW}\right] * \frac{P_{comp}}{3600}$$

Now, the unitary CAPEX $\left(Comp_{UnCapex}\right)$ is obtained by dividing the system CAPEX with the hydrogen produced over the project lifetime, as following.

$$Comp_{UnCapex} = \frac{Comp_{CAPEX}}{Lifetime * H2_{Demand} * 365}$$

$Transp_{costs}$ are a product of fuel consumption, its price, and distance to the HRS, divided by the truck storage capacity.

$$Transp_{costs} = \frac{Fuel_{consumption} * Fuel_{price} * Distance_{HRS}}{Truck_{capacity}}$$

The trailer CAPEX is not considered, as it is assumed for logistic easiness that the trailer is owned by a 3rd party offering the transport service.

For storage costs, $Comp_{costs}$ from the electrolyser pressure to the bulk storage pressure, are considered. Additionally, the gaseous hydrogen storage tank CAPEX ($Tank_{CAPEX}$) is also added as mentioned before. In this order of ideas, the $LCOS$ is calculated with the following equation.

$$LCOS = Tank_{CAPEX} + Comp_{costs}$$

Where the $Tank_{CAPEX}$ is estimated as 5,320 €/GJ of capacity, or 0.0901 €/kg of hydrogen, according to [32].

3.3.1 Results storage, transmission, and distribution of hydrogen

The costs related to storage, transmission and distribution of hydrogen are dependent on several conditions, such as distance between production and consumption, demand of hydrogen, and technologies used.

The centralised production scenario has compressing costs, transport costs, and storage costs. On-site production of low-carbon hydrogen scenario has compressing and storage costs. The following are the input variables for both scenarios.

Table 10. Input variables for storage, transmission, and distribution supply chain step.

PARAMETER	UNIT	CENTRALISED	ON-SITE
P1	bar	15	15
P2	bar	250	-
P3	bar	250	-
P4	bar	500	500
Electricity Cost	€/MWh	90	90
Storage Capacity	kg	1,031	1,031
Hydrogen Demand	kg/day	1,000	1,000
Truck Capacity	kg	350	-
Fuel Price (Diesel)	€/L	1.92	-
Fuel Consumption	L/100km	28	-
Distance To Hrs	km	100	-

Having the input data and equations describing the model, the following are the results for this step of the supply chain.

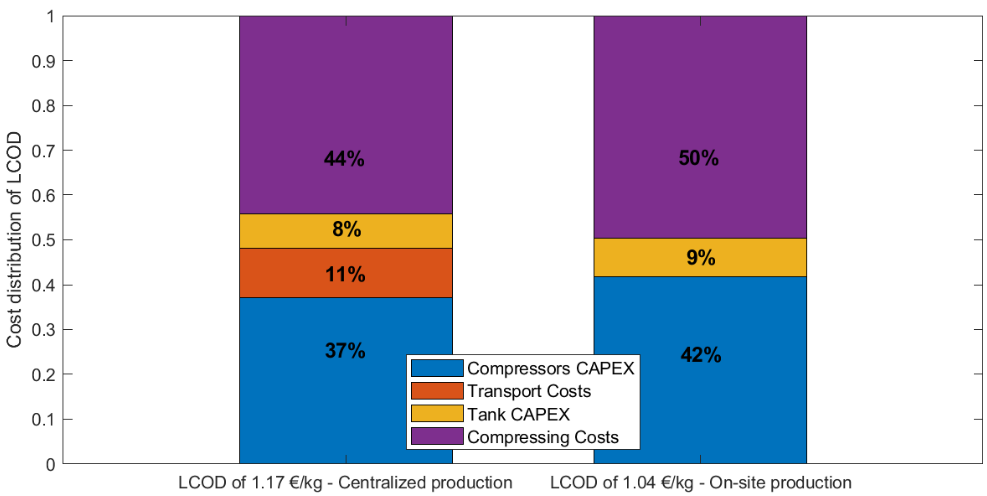

Figure 19. LCOD results for centralized and on-site hydrogen production.

Figure 19 show the distribution of the LCOD for both scenarios, where a difference of 0.13 €/kg between both cases shows the advantage of having on-site production of hydrogen. Is important also to highlight the fact that in this analysis labour costs and other transport fees are not included, and having a more detailed cost structure, together with operational data, would make these results precise for the Swedish context. Nevertheless, the results completely align with other authors. BloombergNEF states in its Hydrogen Economy Outlook of 2020 that this value should be between 0.68 and 1.73 €/kg, depending on the cycles of operation, distance, and amount of hydrogen transported [34]. The European Commission, in its report for overview of costs and key benefits of hydrogen production states that this value is around 0.90 €/kg [32].

The benefits of on-site production of hydrogen, in terms of distribution of the molecule, must be considered in the overall supply chain, and identify whether this scenario provides a clear advantage. Furthermore, sensitivity analyses are not performed for this step of the supply chain.

3.4 Hydrogen Refuelling Stations

The hydrogen refuelling stations, is the last step of the hydrogen supply chain analysed in this model. In this step, variable O&M (VOM), fixed O&M (FOM), and the HRS CAPEX (HRS_{CAPEX}) are used to calculate the levelized cost of an HRS (LCofHRS) of hydrogen dispensed. On the other hand, the hydrogen demand is assumed in terms of a capacity factor of the HRS daily capacity. The following is the equation that describes the LCofHRS.

$$LCofHRS = \frac{HRS_{costs} * (1 + Sales) * (1 + CC_{Fees})}{H2_{sold}}$$

Where CC_{Fees} and $Sales_{tax}$ are transaction fees related to selling hydrogen to the final user. As explained before, the hydrogen demand, or the hydrogen sold, is being expressed as a factor of the capacity factor of the refuelling station, as in the following equation.

$$H2_{sold} = CF_{HRS} * HRS_{capacity}$$

Being the $HRS_{capacity}$ equal to 1,000 kg/day of hydrogen. On the other hand, the HRS costs, are expressed as in the following equation.

$$HRS_{costs} = HRS_{CAPEX} * \left(1 - HRS_{subsidy}\right) + VOM + FOM$$

Where the (HRS_{CAPEX}) is obtained with the following equation [45].

$$HRS_{CAPEX}[USD] = 28000 + \left(\frac{HRS_{capacity}}{100}\right)^{-0.95} * HRS_{capacity}$$

The HRS_{CAPEX} is further expressed in euros with an exchange rate of €0.94 per USD. Figure 20 shows the curve that represents the equation above, and the station CAPEX at a capacity of 1,000 kg/day.

The purpose of this step of the supply chain is to understand the impact of the capacity factor and the CAPEX subsidy $\left(HRS_{subsidy}\right)$ in the final LCofHRS.

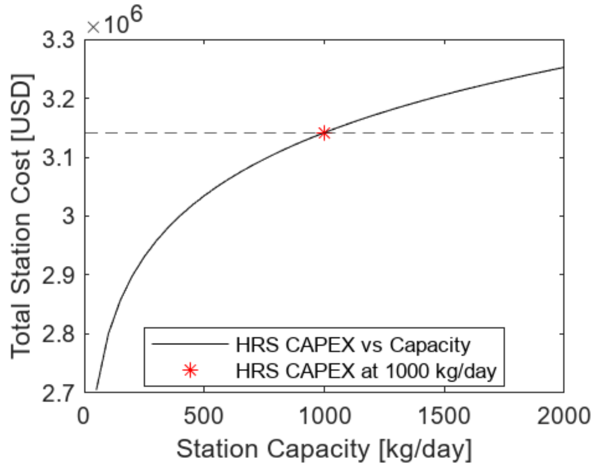

Figure 20. CAPEX curve of an HRS vs station capacity in kg/day.

3.4.1 Results of Hydrogen Refuelling Stations

As the number of refuelling stations in Sweden by July 2023 only reach 5, the gathering of precise costs to exemplify the Sweden scenario, is a challenge as this are operational and private information of the different HRS developers. Therefore, cost data from developed markets, such as the California HRS market, has been used to model this step of the supply chain, and further validated with available data for Europe, and through interviews [45].

Table 11. Input variables for HRS analysis.

PARAMETER	UNIT	VALUE
FIXED O&M		
Internet	€/year	2,162
Fixed Electricity Consumption	€/year	1,974
Permits	€/year	3,478
Hydrogen Quality Test	€/year	5,076
Insurance	€/year	6,768
Property Tax	% of CAPEX	1
Rent	€/year	45,120
Fixed Labour	% of CAPEX	3
VARIABLE O&M		
Sales Tax	% from Sales	2.25
Credit Card Fees	% from Sales	2.5
Variable Electricity Consumption	kWh/kg of H_2	3

The base case is obtained for the HRS step of the supply chain, where a CF_{HRS} of 0.1 is used, and a low $HRS_{subsidy}$ of 10% is used to exemplify a non-favourable business case for HRS developers. Other values as HRS capacity, are based according to AFIR requirements. With this, the $LCofHRS$ obtained is of 4.43 €/kg of hydrogen dispensed. With this into consideration, it immediately shows that the business case for HRS developers is not favourable. Nevertheless, sensitivity analyses are done to identify the impact of a higher CAPEX subsidy as seen today in Sweden, and an increased capacity factor. The following are the results when performing the sensitivity analysis over the capacity factor, and assuming a CAPEX subsidy of 40%.

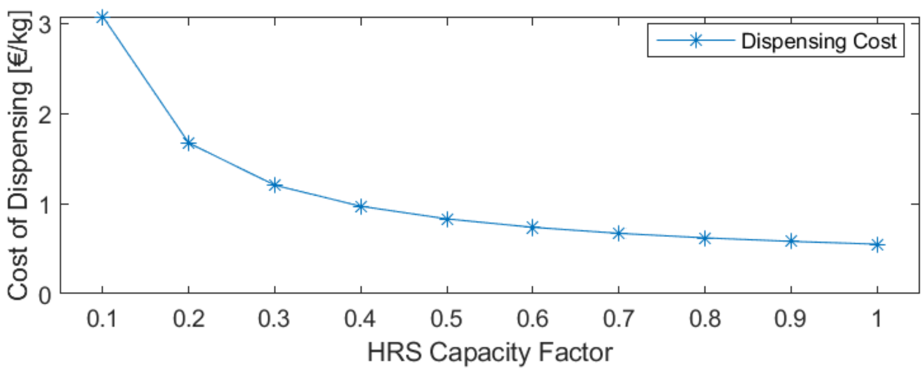

Figure 21. Cost of dispensing (LCofHRS) results from sensitivity analysis of HRS capacity factor.

The results show a cost of dispensing of 3.08 €/kg at a 0.1 capacity factor, and 0.56 €/kg at a capacity factor of 1, showing a maximum impact of 2.52 €/kg. Moreover, it can be highlighted that it is possible to resemble the HRS CF to an operational subsidy, with positive impact in the price of hydrogen at the dispenser, and finally increasing the feasibility for business developers. Is important to consider that as of today, there is no operational subsidy for the HRS owners, therefore, the cost of having low-capacity factors, either is covered by the project owner at its own financial risk or is being paid by the final user, to then offer a feasible price to the final user.

On the other hand, the CAPEX subsidy is present today in the Swedish regulatory framework, averaging today 40% of the CAPEX. Nevertheless, a sensitivity analysis is done with the goal of first determining the impact it has already on the final cost of hydrogen, and later compare with the possible impact an operational subsidy would have. The following is a graph showing the different CAPEX subsidies and the LCofHRS respectively, having as a constant the capacity factor with a value of 40%.

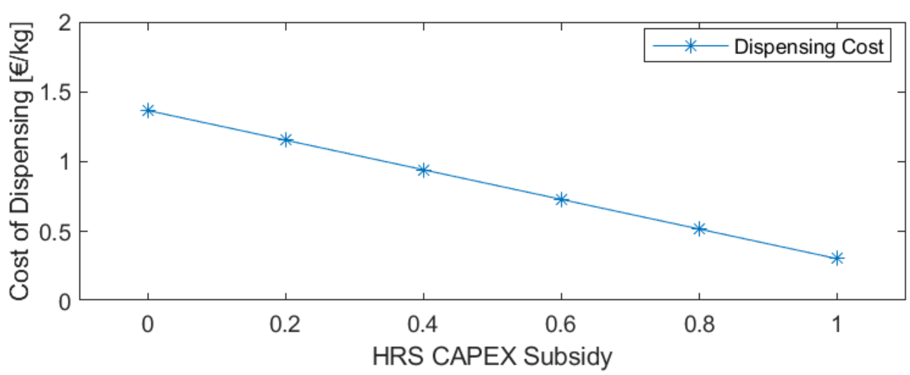

Figure 22. Cost of dispensing (LCofHRS) results from sensitivity analysis of HRS CAPEX subsidy.

While the CAPEX subsidy varies from 0 to 100%, the cost of dispensing in this range reduced from 1.37 €/kg to 0.31 €/kg, having an overall impact of 1.06 €/kg. As the impact of this subsidy is beneficial for project development by kickstarting the infrastructure development, the overall impact on the LCofHRS is not as representative as an increased capacity factor, or an operational subsidy. Lastly, increasing the capacity factor from 10% to 20%, already overcomes the overall impact of the CAPEX subsidy, with an impact of 1.4 €/kg, besides from the fact that it creates cash flows for the HRS owners. Finally, both variables are added together in a sensitivity analysis to have an overview of the impact of both variables on the LCofHRS.

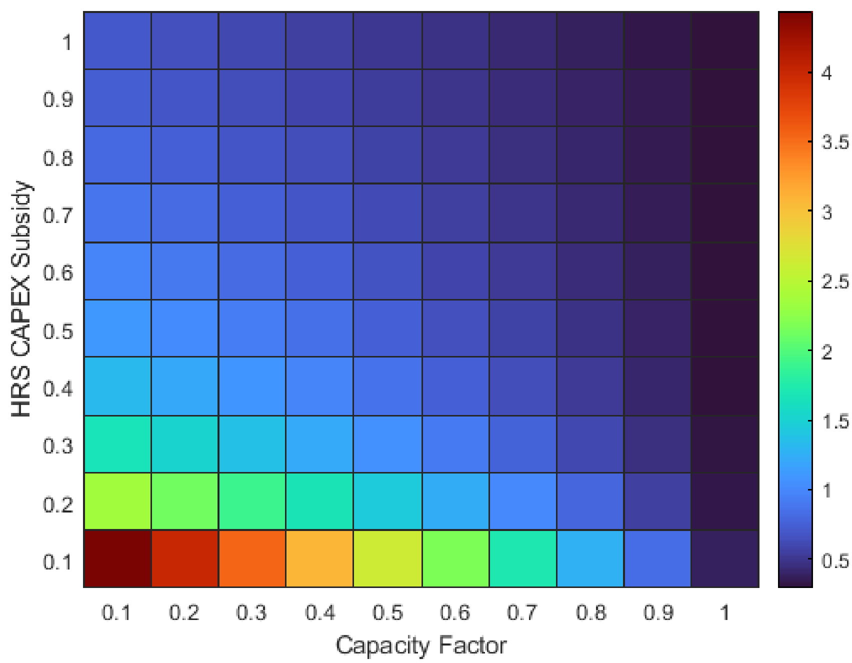

Figure 23. Cost of dispensing (LCofHRS) in €/kg sensitivity analysis heat map result of HRS CAPEX subsidy and HRS capacity factor together.

In fact, both variables are necessary as it has large influence on the project development finances on different instances. First, the CAPEX subsidy, as explained before, enables a project to secure investment as this sector involves high risk due to the uncertainties it carries with related to the hydrogen offtaker, meaning credit risk. On the other hand, the capacity factor or an operational subsidy is necessary to maximize the fixed costs such as the CAPEX and the FOM, reducing the costs to the marginal cost of dispensing. Lastly, the overall impact of having both factors, has a large impact on the final cost of hydrogen dispensed, also increasing the feasibility for the low-carbon hydrogen offtaker.

3.5 Hydrogen Supply Chain Overview and Conclusions

Having all the steps of the supply chain and its variables analysed, to combine the steps and have a holistic overview of the cost reduction opportunities is the goal. To fulfil this task, an overview of the hydrogen cost through the supply chain is developed, with specific cost reduction opportunities, and lastly with strategies and recommendations on how to reach these opportunities.

Starting with low-carbon hydrogen production, the LCOH can be reduced through:

1. Increasing the electrolyser size.
2. Procuring low-cost electricity in the power market.
3. Increasing the electrolyser capacity factor.

The following question arises with these conclusions: in practical terms, what is needed to reach this cost reduction opportunities on low-carbon hydrogen production?

Increasing the electrolyser size without increasing the hydrogen demand, will lead to higher LCOH as CAPEX is not maximised, together with higher operational costs. For this to happen, large demand, or offtakers, are required. According to Deloitte in its European hydrogen economy 2030 outlook, the hydrogen demand for mobility will be 0.29 MtH_2, compared to 2.42 MtH_2 for energy-intensive industries [46]. Moreover, due to decentralised nature of road mobility and transport costs, it is easy to determine that large electrolysis facilities for solely low-carbon hydrogen production for road mobility is not a feasible option. Therefore, as hydrogen is becoming a relevant molecule for many other sectors, there are opportunities on creating cross-sectional synergies. These cross-sectional synergies emerge with the fact that industries require heavy-duty vehicles to transport raw materials and final products, such as ports, and industrial parks. Therefore, low-carbon hydrogen production in industrial hubs and ports for own consumption with the possibility of also selling through HRS, emerges as a strategic solution to produce and incentivize low-cost low-carbon hydrogen for road mobility. Furthermore, oxygen and heat byproducts would be of interest for these industrial hubs, added to power flexibility of some electrolyser technologies in an already constrained grid, enabling additional revenues, and further reducing the LCOH. It is clear the synergy between sectors, where many benefits and risks could be listed. More detailed studies should be carried out to determine the specific impact of this possible revenue streams, as they vary on specific situations.

Furthermore, it is highly relevant to have a robust electricity sourcing strategy for electricity production. For this purpose, Timera Energy has highlighted three different procurement strategies hydrogen producers could adopt to source low carbon electricity, each having its own advantages and disadvantages, and following the latest Delegated Act [47], as in Figure 24.

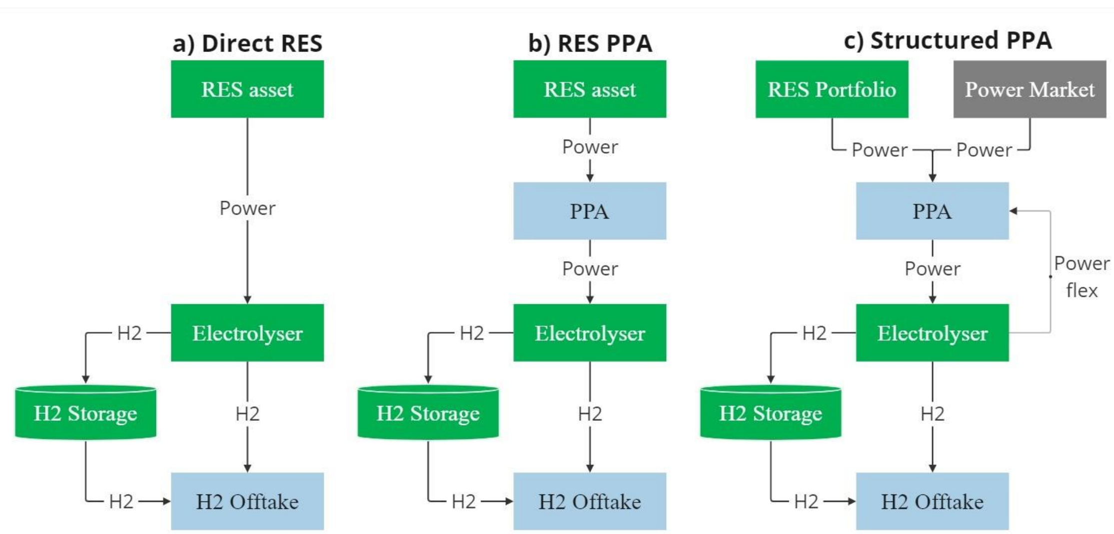

Figure 24. Flow diagrams of low carbon electricity procurement models. Retrieved from [47] .

Model a) has a renewable energy system (RES) directly coupled to the electrolyser as the only electricity source for hydrogen production, or called also Direct RES. Model b), RES PPA, the electricity is sourced via power purchase agreements (PPA) from one or more RES assets and through a 3rd party. Model c), Structured PPA with a trading counterparty such as a utility or an energy trader, manages dynamically its RES portfolio and the power market, where power flexibility from the electrolyser side becomes possible. The following table summarises the advantages, disadvantages, and challenges of adopting the models described.

Table 12. Advantages, disadvantages, and challenges of each low-carbon electricity procurement model. Adapted from [47], with additional analysis.

MODEL	ADVANTAGE	DISADVANTAGE	CHALLENGE
Direct RES	• Supply chain vertical integration, avoiding 3rd party fees. • Possible low electricity price.	• Location constrained. • Inflexible hydrogen production leading to higher costs (constrained by the RES). • Possible electricity curtailment.	• Challenge with RES oversizing. • Competitiveness versus dynamic electricity sourcing model.
RES PPA	• Allows production close to offtake, detached from RES. • Possible risk and cost reduction through PPAs.	• 3rd party fees. • Inflexible hydrogen production leading to higher costs (constrained by the RES). • PPA risks such as fixed power price.	• Signing of long term fixed PPA that enables competitive production. • PPA price risk should be managed through the hydrogen offtake agreement.
Structured PPA	• Flexible sourcing of low-carbon electricity. • Flexible operation of electrolyser. • Access to low-cost spot market. • Guarantee of origin backed by 3rd party.	• Greater PPA contract complexity. • 3rd party PPA fees.	• Increased risk due to exposure to volatile spot market.

The different models offer different possibilities to reduce risk, develop bankable projects, and maximise value, however, every one of them encompass different levels of complexity and new possible related risks. The adoption of a specific model is constrained by the project conditions, and the regulations established for "green power" sourcing for low-carbon hydrogen production in the latest EU Delegated Act.

Downstream the supply chain, there are the refuelling stations, which sensitivity analyses show that subsidies and demand are imperative for having a low-cost hydrogen for the final user. One of the major challenges for a feasible business case is the deployment of FCEVs to increase the HRS capacity factor. Nevertheless, as the deployment of FCEVs ramps up, it is imperative that a "fake demand" is created via operational subsidies to reduce the financial risk of the project developers, increasing bankability, and finally allowing a price reduction that would become attractive for the FCEV owners. In this order of ideas, as CAPEX subsidies are available today in

Sweden for HRS development, easing the finance of projects, OPEX subsidies should be in place to support the supply chain development and creating market signals for the deployment of FCEVs.

Subsequently, the different steps of the supply chain are brought together into a holistic perspective, where specific conditions are considered. For 2023, the following table summarises the variables that are used for cost reduction possibilities and impact identification throughout the supply chain.

Table 13. Input variables for supply chain integration results.

PARAMETER	UNIT	VALUE 2023	VALUE 2028
HYDROGEN PRODUCTION			
Electrolyzer Size	MW	1	100
Capacity Factor	%	0.24	0.9
Electricity Cost	€/MWh	90	40
HYDROGEN REFUELLING STATION			
CAPEX Subsidy	%	0[4]	40
Capacity Factor	%	10	40

An unreal CAPEX subsidy of 0% by 2023 is used to highlight the impact that the lack of the subsidy offered by Klimatklivet for the development of HRS, could bring throughout the Swedish territory. 40% is used as the predicted CAPEX subsidy, following the current trend of bidding processes for assigning CAPEX subsidy, which as of today is 40%. In this order of ideas, the theoretical value chain aggregated cost by 2023 with the input values expressed above is showed in the figure below.

[4] This is an unreal value for CAPEX subsidy in Sweden in 2023. Current average CAPEX subsidies are 40%, and up to 70% for some cases.

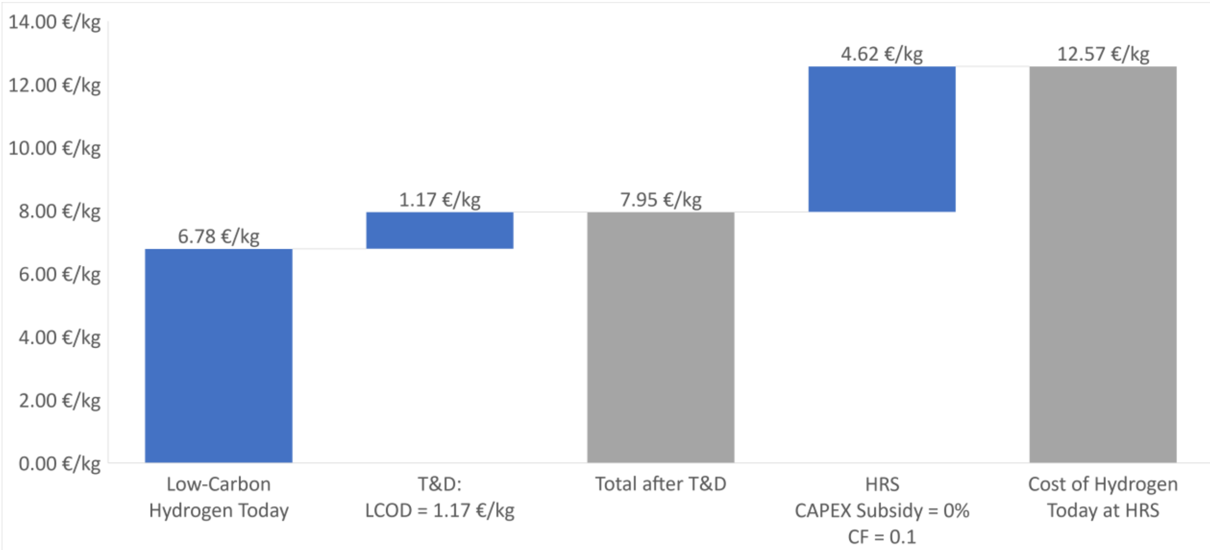

Figure 25. Low-carbon hydrogen value chain aggregated cost by 2023.

As previously showed in the results, the variables that are analysed for cost reduction possibilities and overview of the supply chain where the ones used for sensitivity analysis. Then, the breakdown of the supply chain by 2028 was compiled together under Figure 26.

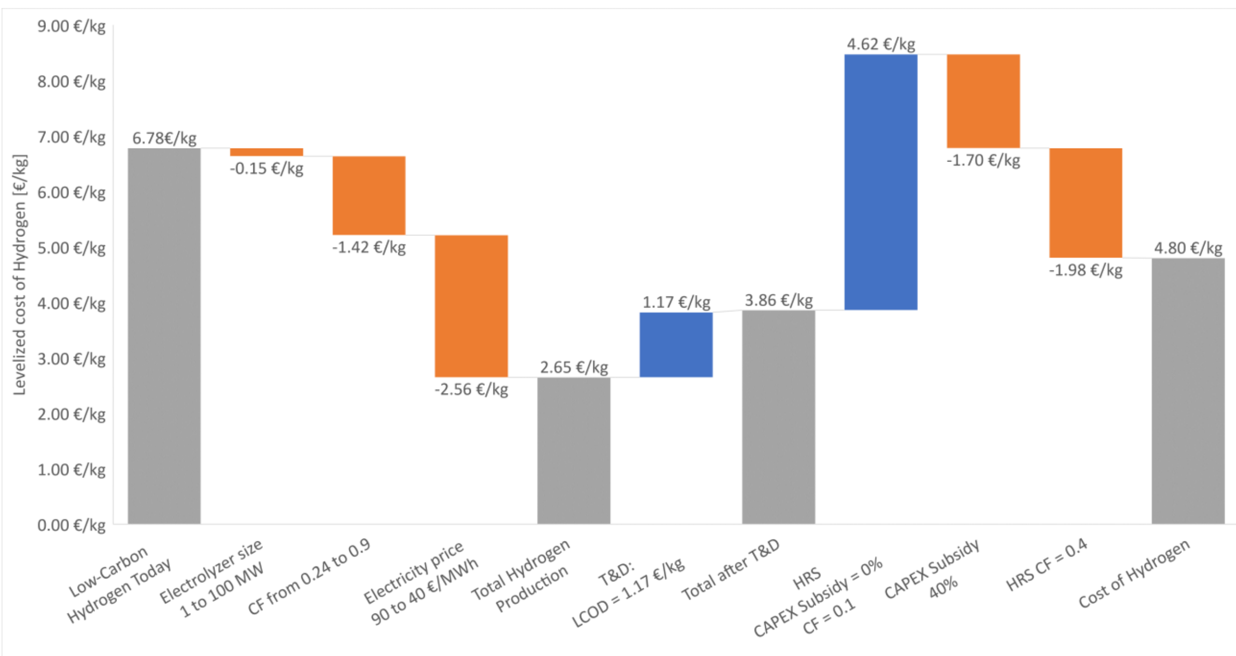

Figure 26. Low-carbon hydrogen value chain aggregated cost by 2028 with cost reduction possibilities.

The before and after stages of the supply chain are represented by the grey bars. In the case of hydrogen production, a cost reduction of 4.13 €/kg is achievable. To make this possible, it is imperative to adopt an electricity sourcing strategy and leverage the grid to maximize electrolyser capacity factor (due to the new DA), leading to an impact equivalent to 3.98 €/kg. Next, the LCOD could be optimised by increasing the transport capacity and reducing the distance between production and consumption, not assessed in this model. Lastly, the refuelling station cost reduction of 3.68 €/kg is dependent on the CAPEX subsidy obtained, and the capacity factor translated as the volume of utilisation demanded by FC vehicles or trucks. The probable CAPEX subsidies for HRSs are later explained in the 5 REGULATORY FRAMEWORK ANALYSIS chapter.

The cost reduction opportunities identified will further increase the bankability, reduce risk, and create value throughout the supply chain, factors not only important for road mobility, but also for the development of low-carbon hydrogen as an economically feasible solution. Nevertheless, the conditions showed here are theoretically possible, however, lack of expertise in the sector, operational data, and know-how, could increase even further the costs, which are not considered in this analysis.

4 INTERVIEWS

4.1 Motive of the interviews

To gain a better comprehension of how the industry and stakeholders perceive and observe the status of the hydrogen value chain in terms of mobility and its progress, some interviews were conducted. Each interviewee belonged to a specific link in the value chain and possessed expertise in their respective field, thus ensuring valuable insights for the project throughout the entire value chain. The thirteen interviews carried out, encompassed the stakeholders of the NHC project, FCEV owners as end users, and other experts in the area, as shown in the next table.

Table 14. Contribution of the participants interviewed.

Participant	Total Duration	Contribution to:					
		Electricity	**H_2 Production**	**S&T&D**	**HRS**	**Automakers**	**End user**
Electricity producer	28 mins	✓					
H_2 Producer (x2 times)	2:02 h	✓	✓	✓	✓		
University PhD Researcher	52 mins	✓	✓				
H_2 related company	43 mins	✓	✓		✓		
Automaker 1	57 mins		✓		✓	✓	
Automaker 2	36 mins					✓	
FCEV End user	22 mins				✓	✓	✓
FCEV End user	26 mins				✓	✓	✓
H_2 expert (x2 times)	2:15 h	✓	✓		✓		
FCEV End user (H_2 expert)	1:03 h		✓		✓		✓
FCEV End user (H_2 expert)	54 mins				✓		✓

By adopting a qualitative approach, the study generated two separate analyses. In the first stage, the literature research revealed different success and risk factors associated with specific areas, such as technology, policies and institutions, supply chain infrastructure, and business and economics. The findings obtained with the survey responses, allowed the identification of the four mentioned areas, and the subsequent in-depth exploration of the H_2 mobility value chain in Sweden for each area. Then, a thorough analysis between each one was done, to understand the bottlenecks, risks, and success factors that the chain currently bears. In the second stage, the most valuable inputs were grouped into the research questions showing a direct assessment of possible gaps and impacts in the chain as the conclusion.

4.2 Results of interviews

Dimensions impacting supply chain for mobility.

There are several factors that influence the development of hydrogen mobility in Sweden, narrowed down to four for the present analysis. First, the country is subject to the EU regulations and the development of its own regulatory framework. Naturally, each directive, act, policy, and institution, will affect the roll-out of hydrogen and its development in mobility, which is the reason to consider Policies & Institutions as one of the four factors. Secondly, the Technology surrounding hydrogen as energy carrier, and for mobility purposes it's a novelty compared with diesel ICE. The fuel cell, HRS, electrolyser, storage tanks among many others, could exhibit limitations or advantages and it should be considered for the project.

As such technologies have not yet reached cost parity with fossil fuels, and some of the elements have not reached the highest maturity level, the market to address, the risks associated, and the uncertainty could be high. Therefore, Business & Economics, the third factor to analyse, as the driver of any business model involved in the value chain and its strategy need to be contemplated among the important factors. Lastly, as there is a need to create synergies between production, transport, storage, refuelling, and end user, it is important to understand the efforts to develop the different steps together, accelerating the Supply Chain development. Additionally, there are synergies between the different areas previously described, as showed in the figure below.

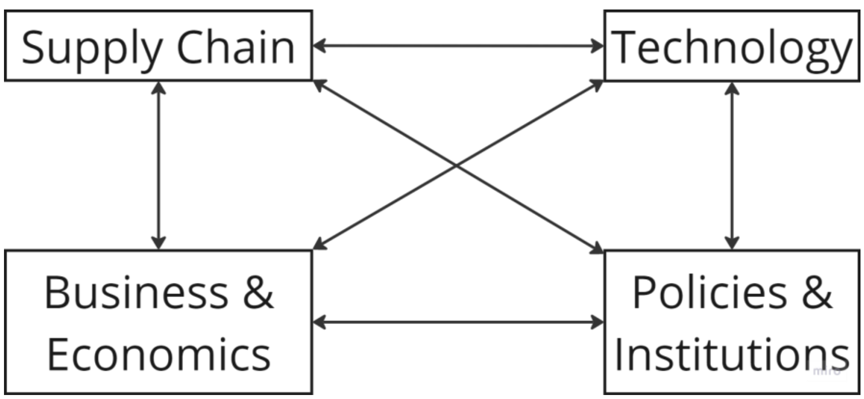

Figure 27. Areas analysed for interviews results and synergies between them.

The goal with this approach is to highlight the answers from the different stakeholders that have influence over more than one area, identifying then individual and holistic efforts for the road mobility supply chain development.

Business & Economics

Joint ventures, state support and extra revenue streams will help reduce mainly the financial risk for the hydrogen value chain deployment. Such synergies seek to create a large-scale market, involve the knowledge of its stakeholders and ease challenges of the supply chain. Once the infrastructure and elements are built, any business model will need an offtaker, that in mobility translates into HRS requiring FCEV with the guarantee of H_2 availability at competitive price to be profitable. This also means that vertical supply chain integration is an option to mitigate risks on finding the offtakers.

From one perspective, HRSs are a highly capital-intensive installation that depends solely on the market dynamic. Without forecasted sales, the operative costs and debt will consume the business and bring it to failure. Therefore, the need of hydrogen vehicles on the road and a competitive hydrogen cost is ultimately imperative. From the other perspective, FCEVs also have several requirements for its adoption. First, cost parity with technologies regarding the vehicle and the fuel cost as well. Second, availability of specialised workers and vehicle OEM to have a convenient post-sale service in their living regions. Third, the possibility of choosing different car models, depending on their need. Last, a strong infrastructure that ensures its demand close to home and in their daily needs.

Supply Chain

From the supply chain point of view, the goal was to understand the synergies between the steps and stakeholders throughout the supply chain, as well as the different weaknesses. Considering the early stage of development in Sweden of the hydrogen mobility supply chain, many stakeholders were aware of the necessary efforts for profitable business cases, together with its challenges. However, the early stage of the supply chain, and the low infrastructure readiness for low-carbon hydrogen production and distribution, has created many inconveniences with non-desired downtime caused by lack of hydrogen, impacting also the end user. The comments align with the conditions of a supply chain in early-stage development, therefore, the perspectives were expected.

Nevertheless, the end users interviewed, were also aware of the challenges involved in participating in such an early stage. Thus, FCEV owners had good relationships with the HRS operators, being able to gather information of the HRS availability. In many situations, they were able to coordinate with them to successfully refuel their vehicles on time. Furthermore, the relationship with the OEMs is to be highlighted. An FCEV user, who obtained his FCEV in the second-hand market, was able to reach an agreement with the OEM for maintenance of the vehicle. This synergy highlights the commitment to successfully develop the supply chain through good vehicle experience, and on the other side, the desire to become part of the hydrogen mobility supply chain as an early adopter.

Another point to highlight is the role of certain elements through the supply chain, such as the electricity. It was inferred that any variation on it impacted the entire chain, mainly from the cost perspective, and of course its availability was of paramount importance for low-emissions H_2 production. As many are betting in the development of the hydrogen supply chain for road mobility, measured risks have been taken. It is also important to highlight the fact that infrastructure has synergies with the other analysed areas. Therefore, as individual solutions for a specific area are necessary to cover individual risks, there is also the need for holistic solutions to cover cross-sectoral risks.

Policies & Institutions

Complicated permitting processes with several decision-making stakeholders (e.g., municipalities), political conflicts in the alignment of renewables deployment and hydrogen importance, safety concerns and lack of education are major barriers to hydrogen deployment in Sweden. As the country stayed behind in the update and development of a strong regulatory framework and institutions that foster the energy transition, EU is setting the main policies for its adoption. Still, reviewed regulations as the AFIR were less ambitious than previously expected. Also, subsidies should be distributed between CAPEX and OPEX, among other possibilities as CCfDs to lower the risk. Still, the future prospect appears favourable with the development of the electrification strategy, which addresses several of the upstream value chain concerns, the development of guidelines for HRS safety measures, and EU policies that impact also the midstream.

Technology

Low-carbon hydrogen electrolysis technology is still developing, as IEA states that more effort is needed [24]. However, due to the lack of experience and readiness of hydrogen technologies, many issues have arisen. In this section the goal is to analyse the answer from the stakeholders on their experience with technologies throughout the supply chain, such as electrolysers, FCEVs, HRS, among others.

A common pattern throughout the supply chain stakeholders has been lack of knowledge and experience on management of hydrogen technologies. This led the stakeholders to learn from operational experience and data, which highlights the need for information sharing and standardization. Some have framed this as relevant business information; therefore, it is not desired to share it with other stakeholders. On the other hand, some have been open to share information with similar stakeholders to promote the usage of a specific technology. Some others frame it also as a risk, where developing more knowledge and experienced workers, is unnecessary due to costs involved, and market uncertainty.

However, stakeholders are in close contact with the OEMs throughout the supply chain to improve technological development, guarantee customer satisfaction, and to build a framework or standards throughout the hydrogen supply chain. This is a pattern which is not only useful for the development of technologies, but also for business creation, regulatory aspects, and supply chain integration. This was seen when one of the stakeholders highlighted that their strategy was to reduce the downtime of HRS, while the FCEV users also highlighted that downtime has been a recurrent issue for them. This information, which is relevant for the HRS developers, is key for business development, therefore, individual efforts on HRS technology will have an impact on supply chain integration and on business and economics.

Synergies between areas

Policies & Institutions – B&E:

Industry stakeholders stated that the government proposals, institutional alignment, and political signals could significantly guide the development of low-carbon hydrogen business models and reduce the risk. However, if industries identify a business opportunity, they will do its best to materialise it and even create the synergies between different players to produce a feasible business model. As hydrogen is a practically a novel element for the decarbonisation of industries, they expect to have signals that a market will be developed and financial incentives or subsidies from the government not only in CAPEX but in OPEX, to endure until profitability is achieved. CEF and Klimatklivet are fundamental funding instruments without which projects highly probable would not get materialised and would not have positive outcomes in Final Investment Decisions FID.

Some sections of the value chain are being guided by the EU regulations, such as AFIR for the deployment of HRS. Also, such regulations could get revenue streams, such as EU ETS or the RFNBO's certificates. Furthermore, industry finds significant complications on permitting processes like the environmental and the safety measures one because of the different assessments that each municipality in Sweden, out of the 290, can make regarding a project. For mobility purposes, some industry players consider that extra subsidies for the vehicle transition e.g., scrap subsidies and more restrictions to polluting engines should be imposed.

After the interviews, it can be inferred that the industry is trying to develop the market for hydrogen, by developing technologies, increasing the maturity of the value chain, and creating new value propositions. Still, the Swedish government needs to show its support through concrete actions like the standardisation of protocols and permitting processes, hydrogen goals and roadmaps for specific sectors, and strengthening the financial support to important decarbonisation initiatives. Without this support, market maturity would be harder and lengthier to achieve.

Technology – B&E:

Low-carbon hydrogen technologies, such as some electrolysis technologies and some HRSs equipment, are either in their early stage of research and development, or in pilot projects or scaling up manufacturing, in this way requiring support for research and development of pilot projects to increase its TRLs. Stakeholders are developing new value propositions based on the possibilities of these new technologies, as is the case of Hydri with its stand-alone H_2 production system for HRS, or developing synergies to have a broader knowledge, minimise financial risk and accomplish its goals, as the case of HYBRIT for green steel, aggregating stakeholders such as LKAB, SSAB, and Vattenfall. Technological elements cannot rely solely on a single developer for the global market, then the necessity of development in regional markets. During the interviews, it was stated that to avoid the potential for financial loss with novel technologies, said synergies intend to develop economies of scale and take advantage of possible revenue streams for a feasible business model.

Focusing on the mobility value chain, some interviewees give an example of how to make a robust business model for H_2, based on the scalability of the technology. The upstream could benefit the most by large-scale hydrogen production in some industrial hubs (through synergies), which lowers the LCOH, and some of this gas can be destined for HRS in the downstream, making it more competitive with other technologies. Focusing on the vehicle technology, the storage tank and fuel cell are elements than can be improved greatly and will undoubtedly reduce its pricing in the future. However, as the market is presently focused on other technologies that are already mature and efficient, then the risk and financial requirements for switching to a different technology are difficult to attain when there are no strong guarantees that the market will thrive. Thus, government and policies are the ones to reduce this risk by giving clear signals that the market will, to some extent, be supported.

Supply Chain – Technology: (Focusing on the supply chain, diversification of key elements is necessary to avoid bottlenecks for raw materials scarcity or production lead-times).

Lack of technological development is counterproductive for the supply chain development. Several stakeholders interviewed highlighted the lack of technological readiness, translating into supply chain disturbances. A specific situation highlighted was the lack of hydrogen distributed to the HRS due to transport logistics or lack of hydrogen availability, affecting the FCEV user. A variation of the supply chain and technological configuration allows to reduce this impact: incorporation of electrolysis on-site for low-carbon hydrogen production. This, also called supply chain vertical integration, are strategies to mitigate risks, in this case, reducing the dependence on logistic companies. Moreover, the technological shift in the HRS configuration from centralized production in hubs to decentralized production on-site, guarantees uptime and fuel availability. These strategies would further affect the business and economics, as this is a new business model.

Furthermore, various stakeholders expressed their concerns over sustainability and raw materials for hydrogen road mobility supply chain. From the electrolysis production, the PEM electrolyser for example, uses platinum group materials which can be scarce and costly, developing production and availability problems from the upstream. Moving to the midstream, it was mentioned that the technology and materials required for storage tanks at high pressures can be also a bottleneck in the chain, while standardization and optimisation of the manufacturing process is achieved. In the downstream, comments regarding HRS issues when cold-starting were received, along with the same possible bottlenecks of the materials for the fuel cells and storage tank for the vehicle. However, it was constantly emphasised that the core of the technology was ready, pilots and demonstrations have succeeded, and the issues mostly encompass optimization and impacted the ramping up of the supply chain.

In general, it is imperative to continue fostering research and development for improving the technology, as it will assuage the supply chain operations, increase efficiency in the processes, and reduce the costs throughout the supply chain.

Technology – Policies & Institutions:

Along the value chain, some technologies have been supported by different policies that target decarbonisation. As electrification is one of the main strategies from countries like Sweden, electricity generation through renewable technologies has been a key policy success that has adhered to the energy markets. Recent EU plans have given even more impulse to them, as the REPowerEU, and some proposals like NZIA seek to support the hydrogen value chain emphasising electrolysers and Fuel Cells among others. Such plans and regulations intend to highlight the importance of these technologies for the industry and market to react and attend a more certain increase, and provide financial support for research & development, pilots and demonstrations, and important projects.

For automakers, this signal can be a pivotal point to also consider as a strong alternative FCEV and trucks as a potential player in the market. Toyota and Hyundai, companies which have superior experience with fuel cells, could take advantage of such incentives in the EU and develop an ecosystem focused on this technology. Sweden, with only 2 automakers supplying FCEV, and with great brands such as Volvo and Scania based in the country, can also align with EU policies, and create stronger incentives for the technology development inside the country. Also, the country currently has 2 different institutions (The Swedish energy agency and the Swedish environmental protection agency) providing subsidies for the purchase of environmental trucks, which, together with the funding for innovative technologies and startups, can be the starting point for market development.

4.3 Concluding remarks

The information collected from various stakeholders across the entire value chain offered a comprehensive understanding of the essential factors influencing the current state of hydrogen mobility in Sweden. To add a different perspective of the information, the most relevant stakeholder's inputs are going to be displayed, grouped in the research questions stated at the beginning of this report.

RQ1. Emphasis on the technical and economic aspects of refuelling stations and its value chain to attain a robust business case.

- Hydrogen technologies should reach cost parity with current technologies. Low-carbon hydrogen needs to lower its cost and increase its availability throughout the value chain.
- Synergies, joint ventures, securing an offtaker, and monetising byproducts are good strategies to produce large scale, low-cost hydrogen.
- Constrains on electricity networks and electricity price volatility can impact the business models.
- A large deployment of HRS will secure a robust business case for Sweden.
- Hydrogen trucks are key for securing a demand that could guarantee business profitability.

RQ2. Focus on the policies, subsidies, and market incentives that impact the market rollout for hydrogen mobility and user experience.

- Lack of political and institutional alignment towards low-carbon hydrogen, with complicated permitting process and safety requirements, could hinder hydrogen development in the country and in its value chain.
- Specific country goals for H_2 and education through all the government hierarchy (parliament to municipalities) are needed to incentivize the market and standardise the project development.
- EU policies are a major guideline for low-carbon hydrogen deployment in Sweden. Some position Sweden in a privilege situation.
- Subsidies can bring to life capital intensive hydrogen projects, but support should also exist for its OPEX while the offtakers' demand develops.
- Some steps of the value chain have more support regarding policies and subsidies. An evenly backing of the entire chain is needed to create a strong business model.

End user perceptions towards:

FCEVs

- The vehicle's performance is remarkable, with a convenient fast-refuelling time, long range, a nice apparel and good performance conditions under different weathers and seasons.
- FCEVs have significantly low or non-existence taxes, but the investment is high even with previous subsidies.

HRS

- Filling stations must be in the vicinity of the residence or daily route, to ease the change to a FCEV.
- HRSs can be out of service for maintenance or lack of fuel, then constant communications with the operator is advantageous.

Automakers

- There is difficulty on getting a FCEV in the current Swedish market.

- There is not a broad portfolio of brands and cars for choosing.
- Drawbacks rely mostly on the absence of refuelling infrastructure, downtime of HRS, fluctuating fuel prices, the possible long periods, and distances for maintenance.
- The brands offer a good post-sale service, but there can exist difficulties in the maintenance of the vehicle because of the shortage of dedicated locations and technicians. The car could even have to be moved to other locations.

General

- End-users don’t have safety concerns during the utilisation of the vehicle or during the refuelling process.
- There’s a joint feeling of the need of a stronger HRS infrastructure.

5 REGULATORY FRAMEWORK ANALYSIS

5.1 Assessment description

The present chapter seek to give an overview of the relationship between the regulatory framework of the EU and Sweden, the legal framework in the country, and the inclusion of some financial instruments towards the hydrogen mobility value chain. The end result is determining through qualitative analysis the strongest incentives or bottlenecks that could affect market rollout for fuel cell vehicles, refuelling infrastructure, and the hydrogen value chain for the country.

First, a literature review of EU regulations will be displayed, trying to analyse the impact of such policies, strategies, or directives upon the hydrogen mobility deployment in EU member states, with emphasis in Sweden. Second, important Swedish laws and regulations will be described with the same correlation on the value chain as before. Outputs of the interviews about specific laws that could impact the chain were considered. Next, the mapping of the entire value chain will be shown, with a discussion upon the implications and gaps found, to close the chapter with concluding remarks.

5.2 Overview of EU policies and subsidies and their impact in Sweden

EU Emissions Trading System

Aligned with the European Green Deal the European Commission developed the EU ETS policy to reduce emissions while creating a carbon market from the energy, manufacturing sector, and aircrafts operators. It bounds emissions from around 10,000 facilities through emissions allowances (EUA), covering up to 40% of EU GHG. Such allowances will be reduced up to 62% by 2030 compared to 2005, ensuring emissions decrease and fostering cleaner technologies [48]. Working as a cap-and-trade system, companies can trade its allowances as commodities in the market, which is highly volatile depending on prices of fuel, weather, etc. Prices have ranged from 77 to 100 €/ton CO_2 during 2023 and it's expected to keep raising in the upcoming years as supply of EUA decreases [49].

Low-carbon technologies investments, such as electrolysers, can receive financial backing from the government through the use of Carbon Contracts for Difference (CCfDs). This mechanism works by securing long-term contracts for projects that abate CO_2 emissions, gaining the difference between the market's ETS price and the contract fixed price. Additionally, this mechanism helps de-risking projects, securing a revenue stream and increasing confidence for capital intensive projects, which can be an important instrument to be developed in Sweden [50].

Currently, as part of Fit-for-55 there's been an extra revision of the ETS phase 4, in which a new emissions trading system will incorporate fuel combustion for buildings, road transport and small companies. The new system that impacts the upstream chain rather than end users, is expected enter into force by 2027, with the goal of a 42% emissions abatement by 2030, compared to 2005. Additionally, free allowances for electrolysers producing hydrogen will be given [48].

Natural Gas Directive

The Natural Gas Directive (2009/73/EC) is undergoing an evolution process with substantial modifications applying to the EU. The proposed changes include the incorporation of a decarbonisation package for hydrogen and gas markets (2021/0425/COD), which will lead to the establishment of a regulatory framework for hydrogen, its infrastructure and market, and network planning. Once the deployment increases its maturity, Transmission System Operators (TSOs) and Distribution System Operators (DSOs) could be established, along new rules for the novel market [51]. As the proposal is set, the discussions within the EU Council are finished and the negotiations with the European Parliament will begin. Particular emphasis needs to be placed on its advancement, as it will greatly benefit the storage, transmission, and distribution of H_2, specifically supporting member states with limited development and knowledge in natural gas and hydrogen. One foreseeable effect will be the revision and probable boost of the European Hydrogen backbone infrastructure deployment, which connects Sweden to Finland in one if its stages.

European Hydrogen Backbone

The European Hydrogen Backbone envisions a dedicated hydrogen transportation framework spanning across Europe that connects hydrogen producing locations to demand centres through a network of pipelines. The success of this plan includes the involvement and cooperation of several TSOs of the EU member states. With a projected investment of approximately 80-143 billion Euros, this pipeline network is expected to grow up to 53,000 km by 2040. The financial purpose is to be the most cost-effective alternative H_2 transportation for large-scale and long distance with a rate of 0.11-0.22 €/kg over 1,000 km for onshore and 0.17-0.32 €/kg for offshore [52].

As important chemical and mining industries are in the southwest, east, and north part of Sweden, the Nordic & Baltic Corridor plans to develop new transmission pipelines in these areas. Considering the high forecasted hydrogen consumption in the northern area (H2 Green Steel, HYBRIT, etc.) and its connection with Finland surrounding the Bothnia's gulf, this corridor called "The Nordic Hydrogen Route" it is of primary significance. Nordion Energy and Gasgrid Finland are the main companies behind said project, accounting for up to 1,000 km of dedicated pipelines [53].

EU Renewable Energy Directive

The Renewable Energy Directive (RED) is a legal framework for the deployment of renewable energy in Europe, also supported under the fit-for-55 package. It has been constantly revised (RED II), increasing targets of renewable energy over the mix by reaching a 40% objective in 2030, and sub targets for Renewable Fuels of Non-Biological Origin (RFNBOs). Together with the Sustainable and Smart Mobility Strategy of 2020, they approach 10 different flagships recommendations for "putting European transport on track for the future" with specific goals that can be tracked by policy makers. In addition, the Hydrogen strategy, the EU Taxonomy, and the Delegated ACT are profoundly influenced by such framework, as later will be explained.

For road-transportation, RED propose a comprehensive network of recharging and refuelling structure should be created, striving for the construction of 500 HRS by 2025 and 1,000 for 2030; such stations should be interoperable in all the territory, meaning that they must use the same technology and specifications in all member states; likewise, a dense network must be guaranteed for all end-users, including heavy-duty vehicles, with adequate pricing information to the customers and cross-border payment methods; also, the "polluter pays" foster the principle of carbon pricing. All these proposals set the starting point of the hydrogen infrastructure development for mobility, that has been since then constantly updated, with target modifications

[54]. Nonetheless, the main regulation setting the specifics behind hydrogen mobility is AFIR, giving support to the TEN-T.

EU Hydrogen Strategy

One of the goals of the Hydrogen Strategy (2020/301) is to accomplish electrolysis installed capacity of 6 GW and 40 GW for 2024 and 2030 respectively. To manage the objective the strategy pursues hydrogen deployment following 20 key actions mainly focused on creating the necessary funding and supportive framework, to have a strong supply and demand market. Initially, an investment agenda for the EU is built with the help of the clean hydrogen Alliance. Having the financial resources to exploit H_2, it becomes necessary to boost the demand for the increasing supply, by pushing economic sectors through stronger policies and new standards. Thorough terminology as the definition of low emissions hydrogen and certifications for low-carbon hydrogen are examples of novel standards, and the development of pilots for a Carbon Contracts for Difference illustrate a viable option to incentivize carbon reduction. Infrastructure and R&D are not left behind when pursuing the purposed goals, coupled with the revision of the market rules when necessary [54]. The hydrogen strategy is being boosted by the REPowerEU, by updating the goals to more ambitious and accelerating the phase of H_2 deployment.

EU Taxonomy

The EU taxonomy regulation (2020/852) came into force as a classification method with transparent criteria that expose the environmental friendliness of a business model, to facilitate investment. In other words, it creates a common language for understanding economic activities that make contributions to climate and environmental objectives, avoiding significant harm (DNSH), by clearly defining sustainability into quantifiable criteria [55]. A Technical Expert Group (TEG) set up by the EU developed recommendations for various industries to address climate change mitigation practices, including hydrogen manufacturing.

By measuring GHG per unit of product, Annex I state that hydrogen production emissions threshold should be below 3 tCO_2e/tH_2 in its GHG life-cycle or have emissions reductions of 73.4% relative to fossil fuels, which favour electrolysis through renewable energy under the measurement of Directive (EU) 2018/2001 Article 28(5). Likewise, releases a comprehensive technical criterion for the manufacture of equipment for hydrogen production and hydrogen storage. Furthermore, for hydrogen-based synthetic fuels or RFNBOs the emissions should remain below 70% when compared with fossil fuels of 94g CO_2e/MJ, meaning 3.38 tCO_2e/tH_2 [56]. New Taxonomy assessments, considering if nuclear energy can produce "renewable" hydrogen is currently in study [57].

Delegated ACT

In February 2023, the European Commission adopted two Delegated Acts (DA) under the RED, which specify standards for RFNBOs and renewable hydrogen, in line with the REPowerEU plan. A target of 14% renewable fuels has been set for the transport sector. As the required targets for renewable hydrogen could entail 550 TWh of renewable electricity, cannibalization of existing infrastructure would be contrary to the directives. Accordingly, the first DA referred to as additionality, addresses the issue by requiring RFNBO production facilities coming operational as of 2028 to have a PPA from a new electricity generation project, that comes into operation no earlier than 3 years. For Sweden, this additionality won't apply until 2028 or later if the clean grid requirements continue to be met [58].

Additionally, the DA added a geographic and temporal correlation for an RFNBO or hydrogen to be considered renewable: whether the H_2 production unit uses a direct line from a new renewable electricity facility or whether the grid can be shown to be "Fully Renewable". For the last, the grid can demonstrably be renewable if RFNBOs are produced in a bidding zone geographically, where renewable level is up to 90% in the grid and the amount of production hours (renewable) cap the same amount 90%; If its outside the geographic zone, but within a bidding zone with emissions below 18g CO_2e/MJ with the corresponding PPAs, the grid can be used; when it's produced with electricity of imbalance settlement or surplus; H_2 produced onsite. Conditions on temporal and spatial correlation apply in most scenarios [59].

For second DA, a methodology for calculating the life cycle GHG across the value chain for the RFNBOs was developed. It considers the emissions from the processing, transport and distribution, combusting the fuel and the emissions savings if CCS is applied. Also, determines that RFNBOs are renewable if their emissions remain below 70% when compared with fossil fuels, as the EU taxonomy stated. Additionally, includes GHG emission intensity values for electricity grid European Union members in 2020, with Sweden being the less pollutant with 4.1 g CO_2e/MJ [58]. Such a clean grid guarantees that the country can use it to produce Hydrogen and RFNBOs, which translates into a great advantage for electrolytic hydrogen production by reaching a higher capacity factor. Such values would increase more than 3 times the H_2 output compared to a solely wind or PV electricity supply.

AFIR

TEN-T goals until beginnings of 2023 were set by the article 6 of the AFIR (2021/0223) regulation. In March 2023, after extensive trialogue discussions between EU institutions, a deal for a new AFIR regulation was achieved encompassed on the Fit for 55 packages. Although the new agreement does not fully meet the industry's demands, it is a good starting point for laying the groundwork for hydrogen transport [60]. Related to the hydrogen refuelling infrastructure, the new regulation target is reducing by 55% transportation emissions by 2030. The specifics for hydrogen deployment are the following [43]:

- HRS should be built at least every 200 km (before was set to 100 km) on core network by 2030.
- Minimum, one HRS should be built in every urban node.
- All HRS will have the capacity to provide 1 tonne/day of H_2, at a pressure of 700 bar.
- In all HRS, allow electronic payments and inform users about pricing options.

For Sweden, approximately 33 HRSs should be built between core network and urban nodes.

Trans-European Transport Network (TEN-T)

As the EU's development progresses, so does the transport network to sustain growth, based on the regulation 1315/2013. TEN-T is a policy aimed at building an efficient multimodal transport infrastructure across the EU to move people and goods, comprising roads, sea and inland ports, railroads, airports, and terminals, among others. Safety, quality, and alignment with the EUGD and AFIR, the Hydrogen and the Sustainable and Smart mobility Strategies represent a constant review of this policy, to achieve climate targets and specific objectives.

The design has two priority levels of deployment. The one connecting major cities and nodes is the Core Network and the current goal is to be completed by 2030. The secondary priority that links all regions to the core networks of EU, is the comprehensive network that should be completed by 2050. A review was proposed in 2021 to encourage emission reductions in the transport sector by 90% in 2040 for heavy duty transport, and to address missing connections of rail lines, shipping, and transshipment terminals, also including an extension of the core network [61].

To give shape and support to the trans-European transport network, nine core network corridors and two horizontal priorities were established (European Rail Traffic Management System (ERTMS) and Motorways of the Sea). These corridors, the backbone of the TEN-T's core network, are strategically situated to cover major traffic routes that stretch across Europe. Scandinavian-Mediterranean corridor is one of the core networks crossing Europe from north to south, going from Sweden to Malta [62]. Up to 29 of the projects completed in this specific corridor from 2019 to 2021 are in road mobility, followed by Rail with 21, with a total cost of €1.2 and €3.3 billion respectively. Such projects encompass upgrade of lanes and railway tracks, developing resting areas, increasing capacity and speed, and availability of alternative clean fuels points, among many others [63].

For Sweden, the TEN-T core networks account for 3,012 km and the non-core for 3,405 km, to sum a comprehensive network length of 6.417 km. Trafikverket is the institution responsible of the transportation system in the country, assuring its efficiency, safety, development, maintenance and planning [64].

Block Exemption Regulation - Article 36a

The EU introduced the Article 36a as an addition to the Block Exemption Regulation 651/2014 in August 2021, which concentrates on the provision of investment aid for publicly accessible recharging or refuelling infrastructure for zero and low emission road vehicles. The main article ensures that the construction, installation, or upgrade of recharging or refuelling infrastructure must follow a Competitive Bidding process. Essentially, from 1st of June of 2022, only some applications will receive aid, based on the clearing price or original bid submitted, being the less costly option the preferred to win. Such regulation must be adopted by member states, including Sweden. It should be noted that hydrogen generation units (electrolysers) are not eligible for the aid [65].

Clean Vehicles in Europe

Under the revised Clean Vehicles Directive European the Parliament & Council defines what is a Clean Vehicle by categorising its emissions per kilometre during specific timeframes. Its objective is to promote clean mobility solutions for public vehicles that will be purchased, leased, rented, or contracted. Restrictions apply to clean light-duty vehicles until December 31, 2025, requiring emission levels to remain at or below 50 CO_2 g/km and to comply with 80% of real driving emission (RDE) limits for Nitrogen Oxides (NOx) and Particle Number (PN). From January 1, 2026, vehicles must have zero emissions. Numerous member states have been assigned specific targets during these time periods, including Sweden's commitment to achieving a 38.5% during both periods [66].

In line with the Fit for 55, by October of 2022 the EU reached a provisional agreement to guarantee that all new light-duty vehicles (cars and vans) registered in Europe from 2035 should be Zero CO_2 emissions [67]. The objective increases pressure in the industry and automakers, considering that only in 2021 there were 9.7 million new registered passenger cars in the EU and 9.3 million in 2022 [41] [68].

Also, heavy-duty vehicles using the alternative fuels catalogued in the Alternative Fuels Infrastructure Directive (Directive 2014/95) such as hydrogen, NG, liquid biofuels, batteries among others, can be considered clean [69]. Is worth mentioning that by February of 2023, the European commission proposed zero emissions for new buses since 2030 and 90% emissions abatement of new trucks by 2040 [70].

REPowerEU

Following the energy impacts caused by the Russian invasion of Ukraine, the European Commission intends to foster its energy security with the publication of the REPowerEU plan in May of 2022. It seeks to diversify its energy sources, ending the dependence of Russian fossil fuel imports and tackle climate change through energy savings and faster deployment of renewables. In the future, the commission will seek to develop a joint purchase mechanism of renewable hydrogen, among others, as gas and LNG while reaching targets of domestic production [71].

The document urges to increase the overall renewables target to 45% (fit for 55 aimed to 40%), raise the share of RFNBOs to 5.7% (from 2.6%), and suggest that 78% of RFNBOs (from 50%) in industry should be Renewable by 2030. To achieve these targets, 10 Mt of domestic hydrogen production and an additional 10 Mt of imports sum the amount needed to accelerate H_2 deployment. From the 20 Mt needed, 2.3 Mt would be needed for transportation. Installed electrolyser capacity should increase to 65 GW, increasing additional capacity in wind and solar of 41GW and 62 GW respectively compared to Fit for 55. Of course, the necessary budget increase in electrolysers and distribution of Hydrogen in the EU would increase to be as high as €27 billion. Bottlenecks are also identified, with hydrogen infrastructure being the most important to address along with an efficient and adapted electricity grid to withstand the electrification growth [72].

Net Zero Industry ACT (NZIA)

The purpose of the Net-Zero Industry Act (2023/0081), published as a draft in March of the present year, is to enhance EU manufacturing capacity in some strategic technologies necessary for achieving climate neutrality by simplifying regulations and improving the investment climate. Wind turbines, solar panels, electrolysers, heat pumps, fuel cells, batteries and carbon capture and storage, would have improved investment certainty through certain policies, easiness of market access and reduced administrative concerns when developed in projects. The last, is considerably important for Sweden by reducing the permitting process times, increase certainty and ease the administrative bottlenecks. For said technologies, the maximum permit-granting process cannot exceed 18 months and, depending on the manufacturing capacity or size of the project (< 1 GW >), between 9 to 18 months [73].

Naturally, raw materials are needed for developing such technologies, so a Critical Raw Materials ACT was also proposed, aiming to avoid dependency by diversifying imports and strengthening supply chains and circularity [74]. As the technologies also require Opportunities to fund the proposal are available through funding institutions and programs such as InvestEU, Innovation Fund, and Horizon Europe, among others. Still, the NZIA must undergo Council discussion and arrive to the EU parliament to become a reality [73].

5.2.1 Valuable EU funding instruments

Connecting Europe Facility (CEF) CEF has been established to promote investment in key initiatives concerning transport, digital, and energy infrastructure, and it possesses a total budget of € 33.71 billion. Within the energy sector **(CEF-E)**, the programme aims to enhance the coherence and effectiveness of the European energy market by increasing the interconnectedness of energy networks across borders and sectors, also fostering energy transition. Moreover, funding opportunities will be available for initiatives promoting renewable energy generation across borders.

Connecting Europe Facility – Transport (CEF-T) is a vital funding mechanism for the completion of the TEN-T Network and the modernization of the EU's transportation system, with a total budget of €25.81 billion dedicated to it for the 2021-2027 period. From such budget, €1.6 billion are being allocated for the Alternative Fuel Infrastructure Facility (AFIF), where grants are mixed with financial instruments and institutions to achieve a higher impact of the investments [75]. The European Climate, Infrastructure, and Environment Executive Agency (CINEA) administers the implementation of the CEF and Horizon projects in the transportation sector, and this includes overseeing the AFIF funding program [76]. AFIF budget aims to finance the deployment of RFNBOs infrastructure across the TEN-T, but the November 2023 filing deadline could be unfavourable if it is not synchronized with the CEF-T's schedule [60].

CEF- T have funded more than 95 project for transportation in Sweden, allocating € 592 M. One of the most important projects for hydrogen mobility is the NHC project, encompassed in one of the TEN-T corridors, which aimed to deploy 8 HRS, 100 FCEV and one electrolyser as a pilot for the country. The project also intends to understand the market and the business models for road mobility, to ramp up the adoption. Also, for the same Scandinavian-Mediterranean corridor railway development with new stations and lanes construction (The west link) are supported by CEF-T, along with many other projects [77].

Some programs, such as **Horizon Europe**, were developed with the objective of funding research and innovation on critical industry challenges that support the transition to decarbonization. Mobility, a high emitting sector was prioritized during the first (2014-2020) [78] and second phase (2021-2027) of the project, which aim is to develop sustainable, safe and smart transportation systems by reducing environmental impact and increasing efficiency and safety [79]. By November of 2021, the integration between Horizon Europe and Clean Hydrogen JU gave birth to the public-private **Clean Hydrogen Partnership**, with the aim of strengthen, accelerate, and integrate EU scientific capacity towards Hydrogen applications [80]. Horizon have invested in Sweden up to €422.72 M between energy, climate, clean energy transition and transport, the last with €171 M until January of 2023. The projects involve research in the efficiency, affordability, and reliability of BEVs and FCEVs, movement of goods impacting logistics of supply chain, maritime and rail transportation developments, among many others.

The **Innovation Fund (InnovaFund)** supported by the revenues of the EU ETS, fund demonstrative programs for innovative low carbon technologies since 2003 [81]. With only 10 projects, it has granted up to €484 M to Sweden. The HYdrogen BReakthrough Iron-making Technology (HYBRIT) project is one of the most important developments in the iron and steel industry, by replacing coal with a direct reduction technology using low emissions hydrogen, supported by InnovaFund with €143 M. Such project will use a 500 MW electrolyser abating up to 14.3 Mt CO_2e emissions during its first ten years of operation [77].

In pursuit of sustainable investment, innovation, and job generation, Europe is also supported by the **InvestEU** Programme. Its objective is to stimulate an estimated €372 billion in additional investment over the span of 2021 to 2027, prioritising sustainable infrastructure, Research, Innovation, and digitalisation, among a range of sectors. Clean energy projects, along with clean and sustainable transportation are supported by the program.

In line with the NZIA, the EU has plans to create by the end of 2023 a **European hydrogen Bank** that will act as a catalyst for investment in sustainable hydrogen production and the entire value chain. The primary objective of the four pillars supporting the initiative is to narrow the disparity between hydrogen derived from fossil fuels and renewable sources. Through auctions backed by InnovaFund, producers will be awarded a fixed subsidy for up to 10 years. The additional pillars aspire to enhance the presence of offtakers and suppliers, facilitate collaboration between them, blend existing financial instruments to support hydrogen initiatives, and develop auctions for H_2 imports to the EU. This plan promises to boost considerably hydrogen ventures across member states and help the entire value chain as the IRA is to the US [82].

5.3 Policies and subsidies Overview in Sweden

Sweden functions as a constitutional monarchy, wherein the Swedish Constitution encompasses four essential laws. The Instrument of Government lays down the fundamental principles dictating Sweden's governmental structure, covering aspects like the mechanisms of the Government, the civil liberties of Swedish citizens, and the mechanisms for parliamentary elections. It also incorporates certain guidelines relevant to matters concerning the environment. The country is divided into 21 counties and 290 municipalities. The CAB, appointed by the Government, has the responsibility of implementing and administering national political goals for each county. A significant portion of all public tasks and services, encompassing environmental and health protection, is delegated to the Swedish municipalities for execution and provision. To ensure the fulfilment of these tasks, they enjoy ample autonomy and independent authority to impose taxes and fees [83].

Sweden embarked on the journey of addressing public health and environmental concerns more than 150 years ago. The legislation for health protection was put into effect in 1874. Subsequently, in 1941, provisions regarding water contamination were incorporated into the Water Act of 1918. Yet, it was not until 1969 when Sweden fulfilled the need for an Environmental Protection Act that aimed to regulate the impact of hazardous activities [83]. The environmental welfare of the country has been enriched by updating Acts and establishing new policies. A primary concern is the reduction of emissions to counter global warming, prompting the country to adopt different strategies aimed at transitioning its energy sectors and achieving decarbonisation [83]. The forthcoming section will detail the most significant strategies applicable to the project.

Climate strategy

The Riksdag (Swedish Parliament), adopted a climate proposal in June 2017 to establish a national climate policy framework (Bill 2016/17:146) comprising a Climate Act, national climate targets, and a climate policy council. This reform is pivotal to Sweden's adherence to the Paris Agreement. The Climate Act stipulates that the Government's climate policy conforms to national targets and lays out the procedures for execution, with yearly reviews from Riksdag. The climate policy council is responsible for assessing the Government's overall approach to climate policy against national targets. National climate targets state the following [84]:

- Sweden will have zero or negative GHG emissions by 2045.
- Emissions that the EU ETS and human land use (LULUCF sector) do not cover, would be reduced by 63% in 2030 compared to 1990, and by 75% in 2040.
- Emissions reduction in transportation by 2030, excluding aviation, is to bring it down by at least 70% from 2010 levels (20.73 MtCO2e) [26].

To accomplish these targets, Riksdag energy policies are set to establish a favourable ecological ground for an efficient and sustainable energy usage in Sweden, while ensuring that the energy supply remains cost-effective, eco-friendly, and low impact on health, environment, and climate. The goals for such policies seek to be 50% more energy efficient in 2030, compared to 2005, and reach 100% renewable electricity production by 2040, with nuclear power yet to be decided if would or not be accounted as renewable [84]. Meanwhile, the current Swedish government is actively supporting a proposition to redefine the national target of achieving 100% renewable electricity production as electricity production without the use of fossil fuels.

To attain the goals and begin to shape the change in industry and transportation, several institutions have developed a roadmap /strategy for the upcoming years, and two institutions were established by the government. The Climate board is responsible for ensuring that policies are appropriately addressing climate concerns and moving towards stated goals. The second institution, Commission for Electrification, focuses among others, in the transportation sector and collaborates with researchers, businesses, and the public sector to develop electric technologies for all modes of passenger and freight transport, which include Hydrogen. Additionally, an energy plan that aligns with the climate strategy is demanded from municipalities. These are supported by the CABs and other stakeholders developing activities such as knowledge transfer [85].

Swedish Hydrogen Strategy

In spite of the government's assertion that hydrogen is essential for meeting climate objectives, no official hydrogen roadmap has been established. Nonetheless, the proposed Swedish Hydrogen Strategy recommends the development of 1.9 to 3.3 GW of installed capacity by 2030, with dedicated electricity consumption of 16 to 28 TWh, and at least 8 GW of electrolytic capacity by 2045 [25]. Furthermore, a collective effort by 22 different industries has resulted in the development of roadmaps that showcase the path to attain competitiveness while shifting towards fossil-free operations. The incorporation of hydrogen emerges as a critical factor in accomplishing the climate goals, where up to 30% emissions reduction can be attained with current planned hydrogen projects [25].

To accomplish the electrolytic hydrogen goals, developments should be made with urgency. As the electricity need will be significantly high, grid infrastructure needs to be planned, strengthened and developed, as well as the hydrogen infrastructure encompassing new pipelines and storage. Both need the proper market conditions, regulatory framework, and financial instruments to guarantee strong business models and guidelines for its development. Additionally, the government parties should align with the benefits and importance of hydrogen, by developing institutions that manage the deployment of H_2 initiatives, not leaving behind research and development [25].

Wind Strategy

The Swedish Energy Agency together with the Swedish Environmental Protection Agency have proposed in 2021, a National Strategy for developing sustainable wind power as production facilities age, end use electrification and biofuels production increases, and high objectives for renewable electricity rise. By the year 2040, at least 100 TWh (80 TWh from onshore), must be replaced and it is logical to use wind power, which has the lowest LCOE of any production technology available [86]. Also, with a huge clean electricity necessity, wind is expected to take even a higher role than the proposed in the strategy for the upcoming years.

Achieving a sustainable wind power expansion requires equitable distribution across the country, factoring in electricity supply and the broader interests of society and land use. Then, is suggested that government appoint county administrators that share a regional plan for potential areas, and municipalities plan for the physical expansion. As permitting is currently a lengthy and often unpredictable process, it will benefit greatly from this change of regional authority. For offshore wind, is the Maritime and Water Authorities who develop the proposal for new projects. Between 20 TWh and 30 TWh are suitable for extraction in today's conditions [87].

Naturally, there are challenges for the strategy to be successful. The approval of wind power by those affected by the expansion is one of the main issues, which is currently addressed by the energy agency and the Wind Power Centre by providing a benefit such as local and regional job opportunities and business alternatives. An extra proposal, that is gaining momentum was to return the property tax to the municipalities. Regularly, the real state tax is 0.5%, but for wind-power plants, its 0.2% unless they fulfil state subsidies which would increase to 0.5% [88]. Then, with a financial incentive, municipalities could be more open to adopt new wind projects, but the general consequences are hard to be determined. Another big problem is the municipal veto, which impact in the upstream of the H_2 value chain will be assessed in the upcoming chapter.

Swedish Power Grid – System Development Plan

The Electricity Act assigned Svenska Kraftnät (Svk) as the responsible system authority with an additional authoritative role. Under government control, they fulfil specific duties and tasks as the Swedish TSO, which is the entity responsible for transmitting energy in the form of electricity on a national level. In 2021 the System Development Plan 2022-2031 for the power grid was published, focusing, among others on the need for investment to increase transmission capacity, renew old infrastructure that is reaching its lifespan, while highlighting difficulties in the legislations, permitting process and future perspectives [89].

Under 4 scenarios, Svenska Kraftnät is forecasting an electricity consumption between 150 and 286 TWh by 2045, which represents from a 7% to 104% compared to the 140 TWh consumed in 2021. The broad range obey to the current global and local policies against climate change, which responses can be transitioning to electricity as an energy carrier or other electricity feed technologies, increase digitalization, and higher renewable generation projects [89]. A clear example is the technology shift that SSAB, Vattenfall and LKAB under the HYBRIT project are developing after the 400 SEK billion investment for reducing iron ore with hydrogen (DRI), resulting in a possible increase of 55 TWh from wind power [90]. Even so, it remains unclear which industrial projects will be realized or which of the many wind farm proposals will ultimately be accepted.

Seeking the strengthening of the network, during the next 10 years more than 2,500 km of overhead lines and cables (currently 16,000km), with over 70 stations between new and renewals are planned to be built by the TSO. The interest from renewable projects to connect its generation to the network is positively increasing. From 2019 to 2021 the applications for connection raised from 46.000 MW to 170,000 MW (116,000 MW offshore), of which 33,000 MW had already a granted permit. Starting in 2022, Svenska Kraftnät was commissioned by the government to construct the expanding transmission network within the maritime territory, which enabled them to strategically establish connection points for enhanced grid optimisation. Additionally, the cost of such connection lines changed from the wind producer to the customers [89].

Larger investments will concentrate on constructing a third high voltage line between Finland and northern Sweden (SE1-FI) for 2026. The new line will increase the trading capacity by more than 66% between said countries, improving energy security as well [89]. Moreover, a 700 MW interconnection between Germany and southern Sweden (SE4 – GE) called the Hansa PowerBridge was planned to be built by 2026, after many years and huge investments. However, due to lack of strong supply in the SE4 and high price differences between internal areas of Sweden, the Riksdag has put the project on hold. The parliament's objective is to create the necessary preconditions for Sweden to be a unified electricity price area in the long term [91].

Electrification Strategy

The Swedish government has taken a significant step towards addressing the country's electrification needs by unveiling a comprehensive electrification strategy. This strategy will guide the government's actions from 2022 to 2024 and is based on twelve crucial areas that will lay the groundwork for implementing 67 specific initiatives. The government agencies and offices involved in this strategy are actively seeking support from the Riksdag different parties [92]. The strategy main areas are:

- Planning and cooperation: Community planning should embrace the progression of the electricity system by endorsing national, regional, and local electricity network planning. Collaboration between industry, government, and stakeholders is necessary.
- Efficient use of power and energy: Flexibility and efficiency through energy storage and energy efficiency improvements are required to withstand the power ramp-up.
- New infrastructure for sufficient network capacity and electric vehicle charging: A proactive approach to expand the electricity network without affecting investors or end-users' budget is required. Shorter lead times for permitting will be a reality thanks to the approval of the Budget Bill 2021/22:1, by developing new regulatory frameworks and augmenting reviewing resources. Another underlying principle is to ensure the convenience of charging electric vehicles, regardless of housing type. A plan of action to expand the charging infrastructure, monitor its implementation and revise existing policies will be developed.
- Secured supply of power and energy: hurdles for power generation projects will be diminished, being favoured clean technologies, such as offshore wind, aiming to keep Sweden as a net exporter. Environmental permits will evolve as well as the electricity market.

- Implementation and endorsement: Boosting innovation and knowledge, with the acceptance and commitment from the society are key points to achieve the deployment [92].

Swedish regulatory framework affecting H_2 Value Chain

Electricity certificate system

The electricity certificate system, implemented on May 1, 2003, has been designed as a market-based support program that aims to stimulate the production of renewable electricity and enhance its profitability by incentivizing its generation in a cost-efficient manner through the issuance of certificates. The joint Swedish-Norwegian market for electricity certificates was founded on 1 January 2012 and was extended up to the end of 2045. The goal set for 2030 is the expansion of 18 TWh of new electricity certificates [93], which is positively observe from the industry [85].

Environmental code

The Environmental Code (EC), published in 1999, serves as a comprehensive legislation that establishes the fundamental principles for protecting the environment applicable in parallel with other legislation. Its main goals are to foster sustainable development, guarantee a safe and thriving environments for all, safeguard human health for both current and future generations, preserve biodiversity, and promote recycling efforts. It also includes specifications for the effective management of land, water, and the physical environment, as well as the regulation of environmentally hazardous activities, chemical products, and waste management practices [94].

Every activity developed by persons or operators that could impact the objectives of the EC, require a permit from the authorities like the Land and Environment Court. The permit lays out the boundaries of the activity and should encompass the stipulations for its execution. Moreover, the permit issuing body has the discretion to reject an application if it determines that the activity does not conform to the Code. Depending on the activity's impact a three-category classification can be used, ranked from the most impactful (A) to the lesser (C). For the B and C activities, Environmental Permitting Committees (12 in Sweden) developed with the corresponding CABs, and Land and Environment Courts are key players when asking for permits for each municipality [83]. Usually, the permit documentation must be accompanied by an Environmental Impact Assessment, that gives the necessary information to the institutions for the decision making. H2 Green Steel, Ovako and Project Air are one of the recent companies that applied for an environmental permit for electrolysis H_2 production and received a positive response. Is worth mentioning that the permit to initiate construction can be given before a full environmental permit decision.

ACT on certain Pipelines and Natural Gas ACT

Some of the laws that could guide the industry in hydrogen storage, transmission and distribution are the ACT on certain pipelines (SFS 1978:160) and the Natural Gas ACT (SFS 2005:403) [95]. The first law requires a concession and a license if the developed project transports hydrogen gas used as a fuel, outside industrial areas and with a length over 20km. Said ACT lacks the definition of fuel, so it's unclear for which purposes could account as such. Also, an environment with land permits should be taken into consideration for a concession to thrive. From 1978 to 2019, amendments have been carried out to the ACT with no inclusion of hydrogen management [96].

The Natural Gas ACT (2005:403) concerns all the elements including pipelines, storage, and gasification facilities, that use natural gas, biogas, or LNG in a natural gas system. An approved concession from the government is also required for the development of said infrastructures, that can last up to 40 years. There's no information about hydrogen utilisation through the NG system, nor the possible effects of a refurbishment of the system, if modified to transmit H_2 [97].

Energy and Carbon tax

Energy taxation and instruments for penalising polluters through a carbon tax were adopted by Sweden long ago, prioritising energy efficiency and the utilisation of renewables. The energy taxation focusses on the actual consumption, whether electricity or fuel. The 2023 tax rate on electricity is 392 SEK/MWh for the majority of Sweden, except for some counties that have a 96 SEK/MWh deduction. Those who are responsible for producing, transmitting, or importing electricity into Sweden will be subject to the energy tax liability [98].

Carbon tax has existed more than 30 years in Sweden, generating considerable revenues to fund specific purposes related to climate consequences. In the past, no taxation was given to industries covered by the EU Emissions Trading System (ETS), and lower taxes were assumed to some industries outside the system, but since 2018 the tax unify reaching 1,100 SEK/tonne, and 1,330 SEK/tonne in 2023 [99].

Special exceptions exist for these taxes, depending on industry and final utilisation. For example, manufacturing processes may have lower taxes or refunds on fuel or electricity usage and no carbon tax when covered by the EU ETS. Private consumers utilising biofuels for engine or heat sources will receive tax breaks on carbon and energy costs [100]. The exemptions or alleviation that could impact the hydrogen supply chain:

- Renewable electricity is not taxable if it's produced from wind or waves with a cap of 250 kW, or 500 kWp of PV, or other energy sources without a generator with 100 kW of maximum capacity for non-commercial purposes. This energy won't pay carbon tax because of its renewable nature.
- Electricity consumption in electrolytic processes for hydrogen production has reduced tax in the form of refund. If a consumer is not liable for tax, a refund is made when the cost is greater than 2,000 SEK, for the amount that exceed such value [101].
- Hydrogen used to power a Fuel Cell in a motor vehicle is not liable to tax, then hydrogen for mobility doesn't have energy nor carbon tax [102].

Swedish Mobility

Mobility, as one of the most emitting ones, naturally has been on the scope of policy makers. During the last years, several subsidies applied in the form of purchase incentives and tax benefits for all the low emissions vehicles, such as BEV, FCEV, Hybrid and Plug-in hybrids. In the meantime, taxes were used to penalise emitting vehicles according to the amount of its discharges. However, by the end of 2022, the state changed some subsidies or abolished them, which could bring consequences in the long term, if technologies are not equally competitive. Handful of the most significant taxes and subsides that are applying and applied in the last few years are detailed next.

Carbon dioxide-based vehicle tax

As all sectors in the country are taxed for its emissions, all the vehicles are also considered in this practice. The carbon dioxide-based tax is calculated according to base fee plus the emissions weight released by km [103]:

- If the vehicles emitted over 111 g/km of CO_2, the cost would be 22 SEK/gr. If it emitted the same value, but it's a biofuel powered vehicle (ethanol, NG, E85), the cost reduces to 11 SEK/gr, plus the basic fee of 360 SEK.
- For light trucks, light buses and passenger cars, the basic fee plus the emissions per km fee.
- For heavy duty trucks, a weight-based tax is implemented. This could include, number of axles, use, coupling method, etc.
- There is a fuel factor for diesel-powered vehicles that are set in the roads before 1st of July of 2018, in which the sum of emissions must be multiplied by 2.37 yearly.
- For diesel vehicles put into service after said date of 2018, the fuel factor increases to 13.52.
- For the same diesel vehicles, there is an environmental supplement charge of 250 SEK.

Climate premium

The climate premium subsidy, awarded by the energy agency, is directed towards heavy duty trucks, electric work machines and environmental work machines trying to close the gap with fossil fuels machines. The subsidy corresponds to up to 20% of the purchase price available until 2024 [104]

- Trucks should be powered by bioethanol, electrical energy, Fuel Cell or a combination of them, with a weight over 3.5 Tonnes.
- For electric work machines and environmental work machines, there is a net power requirement, and the requirement of be powered by Fuel Cell, electricity, bioethanol or vehicle gas for the last.

Klimatklivet, from the Swedish Environmental Protection Agency*,* also can give support to the acquisition of an electric truck or recharging/filling stations as will be explained shortly in this chapter, but the conditions are more difficult to fulfil when competing with other alternatives. To obtain the grant, the machine or truck needs to be owned by the supported recipient, meaning that leasing is not an option when the measure is completed. The two subsidies are mutually exclusive [105].

Emission reduction obligation for petrol and diesel

The 1st of July of 2018, a policy to incentivize energy-efficient vehicles and sustainable fuels was established consistent with the Act 2017:1201. Specific emission reduction targets were set for diesel and gasoline suppliers over a yearly basis, with the aim for 2030 of 66% and 28% respectively [103].

Bonus-Malus

Subsidy that rewards low-emission vehicles and tax high-emission ones during the first three years after the purchase of a new vehicle, applicable as of July 1, 2018. This system eliminated previous subsides like "environmental cars" that lasted for 5 years affecting tax payments and the bonus for "Super environmental cars", which was the backbone of Sweden's EV policies [106]

The "Bonus" subsidy was abolished the 8 of November of 2022, as the government considered that environmental vehicles have reached cost parity with diesel/gas ones. The malus tax remains active for the first 3 years, then the carbon tax enters into force.

- Former purchase bonus: up to 25% of the price for a new car, when the car model was first introduced to the Swedish market, with a cap of 70,000 SEK. Focused on private car class I and II, light lorries and light buses.
- Malus tax: It is the monetary burden for the vehicles that are high emitters, charged according to the amount of CO_2 released for km. From the 1st of June 2022, for these new vehicles put into use, the charge will be from 107 SEK per gram of CO_2 emitted, if the amount ranges from 75g to 125g. If the emissions exceed this value, 132 SEK is the charge per kilometre.

Congestion and infrastructure charges

Sweden operates two distinct road toll systems - the infrastructure charge and the Congestion tax. Both schemes affect Swedish and abroad-registered vehicles. The infrastructure charge comes to action when vehicles pass by the Motala and Sundsvall bridges as a toll. The Congestion tax is a method of traffic management, imposed in central Stockholm and Gothenburg, with the goal of easing traffic congestion at peak hours. For Gothenburg, the rates vary from 9 SEK to 22 SEK, depending on the hour of the day, being 7:00-7:59 and 15:30–16:59 the costliest, and 0 from 18:30–05:59, with a cap of 60 SEK/day. Stockholm functioning is similar, with an extra seasonal category depending on the month. The highest rates at season peak are 45 SEK from 7:00–8:29 and 16:00–17:29, with a cap of 135 SEK/day. Both charges operate as a permanent measure, designed to improve the environment, infrastructure and reduce queuing [107].

Next, a summary of the most important taxes for passenger vehicles in Sweden, for petrol and diesel cars fuelled cars.

Table 15. Summary of important taxes for passenger vehicles in Sweden.

TAXES	COST
Basic Charge	360 SEK/yr
Bonus Malus 2018 (Prices from 1st June/22 - during 3 yr)	107 SEK/gr 75gr < CO_2 < 125gr 132 SEK/gr CO_2 > 125gr
Carbon tax (after Malus)	22 SEK/gr CO_2 > 111gr 11 SEK/gr CO_2 > 111gr (biofuels)
Environmental Charge	250 SEK (Diesel)
Fuel Charge	CO_2 gr/km * 13.52 (Diesel)
Congestion charges and tolls	Stockholm, Gothenburg

Proposal for protective distance for hydrogen installations and HRS

Since Sweden lacks specific guidelines and regulations about hydrogen handling and management, the evaluation of safety infrastructure surrounding hydrogen components could vary across municipalities. Different structures could be built around pressurised tanks, pipes, containers, or even stopped if any risk was detected. Promptly, the Department of Fire Technology at Lund University has unveiled a Proposal for Protective Distance for Hydrogen Installations (**MSBFS 2020:1**), laying the groundwork for determining the protective distance needed during the establishment of hydrogen facilities. The assessment, with several assumptions, e.g., handling taking place always outdoors, focuses on the possible consequences of three holes of varied sizes in pipelines working under different pressures. The report is merely a guideline with useful information, lacking legal status [108].

In response to the specific requirements of FCEV filling stations, Energigas Sverige the industry organisation of Swedish biogas, vehicle gas, LPG, NG and H_2 stakeholders has recently unveiled a set of instructions (**H2-TSA 2023**) that cover an array of aspects, including gas handling, facility design, material selection, legislation, permits, and controls. The objective of these instructions is to facilitate the creation of safe installations that could comply with Swedish policies [109]. Said report also base some of their analysis in the **Gexcon's** Consequence analysis for hydrogen fuelling station developed for Sweden, which investigate the potential consequences and hazardous distances of heat radiation, overpressure, and flammable gas concentrations [110].

5.3.1 Important funding instruments in Sweden

Klimatklivet

Climate Leap (in Swedish *Klimatklivet*), became operational in 2015, aiming to provide financial support to regional, local organisations and company initiatives that seek to reduce greenhouse gas emissions and foster sustainable development, courtesy of the Swedish government. Its broad support ranges from agriculture, energy to transportation, among others, awarding its funding on a competitive basis, where applicants must demonstrate that their projects will have a larger impact on reducing greenhouse gas emissions per kroner invested. The Swedish Environmental Protection Agency (Naturvardsverket) is responsible to receive, review, evaluate, decide the support and make the follow up of the projects following the climate leap regulation (Klimatklivsverordning, 2015:517) [105].

From 2005 to march of 2023, Klimatklivet has granted 13.5 SEK billion for 5208 projects in the country, resulting in the yearly abatement of more than 3.3 Mt CO_2e and the creation of 9,400 jobs. In the transportation sector, out of 722 applicants, only 220 receive the grant, with most of the applications for biofuels and hydrogen filling stations. Specifically for hydrogen related technologies, 42 measures receive 716 SEK millions. Before article 36a of the block exemption come into force, several hydrogen filling stations were allowed the grant. During 2022, more than 29 hydrogen related applications were received by the Naturvardsverket, but due to the bidding process, only some few requests that fulfilled requirements like renewable electricity for electrolysis and utilisation of by-products, were granted. The same applies to recharging stations for BEVs [105].

Qarlbo company develop a project with the Hydri start-up and Nilsson Energy, winning a Klimatklivet grant for the construction of 24 HRS for 354 SEK million, which corresponds to approximately the 69% of the total investment. The remaining amount and operative expenditure will be provided by Qarlbo with the expectation to finish all the stations by 2025 [111]. As a general overview, the historical grant given for all the application correspond in average to 42% [105].

Industriklivet

To ensure the success of Sweden's industrial decarbonisation efforts, the government has given the Energy Agency the mandate to lead Industriklivet (Industrial leap), a program that will provide financial support to the industry for implementing innovative climate-driven technologies. The budget is part of the NextGenerationEU initiative and targets research, studies, pilots, and demonstration projects for the reduction of emission in industries, negative emissions and strategic important initiatives. So far, 2.1 SEK billion has been given to 124 projects, mainly in the iron and steel industry (34%) and 31% of the budget destined to low emissions hydrogen. The support is forecasted to last until 2030 [83].

Other financial supportive organisations

Almi

Almi, a state-backed financial enterprise, grants loans to both start-ups and well-established companies with significant potential for growth, further supporting them in their business expansion efforts. "Almi Invest" specifically focuses on providing venture capital to newly emerging businesses with a strong potential for high growth and a scalable business model. All the models tend to focus on sustainability issues in effort to help Sweden [112].

Swedish innovation agency (Vinnova)

As part of the Ministry of Climate and Enterprise, Vinnova functions as a government agency and acts as the national contact authority for the EU framework programme for research and innovation. It also serves as the Swedish Government's authoritative body in innovation policy [113]. Among its 8 focus areas, sustainable industry, emerging innovation, and sustainable mobility stand in importance. For the last, the agency grants up to 50% [113].

5.4 Implications and Gaps

Low carbon hydrogen has shown increasing interest from industrial players to decarbonise its businesses in different economic sectors. To attain the climate goals of the country, the entire electricity and hydrogen value chain must be fortified easing the transition and drawing more investors and competitiveness. Specifically for hydrogen, its upstream has already achieved a significant level of maturity, evidenced by the presence of numerous ongoing and planned low emissions generation projects and a structured energy market. Nevertheless, there exists ample room for reducing risks related to the implementation of new renewable and electrolytic ventures. This can be accomplished by fortifying the electricity network, updating the market rules, streamlining permitting processes, and fostering the adoption of innovative technologies through goal-oriented initiatives and state backing.

The hydrogen midstream has the bigger opportunities, where the lack of infrastructure, market and know-how in the country are important drawbacks, adding the lack of regulations and subsidies as the main weaknesses. The downstream for hydrogen mobility present several bottlenecks as the market is still in developing phase. With few demonstration projects in the country, knowledge of the technology, a robust infrastructure, variety of FCEV and price competitiveness are some of the highlighted challenges for a user adoption. Throughout the entire H_2 value chain, the EU regulatory framework is the one steering a faster change in Sweden, due to the slow adjustment and alignment in the Legal and institutional framework of the country. Next, a profound analysis of the mentioned value chain.

Upstream

From the electricity generation, challenges need to be overcome to accomplish electrification goals, many of which the Electrification Strategy already considers. The most important one regarding the regulatory framework and institutions is stated in the EC, where a clause regarding municipal views, commonly referred to as the **municipal veto**, grants municipalities the right to dismiss requests for substantial wind farm permits. These decisions are unappealable and radical, usually concerning the impact on the environment, landscape, and property values, contributing to the unpredictability of the permitting process. So far from 2014 to 2020, the wind national strategy accounts for over 45% of unsuccessful permit applications from a total of 251. Of this, the veto accounts for 50% of the applications completely rejected or withdrawn, as shown in Figure 28.

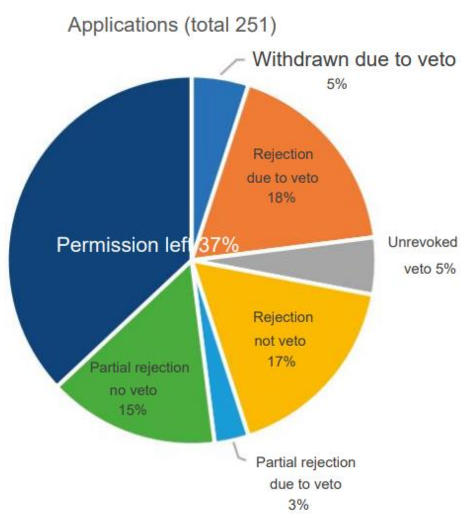

Figure 28. Classification of permits for wind projects considering granted, refusals withdrawn due to veto [87]

Municipalities may prolong the grant-approval process for wind projects and make decisions after project initiation. Furthermore, municipalities may alter their approval decisions during environmental assessments, later in the project development. Consequently, plans and investors could take higher risks and get discouraged to pursue wind projects [87]. To adjust the process and reduce rejections, the government submitted a bill in which a prior decision should be made during the project, but it was overruled by the Swedish Parliament.

From the bill, the Riksdag has backed the proposed measures aimed at providing benefits to property owners who agree to the installation of wind farms, while also advocating for incentives for municipalities that promote wind power. One of the parties rejecting the bill was the Christian Democrats, who argue that municipalities can't take big decisions with insufficient information, and without a full environmental impact statement [114]. Such information is naturally necessary to make any decision, then the information flow and knowledge should be easily accessible and standardized for every county and municipality. The party also mention that incentives and conditions for compensations should be settled before the municipality's approval [114]. A revision of wind incentives for municipalities, landowners with constitutional proposals is expected be delivered to the state during the first semester of 2023 [115], which is aligned to the electrification strategy.

Also, according to the TSO, capacity increase for the transmission network needs sufficient study and understanding, because the expansion and strengthening of old and new lines can take up to 7 to 15 years. The Energy Market Inspectorate manages the licenses for building and operating electricity grids. A permit application for a concession requires multiple steps, such as studies, dialogues, consultations with stakeholders, etc. Even after the approval, there are still some issues that are not considered, such as some land needs, possible land change utilization, legal issues with the environmental code and posterior risks. In June 2021, the Riksdag positively answered to the government's proposal for changes in the Electricity Act reported in the Modern Permit Processes for electricity grid, which will be fostered by the electrification strategy further. The amendments could make easier the electricity grid expansion as some management proceedings could initiate before a concession decision is made [89] under the SFS 2021:910 [116].

Electrolysis plant developments also have the same concerns regarding permitting process and EC. Moreover, environmental permits need to be reissued if the activity of the industry changes, which also could limit the transition. So far, in the EC there's no specific guidelines for hydrogen as for diesel or petrol, which also could play a subjective and uncertain assessment depending on the municipality or county. For this specific technology and renewables deployment, the NZIA from the EU could be an essential policy instrument driving the reduction of lead time for permitting procedures and fostering the development of new environmental code extensions, as promised in the electrification strategy in the country.

Revenue streams should be considered for electrolytic hydrogen if a successful business model is desired. The main advantage that the new DA gave to Sweden is the possibility to use the grid to produce hydrogen, which as stated in previous chapters, will increase the capacity factor, lowering the price of hydrogen under optimisation of production with low electricity prices. Furthermore, a current reality in Sweden is the district heating and frequency regulations of the market that could help lowering more the LCOH. The last, appointed by the TSO, addresses up to 6 different ancillary services to the electricity network [117] in which, according to a recent study, under the right optimization process will benefit the electrolytically produce hydrogen business model [118].

The low emissions hydrogen production link of the value chain benefits greatly from subsidies granted by the Swedish state and EU. On one hand there's the tax-free electricity for electrolysis purposes which slightly reduce the operational cost of the procedure. On the other hand, Klimatklivet and Industriklivet play a crucial role in supporting the CAPEX of new projects that effectively reduce emissions, as examples have proven. Yet, EU article 36a of the Block Exemption will impact new projects that are now subject to auction, winning the less costly and more efficient, which could reduce the number of deployed ventures. Another remark is the lack of other sources of OPEX subsidy, which increase the risk if a market is not defined. Last, the European hydrogen bank promises to be a great financial tool for new projects with its subsidy mechanism that will help the entire value chain.

Midstream

Storage, transmission, and distribution of hydrogen currently have a lack of regulatory framework and market structure in Sweden. As detailed, there's no specific Act or procedure to follow when applying to a concession, and unclarity if a concession is even required. As mentioned, the EC lacks details about hydrogen management, so also the required permits are vague. If a purely hydrogen pipeline is to be built, the Act on Certain Pipelines could be considered if used as a fuel, which is the case on hydrogen for mobility purposes. Then, according to the EC, a concession would be required, but it is also unclear which institution would be the one to regulate such market and if the Natural Gas Act would be its guide.

The proposed revisions to the Gas Directive in the EU are set to bring about regulations and obligations regarding the control of the hydrogen market, along with its stakeholders. Undoubtedly, the Swedish government will need to designate an authority responsible for its planning, similar to how Swedegas operates as the TSO for Natural Gas, while also implementing a specialized Act or an extension of an existing one for H_2. Additionally, is expected that the infrastructure planning of the EHB could be an important stage for the first pipeline development, together with the industrial clusters in the country, up north and in the west. Furthermore, subsidies or important financial instruments from the government will be required in this step of the value chain. So far, CEF-E or the EU is the one providing support, encompassing the Important Projects of Comon European Interest (IPCEI) projects, which potential developments that help achieving EU climate goals, usually cross-border and without private support [119].

Downstream

Sweden is committed to abate 8.841 $MtCO_2e$ (2020 total transportation emissions excluding aviation) of transportation emissions by 2030 [26]. Penalties settled by carbon taxes have help reducing the emissions up to 5 $MtCO_2e$ from 2010, together with bonus aids. Subsidies as the "bonus malus" have impacted the acquisition of PCs, which were responsible of two thirds of the transportation emissions in 2020, from its conception in 2018. As an example, the market share for EVs (mainly BEVs and PHEVs) grew from 7.6% in 2018 to 43% in 2021 [120], along with the charging points which tripled over the same period. By abolishing the subsidies, the price of the vehicle and its emissions could play an important role in the users' choice.

Naturally, FCEVs are not price competitive with the market alternatives yet and its refuelling infrastructure is lacking in the country. Addressing the last, on one hand, EU regulations are pushing the development of a central refuelling infrastructure through the TEN-T policy and its funding instruments (CEF-T and the local Klimatklivet) are aiding in the deployment, as is the case of the NHC. Private investors as Qarlbo – Hydri also see the potential of hydrogen for mobility and seek for subsidies to lower the risk of the capital-intensive investment, highlighting the importance of such financial instruments. On the other hand, the lack of knowledge of hydrogen management raises safety concerns that are assessed differently in each municipality and county. The MSB proposal promises to ease such concerns by standardising the procedures and giving more information on safety issues to the decision-making institutions. To support the flow of information, guidelines such as H2-TSA are expected to contribute to lower the risk and uncertainty of the HRS construction process.

From the PCs perspective, there's no policy support exclusively for FCEV, but a general one to support low emissions vehicles in Sweden. Is clear then, that there is a gap between the infrastructure development policies and the EU or local strategies for FCEV adoption. If there is not a sustainable business model in the future, considering that low-carbon hydrogen is expected to contribute to the decarbonisation, a revision of the targets in FCEV vehicles and subsidies could be necessary. Despite this assertion, a market pull is expected to fill this gap, and automakers present alternatives for the end users. As the price of an FCEV is high, grants for R&D from the EU (Horizon, InnovaFund) and the country itself (Almi, Vinnova) should help in the development of most efficient technologies and finally a price reduction in the upcoming years. It should also be considered that the industry is looking forward to the emergence of H_2-powered buses and heavy-duty trucks because of their promising technology, substantial government subsidies (Climate Premium and Klimatklivet), and capacity to generate greater revenue for HRS through their higher fuel consumption.

The price of hydrogen is an important concern for accomplishing a successful market ramp-up for hydrogen mobility. The scale of low emissions hydrogen production needs to scale-up for it to see price reductions, and efforts should be made for the industry to take over. Despite the fact that there are subsidies along the value chain, they are mostly focused on CAPEX, which of course alleviate the capital-intensive infrastructure but give uncertainty in the future, especially with the lack of offtakes and clear government signals towards this gas. The country should look for financial instruments that help the entire value chain become more cost competitive. One simple example should be the development of CCfDs in the upstream e.g., H_2 production, which will create certainty and reduce the risk for the lifespan of the contract. A better example to be taken by the country is the Inflation Reduction Act (IRA) of the US, which triggers a huge amount of available investment to scale up the value chain and increase maturity of clean technologies. Under certain circumstances, the IRA may provide funding of up to USD 3 for every kilogram of clean hydrogen generated, as long as the emissions throughout the entire lifecycle remain under 0.45 $kgCO_2e$ per kilogram of H_2 produced. However, if the emissions rise to 4 $kgCO_2e$ per kilogram of H_2 created, the IRA's support will be reduced to USD 0.6 [121]. Then, it is greatly expected how the NZIA and the Hydrogen Bank will impact the development of the H_2 market with its IRA alike subsidies for production and technologies. Such EU focus could indeed, be a pivotal point for Sweden and the member states to accelerate the market creation, value chain development, private investment, knowledge, and stakeholders' acceptance.

5.5 Concluding remarks

In a broad sense, the hydrogen mobility value chain relies on specific policies and subsidies to initiate its implementation. However, the risk involved is substantial as it is uncertain how the future market will develop, and the government's support appears weak. The EU regulatory framework is driving most of the change in Sweden, then the country needs to start building its own measures, from the adoption of clear hydrogen goals and a government supported roadmap, to the development of institutions and a regulatory framework that backs such developments. Moreover, financial instruments along the value chain must accompany the transition, not only in

CAPEX but also in OPEX to reduce the burden and risk on specific links or end users of the chain.

Next, there's a resume of the most relevant policies and regulation, with subsidies and funding at every link of the value chain. The biggest gaps noticed during the assessment were on the storage, transmission, and distribution of hydrogen, and the misconnection of supportive infrastructure policies-subsidies, with the deployment of FCEV. It is noteworthy to mention the broad support that R&D enjoys from Sweden and the EU, along with the favourable new policy developments in the EU, such as the Delegated Act, Gas Directive, NZIA, Hydrogen bank, REPowerEU, as well as in Sweden, such as the Electrification Strategy, the MSB, and the industry's commitment to hydrogen development.

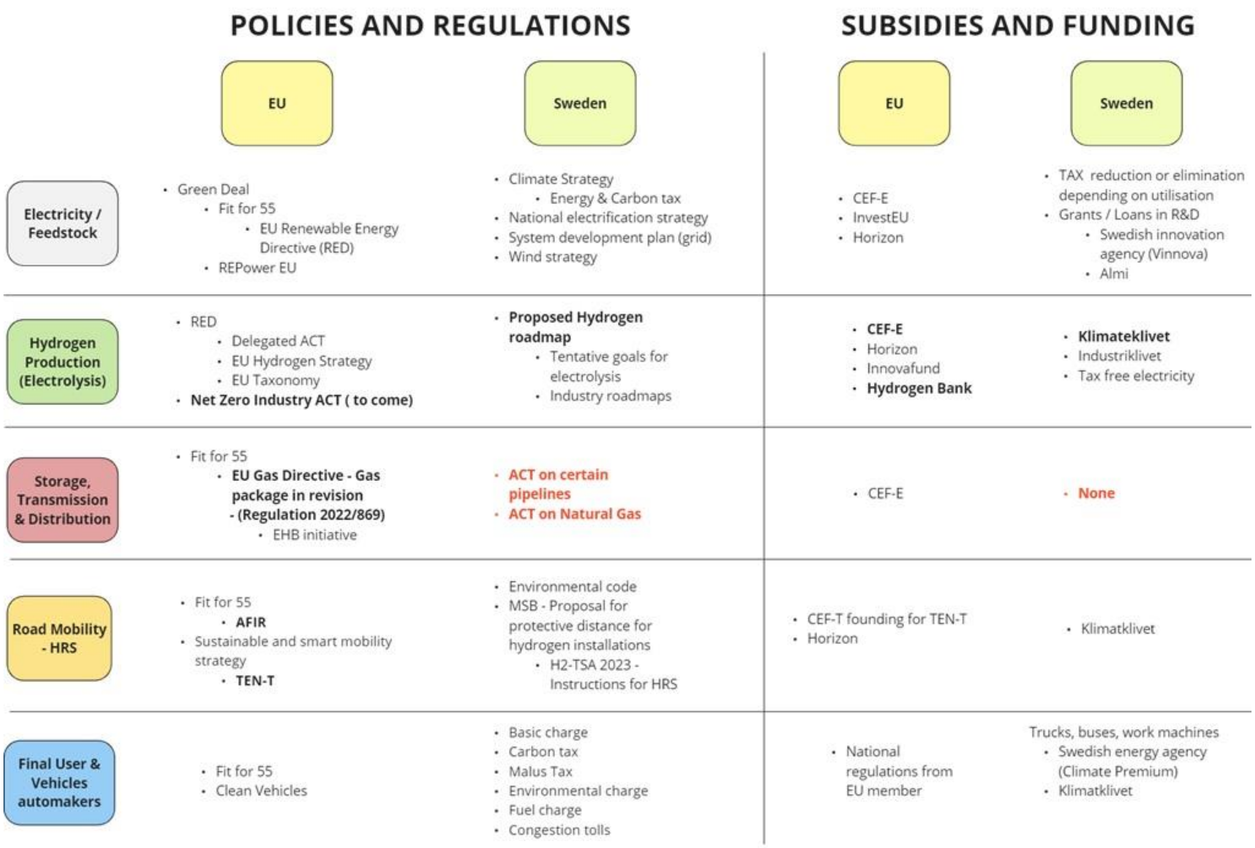

Figure 29. Summary of policies and regulations (left), and subsidies and funding (right) throughout the supply chain and at Swedish and EU level.

6 RISK ANALYSIS

6.1 SWOT Analysis

In the following section, a SWOT analysis will be showcased, highlighting the main aspects of the hydrogen value chain in Sweden, particularly in relation to H_2 road mobility. The analysis is based on the previous chapters and offers a thorough understanding of the Swedish context.

Strenghts

- High availability of Natural resources translates into a clean grid.
- Clear goals of emissions reduction with policies supporting its abatements.
- Electrification strategy pushing to change status quo.
- EU directives driving the H_2 value chain change in Sweden.
- Tax-free electricity for electrolysis purposes.
- Possibility of H_2 production from the grid, allows high-capacity factor (0.9) for electrolysis.
- Industry push for H_2 - production and utilization in clusters.
- Number of planned HRS is higher than EU regulations requirement.
- High percentage of CAPEX subsidies from the government.
- Several Planned HRS close to highly populated areas.
- FCEVs have high performance, good apparel, and low taxes.

Weaknesses

- Fast changing EU policies translate in high market dynamic.
- Uncertainty of future renewable electricity demand.
- Lack of accepted Hydrogen Strategy from Gov – Riksdag.
- Shortage of policy framework for hydrogen and know-how.
- Lack of country wide gas or hydrogen infrastructure, its regulatory market, and institutions.
- Abolishment of subsidies for low emissions vehicles with high CAPEX
- No OPEX or other subsidies for H_2 projects so far.
- Few automakers with scarce alternatives, and few on-road FCEVs.
- Shortage of FCEV availability from automakers in the country for Trucks and PCs.
- H2 dynamic costs per kg at HRS and downtime.
- Other technologies are cheaper and turning competitive for PCs.
- Not a robust area of FCEVs technical service in the country yet.

Opportunities

- Proposal Net Zero Industry ACT seek to speed up renewable projects and some hydrogen technologies.
- State and EU subsidies for hydrogen value chain and decarbonisation projects.
- Subsidies from European Hydrogen bank plan.
- Increased renewables and H_2 deployment create jobs.
- Industry gaining awareness of hydrogen benefits for decarbonisation.
- Join ventures of mature industries can take advantage of bigger electrolysers size.
- High possibility for extra revenue streams for electrolytic H_2 production (District Heating + O2 + FCR + others TBD).
- State subsidies for heavy-duty trucks, buses and working machines.
- Synergy opportunities for automakers, industry, and energy producers.

Threats

- Lack of alignment in the government and institutions regarding hydrogen.
- Subsidy auction for infrastructure development (EU - Sweden).
- Lack of H_2 goals and education through the government hierarchy, from parliament to municipalities.
- Complicated permitting process for value chain projects (mainly environmental and safety permits).
- High electricity price variation during the last years
- Absence of robust HRS infrastructure.
- High price of fuel turns H_2 into a non-competitive alternative.

Figure 30. H_2 mobility value chain SWOT Analysis for Sweden

6.2 Risk assessment for hydrogen road mobility supply chain

The purpose of this section is to condense the previous chapters' outcomes and identify the risks associated with developing the hydrogen supply chain from the financial perspective. This becomes relevant due to the uncertainties associated with the development of new technologies. Due to this, investments must be measured against the risks and the potential benefits, and early adopters should be aware of this. Projects with low or predictable risks, meaning well-known technologies such as natural gas power plants, are able to obtain financing in relatively easier conditions. Instead, novel technologies such as offshore wind energy during its early stages of development, had higher risks with high cost of capital and barriers for financing.

In a summary of its Project-Finance Green Hydrogen report, Fitch Ratings states that "the credit risk of project financed green hydrogen assets are, at present, similar to those of thermal power for standalone assets, or potentially greater" [122]. Said statement was determined after an analysis of three risk perspectives: operational risk, supply risk, and revenue risk. It was highlighted that lack of experts and complexity of projects might lead to different risk profiles for different projects, mostly based on independent experts' views. Therefore, a more established market is necessary for a standardization of risk profiles and smooth development of projects, which today is a major bottleneck for accelerated development of the sector.

Furthermore, considering the risks assessed by Fitch Ratings, development of innovative and new projects might be involved in extra costs due to delays and difficulties. These overcharges need to be assessed in different scenarios to obtain the desired financial coverage. During the early stage of development of the offshore wind sector, these assessments were usual, as there were unknowns and uncertainties over the development of such projects. Jérôme Guillet, in a report written for the World Forum Offshore Wind, highlighted said concerns, together with the lack of experts, and the easiness of financing. The outcome led to the first project sponsors reaching out to the same financing and construction stakeholders [123]. The bank Rabobank and Dexia played a major role during this period. As Jérôme phrases, these two banks, and several other advisors that were part of the Q7 (first offshore wind project), allowed for negotiations to move fast, due to lessons learned from Q7 project.

A major advantage of the first offshore wind projects was the location, as they were in close or very similar areas and markets, such as Belgium, Germany, and UK. Nonetheless, hydrogen projects have different geopolitics, varied conditions, and usually tailored development to the project configuration. Therefore, the development of knowledge, experience, and financial support are necessary to accelerate the development of hydrogen and its supply chain. Nevertheless, public initiatives for the development of the hydrogen supply chain are creating the conditions for this accelerated development. The EU initiative with the European Hydrogen Bank aims to stimulate and support investments in sustainable hydrogen production, CEF with its support of infrastructure for clean technologies, the European Green Hydrogen Acceleration Center (EGHAC) supports the creation of industrial players which help to de-risk and accelerate their green hydrogen initiatives through early-stage investment and acceleration services [124].

To de-risk and increase bankability of H_2 projects, other countries' governments, such as USA and UK, have delivered incentive schemes providing CAPEX and OPEX subsidies [125] [126]. Such a strategy immediately creates interest from several stakeholders along the value chain, and an ecosystem of knowledge, expertise and increasing experts. One more alternative for obtaining a similar result in a lengthier duration is by utilizing pilot and demonstration projects. Sweden is influenced by key initiatives like the Nordic Hydrogen Corridor and the European Hydrogen Backbone, which receive backing from public financing. Their objective is also to speed up the advancement of the supply chain, encourage confidence in private investors, and enhance knowledge and expertise.

This all mentioned goes hand in hand with the recommendations by the European Investment Bank (EIB) and the European Commission to stimulate investment across the hydrogen value chain. The recommendations come from an analysis of four major forces and consultation with several experts. These are economic competitiveness, clear and streamlined regulation, a value chain approach, and ecosystem support. 7 recommendations, divided into three areas, where developed, and showed in the following image, out of such consultations.

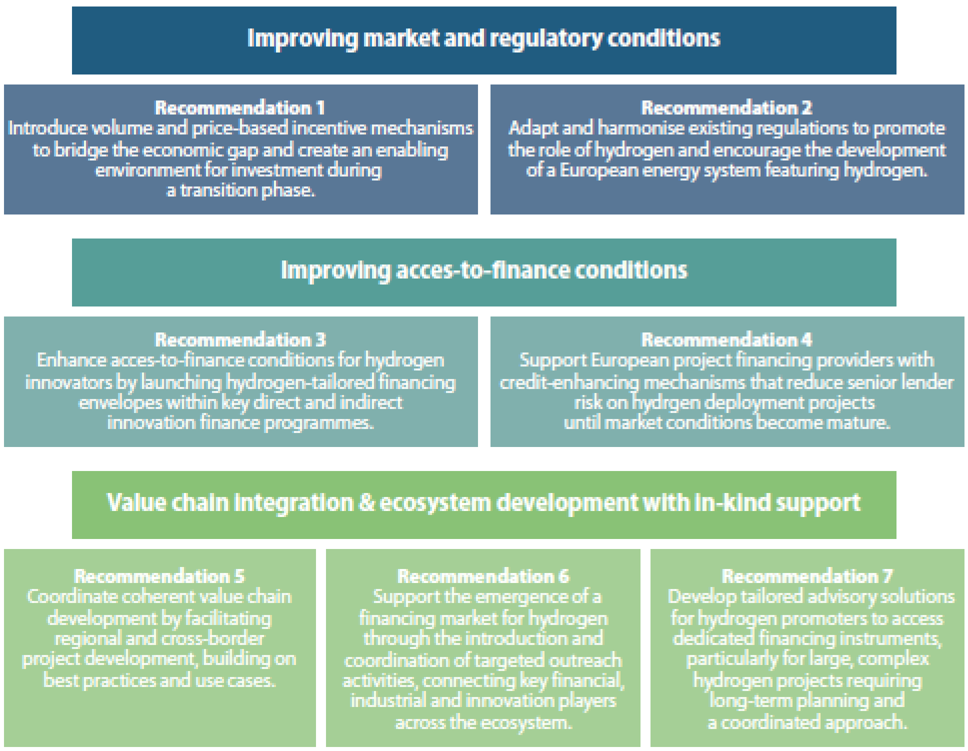

Figure 31. Recommendations to stimulate investment across the hydrogen value chain by the European Investment Bank [127].

The following are the analysis done on the recommendations above for the Swedish context:

- Recommendation 1:

The government of Sweden currently holds tax relief rather than incentives for some links of the hydrogen value chain and lacks supported H_2 volume consumption. Small scale non-marketable electricity generation from renewables is free of taxes for specific cases, just as the electricity used for electrolysis purposes. The proposed hydrogen strategy suggested a CCfDs for H_2 projects to attain an extra revenue stream. Also, consultations show that incentives for OPEX rather than only for CAPEX are required. For mobility purposes and specifically for HRS, OPEX support appear a key element to materialise projects. Despite all these efforts, there's a considerable gap between fossil fuels and low emissions hydrogen along the chain. However, the EU subsidy instruments are trying to give the extra boost to reduce a little the imparity (CEF, InnovaFund, Horizon, etc.), and future incentive mechanisms as the hydrogen bank, suggest that an investment environment can be a reality for the country.

- Recommendation 2:

The country has strict measures for reducing carbon emissions through energy and carbon taxes. A cross-border electricity certificate system for renewable energy is already running in the country. Specific funding is given through state institutions to projects that align with decarbonisation goals. Despite hydrogen being conceived as a potential element for transitioning, and having a proposed hydrogen strategy, the country lacks hydrogen targets and specific regulations backed by the government and parliament. The most ambitious plan is the electrification strategy, that would help the upstream of H_2 by increasing electricity generation and easing permitting, but in general terms, the industry is the one driving the change through innovative projects. The guiding principles for Sweden's policies right now are the regulations and directives initiated by the EU Commission. Mobility is one area where these directives have been particularly influential. The AFIR has established the necessary number of HRS, setting the minimum threshold of 33, where 12 are for core networks and 18 for urban nodes.

- Recommendation 3 & 4 – Improving access-to-finance conditions:

Sweden is giving financial support for projects that help in the decarbonisation of the country, through programs such as Klimatklivet and Industriklivet. Additionally, as a specific program for innovators, the Swedish innovation agency (Vinnova) invest up to 3 SEK billion yearly in R&D, and Almi offers financing as loans, business development services and risk capital for small and medium-sized companies with an environmental and sustainable approach, as a market complementary system. All these institutions are government supported, which lowers the lender risk, but they do not focus solely on hydrogen, therefore, a lack of expertise to address the challenges of the sector is recognised.

Naturally, the EU has also strong subsidy mechanisms as stated before, that could benefit innovative business ideas. In terms of mobility, CEF-T has granted financial support for some of the planned stations in the country like the NHC project. Klimatklivet also granted a great support for the deployment the 24 stations of Hydri and Almi's green loan help Oazer AB acquire components for refuelling stations commercialisation, but all the current subsidies are highly competitive so more alternatives should be developed.

- Recommendation 5, 6 & 7 – Value Chain Integration and Ecosystem Development with in-kind support:

Sweden's government has a lack of measures for a coherent coordination of the hydrogen value chain and a lack of institutions that address it. Instead, some developments can be found in some parts of the value chain. In the upstream, recommendation 2 encompass the most significative developments. As stated, the midstream has the greatest gap, and the downstream has some proposals and policies but mainly for encouraging emissions abatement. Yet, a recent development should be highlighted, being the case of the protective distance for hydrogen installations proposal, which could guide all municipalities and counties of the country. The state supports the financing of projects and innovative ventures, but they are technology neutral.

Swedish industries are the ones willing and pushing for the ecosystem development and coordination of H_2 value chain. Moreover, the EU is the one presenting some cross-border initiatives to support such development, like the European Hydrogen Backbone for the deployment of hydrogen pipelines. Also, the IPCEI has promoted together with AFIR and TEN-T the development of sustainable road mobility, and in Sweden, together with Vätgas Sverige, the Nordic Hydrogen Corridor for the hydrogen road mobility supply chain. Such projects encompass different links of the value chain, attaining the needed know-how and connecting the stakeholders to develop synergies along the chain.

Moreover, many of the projects require integral support to de-risk and accelerate their development. Non-profit initiatives, such as EGHAC, the European Green Hydrogen Alliance, Hydrogen Europe, and Vätgas Sverige, creates the environment for this support. Most of these initiatives provide support by leveraging their subscribed stakeholders, as the ecosystem facilitates communication, centralises relevant information, and develops integration strategies. For this to be possible it is necessary to provide financing services, to incentivize other investors, to address financial and technical uncertainties, and consolidate feedback for the development of future financing instruments and policy measurements. Vätgas Sverige plays a major role today in Sweden by providing the necessary holistic advisory in various hydrogen supply chains, and especially in the hydrogen road mobility with its leadership in the NHC.

6.3 Bottlenecks & impact classification towards Mobility

A compilation of the major hindrances within Sweden's hydrogen value chain will be exhibited next, categorised into three main sections along the chain that encompass technical challenges, economic & financial constraints, and political & institutional barriers. Each bottleneck's impact on hydrogen mobility will be assessed on a scale of 1 to 3, with 3 denoting the most critical obstacles. Such scale considers the tentative proposals, plans and technology developments that are highly likely to be developed in the next 5 years, considering all the outcomes of this project.

Table 16. Electricity associated bottlenecks of the H_2 Value chain with its classification impact and description.

Level of importance	Criteria description
1	***Expansion planning complications***: Accurately forecasting grid expansion is paramount due to the high costs and efforts required, but significant dynamics in industrial projects, increased electrification efforts, and new electricity generation projects countrywide, complicate the task.
1	***Grid constrains and transmissions zones***: A vast number of lines are reaching their lifespan and electrification increase requires higher capacity lines to keep up around Sweden. Also, northern industries' planned consumption is high, reducing possibilities to transmit to southern zones SE3 and SE4, therefore, more imports will be required from neighbour countries.
3	***Electricity price fluctuations***: Despite having diversified the energy sources and low reliance on fossil fuels, electricity costs tripled since the pandemic began, with notable fluctuations during the last years, as a consequence of global dynamics.
1	***Difficulty and uncertainty for permitting processes***: Permits for renewable projects or grid expansion can be rejected by municipalities even when planning phase has already started, arguing different priorities for land utilisation or environment concerns. Additionally, time for the permitting for grid additions can last from 7 to 15 years.

Electricity bottlenecks have impacts on many different sectors besides hydrogen mobility. The direct impact of grid expansion planning on hydrogen mobility is rated 1 as electrical planning, while beneficial for an organised planning of hydrogen production sites, is not imperative due to the low hydrogen demand involved for road mobility. This means that, if hydrogen is produced solely for road mobility, the impact on grid scale is minimum. It is possible to conclude that the current status on electricity planning is not going to be a major bottleneck for the development of the hydrogen road mobility supply chain during the project timeframe assessment. The same conclusion replicates to grid constraints and transmission zones, together with difficulty and uncertainty for permitting process, as all of them also are being addressed by the electrification strategy, and possible developments can come in the next years. Also, the NZIA can be considered for the permitting times, which impact would shorten them significantly.

Nevertheless, the indirect impact of this bottlenecks is increased fluctuations in electricity prices, mostly due to the grid constraints, and the increased need to import electricity from neighbouring countries with fossil-fuel dependence. A scenario with increased electricity price fluctuations becomes highly risky for the hydrogen road mobility supply chain, as it induces higher volatility in the hydrogen cost. Throughout the report, it has been highlighted the undeniable linkage between electricity cost and hydrogen cost, therefore, it becomes clear that this will become an impact for the final user. Moreover, as PPAs are an option to reduce the exposure to fluctuations, the increased risk due to uncertainty, will increase the negotiation costs and PPA negotiated price, undermining the supply chain development.

Table 17. Hydrogen associated bottlenecks of the H_2 Value chain with its classification impact and description.

Level of importance	Criteria description
2	***No clear national hydrogen goals***: Despite a proposition for a Hydrogen Strategy and EU increased focus on H_2, the government has not adopted specific targets for low-carbon hydrogen production in the future.
3	***Absence of market regulation and institutions****:* Sweden does not have a concrete framework in place to regulate the production and allocation of hydrogen, nor is there a hydrogen market or a defined institution to manage its development.
2	***Minor gas infrastructure:*** Natural gas has a minimal contribution to the energy consumption of the country, with the existing infrastructure confined to the west.
3	***Lack of expertise:*** There is a shortage in hydrogen expertise and comprehension within the country's government hierarchy (from parliament to municipalities) and institutions, leading to significant risks and uncertainty in hydrogen ventures from initial studies to financial decisions and execution. Also, government is not fully aligned and educated towards the role that hydrogen could play in Sweden.

As previously mentioned, uncertainties translate into project risks, therefore, no clear hydrogen goals from the Swedish government are an increased risk for project developers and private investors. The unclear role of hydrogen and the uncertain political and regulatory conditions goes against the recommendations done by the EIB and analysed in the previous section. The impact towards mobility is clear as currently there is no goals towards hydrogen mobility, compared to the already established goals of other mobility technologies, in this way, slowing down the development of the supply chain. To overcome this, holistic studies and planning from the government is required to determine clear hydrogen goals in mobility.

The impacts described above, are also relatable to the "absence of market regulation and institutions", and "lack of expertise" bottlenecks. The lack of expertise in government hierarchies, induces lack of goals and absence of regulations. This furthermore highlights the lack of government desire for the development of the hydrogen sector, specifically, hydrogen road mobility. Added to this, the lack of liquid market, with no transparency in costs and transactions is another major impact. For this, Germany has created with the EEX group the HYDRIX indicator, increasing market liquidity and bankability, reducing risks and uncertainty due to increased transparency, while supporting market players and industries with guarantees of origin and certificates. However, it has been noticed throughout the development of other energy sectors, that unregulated markets increase easiness of supply chain development, but with increased non-desired impacts.

Sweden has today a small natural gas infrastructure, mostly concentrated in the southwest and interconnected with Denmark. As explained before in 2.4.3 Storage, transmission, and distribution section, the refurbishment of natural gas infrastructure for hydrogen usage will allow lower costs in the transport of hydrogen, a condition that is not applicable for Sweden. Moreover, the lack of expertise in large scale storage of gases and the operation of a gas market and assets are two of many other skills the Swedish government would need to develop for the smooth operation of the hydrogen market. Due to all of this, the impact on hydrogen mobility is 2 due to the low demand scenarios as a result of no clear hydrogen goals and the current possibility of distributing the gas through tanker trucks.

Table 18. Hydrogen mobility associated bottlenecks of the H_2 Value chain, with its classification impact and description.

Level of importance	Criteria description
1	***Low awareness of recent national guidelines for HRS construction***: Municipalities can assess the risks differently and mandate alternative methods that guarantee safety when knowledge of the process is lacking. Guidelines should be broadly recognised.
1	***Abolishment of low emissions PCs subsides***: Government considers there's price parity between technologies, which could turn the end user to the more mature and cheaper technology.
2	***The chicken-egg dilemma between infrastructure and FCEV:*** Sweden does not count on enough HRS for increasing the adoption of FCEV. However, without vehicles, hydrogen stations could not create revenue.
2	***Market introduction of new FCEV models is at very low pace in Sweden:*** As there is not a robust refuelling infrastructure in the country, automakers don't find the market attractive with the addition of high cost to operate and provide a service to few end users.

3	***HRSs are capital intensive and in need of revenue:*** The CAPEX for building a HRS that fulfils AFIR requirements tend to be high, and only with subsidies are achievable so far. In addition, if there are no revenues, an OPEX subsidy or another financial mechanism is necessary to keep them operational.
3	***End users require a local and functional HRS to consider purchasing a FCEV:*** Hydrogen Vehicle drivers require a nearby filling station that is within their weekly travel or close to their home. The stations should be functional to supply the gas, increasing the confidence on the technology. Without such, FCEVs are not a viable option for users.
3	***Dynamic costs:*** As the last step of the value chain, HRSs fuel price can vary significantly with any dynamic impacting the upstream, which could affect immediately the FCEV owners.
3	***Uncertainty and lack of strong subsidies throughout the value chain:*** Low-carbon hydrogen can be costly and not competitive compared to fossil fuels. Subsidies throughout the value chain (CCfDs, CAPEX and OPEX, etc,.) and favourable signals to stakeholders and private investors must be stronger.
3	***Few FCEVs***: Hydrogen vehicles have a higher cost compared with other technologies, which could discourage new users. The deployment of vehicles is necessary to create a business case in HRSs. Trucks are also needed to kick-start a big share of demand.

Irrespective of the influence of certain EU strategies and policies, like AFIR on Sweden, it is worth mentioning that industries are recognizing the potential of this element for transportation. Many HRSs are coming into existence due to the industrial sector's plea for government CAPEX assistance, evident through notable examples such as Hydri and the NHC at the EU level. This means that the planned HRSs in the country are already exceeding the AFIR requirements and effectively tackling the Chicken-egg dilemma by establishing a modest infrastructure. Recommendations 5, 6 & 7 from the EIB for hydrogen value chain development explained before, highlights the need for coordinated supply chain development through projects, which is addressed today by the NHC. The existing infrastructure is already incentivizing the development of more HRS around Sweden, influencing Swedish vehicle manufacturers to produce heavy-duty vehicles [128] [129]. Users need to have a close station to consider FCEV a real possibility and the infrastructure needs FCEV to meet its supply.

An HRS needs vehicles that translate into revenues to support its business model. Hydrogen cost for the final user is higher if there is a lack of revenues, and finances for HRS developers are not positive. Therefore, an OPEX subsidy, as determined in previous sections, becomes necessary for successful business cases. This is a major bottleneck to be solved, also relatable to the bottleneck "uncertainty and lack of strong subsidies throughout the supply chain", where subsidies would reduce uncertainty in terms of demand, and increase the feasibility not only for HRS developers, but also for heavy duty vehicle developers.

7 CONCLUSIONS

This master thesis has performed a holistic assessment of the hydrogen road mobility supply chain, all the way from electricity procurement and hydrogen production, until the FCEV users and automakers. Thus, it has been possible to identify bottlenecks and relevant variables to reduce the cost of low-emissions hydrogen, necessary for obtaining feasible business cases for hydrogen refuelling stations and to incentivize demand, solving the chicken and egg dilemma. Due to the rapid development of hydrogen technology, regulations, and studies, this project has focused on analysing variables relevant for short and medium-term development of the sector.

Also, it has been possible to determine that government support is lagging today in Sweden and is necessary the development of subsidy schemes to support CAPEX and OPEX of low - emissions hydrogen related projects. For this, policymakers must align on the role of hydrogen in its economy, establishing goals and reducing uncertainty for private stakeholders. As a conclusion, a detailed checklist of efforts for the development of strong business models is developed.

7.1 Checklist of efforts for strong business model and comments

To achieve a successful deployment of hydrogen mobility in Sweden, it is imperative to identify and emphasize specific factors and essential needs. Besides the bottlenecks registered before, the forthcoming list will present the necessary considerations to turn this ambition into a tangible achievement and stimulate market expansion.

1. **Synergies and joint ventures to secure all revenue streams**: To lower the project risk and achieve a bigger emissions reduction impact, industries and firms can develop relationships for successful large hydrogen deployment projects. It ensures the possibility of securing a supply-demand, higher chance of an initial deployment of a large-scale infrastructure and maximise all the possible revenue streams to further reduce the LCOH along the chain. Automakers and HRSs could partner up with such joint ventures, guaranteeing offtakers (e.g., heavy-duty trucks) and the commercialization of the gas in mobility.

2. **Faster and more reliable approvals throughout the value chain**: ongoing proposals from the EU and the state suggest a reduction of the administrative burden of permitting and the length of such processes in a near future. Developing the regulatory and institutional capacity to streamline hydrogen projects permits and therefore the infrastructure, is imperative for a faster development of the value chain.

3. **Have a stronger HRSs network**: End users require to have a refuelling point in its vicinity to think of adopting a certain vehicle. If a modest amount of HRSs is deployed in the country, end users will feel comfortable switching to a FCEV, and automakers will react to the market need in some time. The planed stations are a good starting point, but a greater network is needed.

4. **Technology cost parity with competing alternatives**: From the cost of low emissions hydrogen to the cost of a FCEV, hydrogen technologies and production needs to lower its cost and increase its availability throughout the value chain. Subsidies, in early stage of

supply chain development, are a solution to reach cost parity sooner. Also, some subsidies to specific technologies, such as the NZIA is doing, can be adopted by the country, which can encompass FCEV.

5. **Greater subsidies**: Current subsidies are not enough to close the gap with fossil fuels and are extremely competitive. More easily accessible subsidy instruments for CAPEX and OPEX, and also possibilities for developing CfDs or CCfDs are needed along the value chain to create a long-standing business case, while the time and market maturity for securing profits achieved.

6. **Develop a robust electricity procurement strategy**: As the LCOH is greatly affected by the electricity cost, optimising hydrogen production with electricity pricing becomes a relevant activity for achieving low hydrogen production costs. PPAs comes practical to have a long-term low electricity price and secure hydrogen production. Electricity traders becomes a useful stakeholder for this task. The Delegated Act, establishing the rules for green electricity sourcing for hydrogen production via electrolysis, gives an advantage to Sweden over other EU countries, allowing to reach higher operational hours with lower restrictions.

7. **Development of Hydrogen Ecosystems**: Hydrogen ecosystems must be developed to integrate supply chains and reduce costs, increasing profitability for the stakeholders and reducing financial risks. Hydrogen clusters with financial services, researchers, NGOs, consultancy services, supply chain development and integration, and industrial matchmaking are recommended by the EIB to reach this hydrogen ecosystem goal. The key to make it possible is the development of knowledge translated into expertise. Individual experts, at the beginning of its development, become relevant to provide consultancy when evaluating project risks, and for every technical, political and environmental task related to the steps of the chain. Institutions and non-profit organisations become equally important to provide a transparent assistance on these topics and spread even faster the knowledge to kick-start and lead this hydrogen ecosystems.

8. **New regulatory framework and market environment**: Sweden need to create a whole new regulatory framework for hydrogen management that considers the specifics of the value chain and its possible uses. In parallel, consider the development of institutions that develop and regulate the market, capitalising the needs of supply-demand, forecasting H_2 deployment and assessing the infrastructure needs. This will increase transparency in future projects to be developed and integrate the market players with healthy competitiveness. Also, H_2 goals and even HRSs own objectives for the country could come naturally.

9. **Standardisation of hydrogen supply chain**: Standardising the technologies, regulations, and protocols throughout the supply chain and together with neighbouring countries, is a relevant activity that will allow to reduce negotiation costs, project development costs, and bring transparency. This will allow easier education of policymakers and permitting institutions, therefore reducing the quantity of stranded projects.

10. **Offtakers are greatly needed**: To enhance the H_2 volume demand in mobility, industry should prioritize FC vehicles (mainly trucks) by using the existing subsidies for heavy-duty

trucks and take advantages of the technology perks. Industry synergies could pave the way for its adoption, and, with a market pull, automakers would accelerate the truck technology development process to effectively respond to the growing demand.

7.2 Limitation and future work

Developing a holistic assessment, where policies, regulations, technologies, and finances are assessed together, becomes important to identify missing pieces or rough estimations on the build-up of a supply chain. Therefore, detailed assessments of each step of the supply chain and individual impacts must be carried out and added up, to attain a comprehensive understanding of the key elements and connections of the chain. The recommendations are divided over scopes of the RQs 1 and 2.

- RQ1 – Quantitative assessment over the supply chain for robust business model:
  - ✓ Detailed techno-economic assessments to each step of the supply chain, incorporating uncertainties and probable scenarios over time to achieve stronger recommendations for robust business models. These assessments must encompass costs associated with the risks of project development and involvement within the industry experiences. The goal is to have statistical and more realistic goals for hydrogen costs over each step of the supply chain, from low-carbon hydrogen production to its dispensing in the refuelling station.
  - ✓ Cost-parity analysis between conventional fuels and low carbon fuels, to identify possible subsidy schemes that incentivize a cleaner supply chain development. For this analysis, and to determine the subsidy levels in a subsidy scheme, country-level and external policies, such as EU, must be considered and modelled. If cost parity is not yet achieved, simulations and different sensitivity analysis are recommended to find several constructive scenarios.
  - ✓ Development of real case studies along Sweden is recommended, seeking to assess specific business models and value propositions. Such studies could bring insights on key points to consider when deploying hydrogen mobility, such as optimal size and refuelling points of HRSs depending on location, minimum amount of volume or financial support to reach a break-even point, the specifics for hydrogen project deployment in different municipalities and counties, etc.
- RQ2 – Qualitative assessment to determine factors that impact the market rollout of the road-mobility hydrogen supply chain:
  - ✓ Impact assessment of the regulatory framework and subsidy schemes over every step of the supply chain, including an analysis of the investor confidence. Using the findings and analysis of the regulatory framework and subsidy schemes throughout this report, the impact assessment must focus on bringing efficiency over the existing framework, enhancing then the positive impacts, and strengthening the weak areas.
  - ✓ For the impact assessment, partnering up with a policy expert can give advantages in the understanding and quality outcomes of the analysis. As there is a constant revision and new developments of policies, such partnership can help tracing the most impactful and determine if gaps or specific outcomes are already being addressed or indeed need to be highlighted.

The recommendations listed above for future work moreover require the need for an integrator of outcomes to build up the supply chain puzzle.

On the other hand, the development of this report has faced different limitations that did not allowed for a more comprehensive study. First, the usage of MATLAB as a tool is highly important to build up scenarios and complex assessments, however, the inexperience with the tool did not allow for this detailed study. Secondly, there is a lack of reliable and operational data on hydrogen supply chain costs as it is valuable information for businesses. In this way, the results might not resemble the reality when projects are being developed. Third, as the supply chain of low-carbon hydrogen for road mobility is still in early stage of development, the availability of experts and end-users is limited, therefore, the outcomes of part of the assessment are limited and dependent on their judgement. Quantitative assessments on interviews offer an unbiased and statistical perspective of the interviewed people, however, more experts and end-users would be required, and are not available today.

Furthermore, there several are ongoing changes and advancements in policies within Sweden and the EU that directly influence the evaluation of the value chain. The authors humbly recognize their lack of expertise in this policy domain, and as a result, every statement made is based on credible sources or the impact that can be expected according to the policy source, without a deeper analysis.

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APPENDIX

Appendix A: List of HRS projects announced in Sweden.

The following is a compilation of existing HRS and announced projects in Sweden. The compilation of projects was done through extensive research of news and webpages of HRS developers-

Table 19. List of HRS projects available and announced in Sweden.

HRS Location	**Developer**	**Source**
Arboga Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Arjeplog Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Arvidsjaur Municipality	Lhyfe	- The Botnia Hydrogen AB consortium aims to develop hydrogen production and refuelling stations in Piteå and Arvidsjaur in Northern Sweden (lhyfe.com)
Båstad Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Boden Municipality	Zelk Energy	- Go-ahead for Zelk Energy - (affarerinorr.se)
Falköping	Hydri	- Hydri | Vår vision: fossilfria transporter
Gimo, Sweden	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Götene Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Gothenburg	Circle K	- Circle K opens the Nordic region's first electricity and hydrogen station for heavy traffic | Circle K Sverige AB (mynewsdesk.com)
Gothenburg	Power Cell - AGA – Hynion	- PowerCell invests in solar cells and electrolysers to create industrial test bed and own hydrogen production - Hydrogen Sweden (vatgas.se) - HRS Availability Map (h2-map.eu)
Grums Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Hamrångefjärden	Hydri	- Hydri | Vår vision: fossilfria transporter

Helsingborg	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com) - New filling stations in Electrification pilots - Hydrogen Sweden (vatgas.se)
Jönköping	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Jönköping	Hynion	- New filling stations in Electrification pilots - Hydrogen Sweden (vatgas.se)
Kalmar	Hydri	- Hydri | Vår vision: fossilfria transporter
Karlshamn	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Karlstad	Everfuel	- Därför siktar Karlstads Energi på vätgasproduktion
Kumla	Hydri	- Hydri | Vår vision: fossilfria transporter
Lilla Edet	Hydri	- Hydri | Vår vision: fossilfria transporter
Linköping	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Det blir ingen vätgasmack: "För få använder bränslet" - P4 Östergötland | Sveriges Radio - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Luleå	Everfuel	- New filling stations in Electrification pilots - Hydrogen Sweden (vatgas.se)
Malmö	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com) - City of Malmö applies to participate in international hydrogen project | City of Malmö (mynewsdesk.com)
Mantorp	Hydri	- Hydri | Vår vision: fossilfria transporter

Mariestad	Hydri	- Hydri | Vår vision: fossilfria transporter
Mariestad	VänerEnergi & Nilsson Energy	- Construction begins for world-unique energy solution with solar and hydrogen in Mariestad | Mariestad Municipality (mynewsdesk.com) - HRS Availability Map (h2-map.eu)
Markaryd	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com) - Refueling hydrogen in Markaryd - Step 2 - Markaryd
Markaryd Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Munkedal Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Nyköping	Hydri	- Hydri | Vår vision: fossilfria transporter
Ödeshög	Hydri	- Hydri | Vår vision: fossilfria transporter
Örebro	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Oskarshamn	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Piteå Municipality	lhyfe	- The Botnia Hydrogen AB consortium aims to develop hydrogen production and refuelling stations in Piteå and Arvidsjaur in Northern Sweden (lhyfe.com)
Ringarum	Hydri	- Hydri | Vår vision: fossilfria transporter
Sandviken	AGA (Pipeline AGA - Industrial Area) - Hynion	- Hydrogen - Sandviken PurePOWER - HRS Availability Map (h2-map.eu)
Skillingaryd	Hydri	- Hydri | Vår vision: fossilfria transporter
Söderhamn	Hydri	- Hydri | Vår vision: fossilfria transporter

Stockholm	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Stockholm	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Stockholm - Arlanda	AGA - Hynion	- AGA builds hydrogen filling station at Stockholm Arlanda | INDUSTRInyheter.se - HRS Availability Map (h2-map.eu)
Strängsered	Hydri	- Hydri | Vår vision: fossilfria transporter
Sundsvall	Everfuel	- New filling stations in Electrification pilots - Hydrogen Sweden (vatgas.se)
Tanumshede	Hydri	- Hydri | Vår vision: fossilfria transporter
Trelleborg	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com) - Vätgas - Trelleborgs Energi
Uddevalla	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)
Umeå	Skallafteå Kraft	- What place and potential does hydrogen have in Västerbotten? - Luleå University of Technology, LTU
Uppsala Municipality	Uppsala Vatten	- Uppsala vatten accelerates – now also with hydrogen | Uppsala Municipality
Vårgårda Municipality	Hydri	- Hydri | Vår vision: fossilfria transporter
Värnamo	Hydri	- Hydri | Vår vision: fossilfria transporter
Väse	Hydri	- Hydri | Vår vision: fossilfria transporter
Västerås	Hynion	- New filling stations in Electrification pilots - Hydrogen Sweden (vatgas.se)

Växjö	Everfuel	- Everfuel plans 15 hydrogen filling stations in Sweden - Hydrogen Sweden (vatgas.se) - Everfuel launches plan for Swedish hydrogen fueling network - Everfuel A/S (cision.com)

Appendix B: Interviews: summary of questions & answers

- ***Electricity producer***

- Is there interest in considering H_2 production as a business?

There are a lot of investment right now in new industries. Swedish industry has shown interest in hydrogen, so there's a window of opportunity. NHC is part of it with transportation sector.

- Which factors are the most important for bankability /investment risk in hydrogen production?

Alignment on a framework and standardization of how to handle hydrogen in the value chain, could reduce risk in EU. Starting countries are needed.

3 years ago, it was expected the LCOH to be below 2 eur/kg. Inflation and global circumstances make it right now unreal, below 4 EUR/kg.

- What are your thoughts about the future of transportation?

Regarding FCEV the larger volume I would say will be during 2027-2028. Right now, BEVs are a really good option (efficiency has increase), delaying process of H_2 adoption.

- What bottlenecks do you consider should be firstly addressed?

There is low interest in taking the risk of H_2 infrastructure. No automakers and no users are willing to, so subsidies and restrictions need to be developed.

- Which would be the main actions that you do to improve the market of H_2 regarding policies, economic matters, and subsides?

A way of starting could be:

Implementing more restrictions for pollution (as CfDs) and to polluting engines

Having CAPEX and more importantly, OPEX subsidies that last 3 to 5 years to keep things moving.

Scrap subsidies to old vehicles to help in the switch.

- What are the main Bottlenecks for hydrogen deployment?

Permitting process and license for setting mobility should be smoother.

Politicians think that current subsidies are enough, so they need to evolve to ease the risk.

- ***H_2 producer (1st interview)***

- What could mitigate the financial risk for the projects you develop in the mobility sector?

First educate investors. If they understand that 5% of all the energy mobility consumed in Sweden will come from Hydrogen, they will see the opportunity, even when profit will come in the future.

- Which would definitely ramp up the adoption of hydrogen in mobility?

Cost parity with current mobility technologies

- What other financial aspects would help in the deployment of HRS projects?

Every business model is different, but a big plus is having extra revenue streams in the production process for example.

- What considerations are wort doing at some links of the value chain?

A good starting point for hydrogen production is having 20MW of electrolyser capacity.
For each HRS the H_2 production shouldn't be decentralized. The distribution distance should be considered as its transported by trucks. The HRS should be easily scalable. There should be up to 200 stations in Sweden for a strong business model. Trucks are the largest consumers, so they will drive market demand.
Summary of 1st interview:

They have learned that the OPEX (maintenance of a plant) factor is bigger than what is shown in literature or reports.
The cost of running small electrolyzers (maintenance perspective) is higher than in big plants. This is explained by the manpower required to carry out the maintenance of small distributed electrolyzers, compared to having a centralized production plant.
Certificate for RFNBO's and EU ETS are also an income stream.
4 tons divided into 60 kg trucks on average a day, 66 trucks per day = 3 trucks an hour, # of dispensers. Average mobile storage 1.2 tons equals then to 3 storage tanks. 1 trailer every 8 hours. Liquified hydrogen is limited, increased cost at the station because of boiling effect, however boiling is not an issue with a steady demand. Fixed O&M in an HRS are not major facts when going into a business case. Total CAPEX is 3 million euros.
700 bar refuelling protocol is not decided fully yet; therefore, the equipment is not engineered fully. More costly 700 bar infrastructure. Around 4 million for a station of 4 tons a day and 700 bars. Have as a base the 700 bars as this is what everyone is aiming for.

- ***H_2 producer (2nd interview)***

- What aspects could help mitigate risks for HRS?

The government maintaining subsidies for several years (OPEX). Benefits and profitability may take a few years to start.
Legislation that ease the HRS deployment. Sweden have more than 290 municipalities and is difficult to follow its specific requirements. The good news is that is already being developed.

- What do you think about the outcome of the AFIR package, released at the end of march?

It lower the tentative requirements for the countries. Sweden should build a number close to 33 HRS by 2030, but many more should be deploy in such a vast country.

- What bottlenecks are stopping a faster deployment?

Timing when vehicles become available. If trucks that are the bigger consumers don't arrive, nothing will move forward.
Summary of 2nd interview:

Industrial offtaker for hydrogen as base load for production units. Now aiming for harbor-based hubs as then you have the maritime sector as well (hydrogen and methanol production).
Having the ports covered will allow to cover almost all of Sweden in hydrogen production for road mobility. The goal is to also connect wind turbines as these projects are struggling with grid connection.
Finding the right location to build an HRS is a major bottleneck for HRS developers, as it must be close to a highway. For production an environmental permit is required and could

take from 6 months to 2 years. Building an HRS is easy, building production is not easy, as local municipalities don’t have resources or knowledge to allow this. In bigger municipalities there is experienced people, in smaller there is no knowledge, experience, or resources.

- ***University PhD Researcher***
  - How can HRS value chain reduce its costs?

  Mostly focusing on hydrogen, besides the electricity price, large-scale production and storage.
  - What bottlenecks can exist in the HRS value chain?

  Constrains in the transmission network, and the financial gap that make it competitive with other technologies, and the chicken egg situation with HRS and FCEV.

  Long permitting processes

  As hydrogen is explosive, possible risks with the hydrogen management. It needs to be safe.
  - What can be done to overcome this chicken and egg situation with infrastructure and vehicles?

  Strategy partnerships with automotive company to build and feed HRS.
  - What actions do you consider are needed to foster hydrogen in a country?

  Policies. In the case of Japan, energy security drives the change for a national hydrogen plan
  - What about hydrogen mobility?

  The government should give clear signs of technology adoption. As HRS and end users are the ones paying, subsidies and incentives from municipalities and government are needed. This support should last until enough demand is created. Government promoting new technology to reduce costs and create market pull.

- ***H_2 related company***
  - What is the most important aspect in the deployment of hydrogen projects?

  The Offtaker, to secure that supply meets demand.
  - What do you consider could be the main cost driver for HRS?

  Electricity.
  - What extra insights can you give regarding hydrogen projects?

  The business developers come from the energy field, where locations are what matters the most. In H_2 projects, that is false, you only need to connect to the grid with less complications.
  - What needs to be accomplished for making Hydrogen mobility a reality?

  First, hydrogen has to reach maturity in chemical, steel or other industry. Once it happens, heavy duty will be the first adopter and if it's successful, light vehicles could follow.

- ***Automaker 1***
  - How do you foresee FCEV's sales forecast in the next 3 years, what are the main drivers or bottlenecks of the market?

  Despite the good performance of the technology, the sales have been low and mainly out of technology fans. Our vehicle is a luxury car with limited baggage, not the usual passenger car.

  Regarding bottlenecks:

  Lack of infrastructure. Even 50 HRS could be low for Sweden.

  EVs competition is high and more manufacturers must enter the FCEV market.

Automakers are focus on BEVs and all resources are exhausting into its deployment, so its complicated to pursue at the same time FCEV development.
Regarding technology, storage tanks are an engineering challenge for FCEV
Green hydrogen availability and price would be the next bottleneck after HRS and FCEV are deployed.
Not many educated technicians to attend FCEV O&M

- Are there any other promising technologies with H_2 as a feedstock?

There is the possibility of developing ICE with hydrogen, but the NOx emissions and temperature can be a bigger problem. The main technology right now are the FC and the company has been developing for many years, and looking to make partnerships for its utilisation.

- Do you feel that the policies and subsidies of Sweden are motivating FCEV?

They are favouring EVs in general, not a specific technology. The subsidies are good because HRS are capital intensive and can be hard to build without support.

- Are you educating the end user about hydrogen or what actions are you implementing for the people to approach this technology?

The company is leasing the vehicles to make sure that customers know the FCEV limitations. Also are in communication with Research institutions to address security studies and other limitations.

- ***Automaker 2***
  - How do you foresee FCEV's sales forecast in the next 3 years, what are the main drivers of the market in Sweden?

Demand has been very low for PCs, mostly because of the chicken egg dilemma. After having FCEV availability in the Swedish market, most of those cars had to be re shipped to other countries.

- What are the main reasons that you can think of?

Infrastructure is the first reason. Second, low incentives for purchase for PCs.
The high cost of vehicles compared to other technologies, and rising inflation rates.
The high cost of O&M and complications with repairing and the OEM parts.
Other technologies for PCs are more promising, like BEVs fast charging.

- Is it an option for the company to lower the price of vehicles or develop some partnerships seeking for supply chain optimization costs?

The company is compromised with hydrogen and has shown with continuously improving its process. Having a role of distributer only, the risks that we can take are less than bigger companies, then lowering prices wouldn't make the business profitable right now.

- What can be done to make hydrogen mobility a reality?

That end users start requesting vehicles. Of course, the government can't only subside the few hydrogen PCs cars, and even so, they are more expensive. Not even previous subsidies were significative.

- If demand were to increase, how long would it take to respond, given the problematic supply chain situation?

For Short run, supply will be slow. A year would be enough to respond. It would depend also in the Semiconductor industry response. At the end only depends on the market.

- ***H_2 Expert (1st interview)***
  - How can hydrogen deployment thrive?

  By integrating business models between different companies.
  - How many stations are planned to be built in the next years?

  So far between 60 to 65. AFIR reduced the need for this number, but with a mandatory objective.
  - How will the new delegated act affect hydrogen projects in Sweden?

  The country is in a great advantage compared to others, by having the chance to use the low emissions grid to produce hydrogen, without additionalities.
  - What are your insights about the just released AFIR package?

  Is a drawback. Decision makers are reducing the efforts needed by not following the IPCC recommendations.
  - What do you think are the main bottlenecks or risks for hydrogen deployment in mobility?

  Political conflicts. Parties need to align strategies and understand the potential of hydrogen. Even if nuclear is promoted, pink hydrogen should be part of the strategy.

  A major risk would be that automakers would not step up and supply vehicles.

  Also, as supply chains are stretch, delivering time of components for the value chain.
  - Are there administrative barriers and any type of guidance for a low-emission hydrogen project from the government?

  No, not really. There are two national proposals for a hydrogen strategy from 2021, but still no decision from the Parliament regarding making these into a road map or action plan. The new Government is only almost 6 months on the post, so we have not gotten any clear signal what they intend to do with H_2.
  - What could be the most powerful grants or subsidies that aid in the new H_2 project deployment task?

  There are plenty of tools that could be used as incentives for hydrogen. I believe a production subsidy like the one settled in the US recently would be a good solution. A 30 SEK/kgH_2 should match the US IRA subsidy, and this would be a powerful support. We also would like to see not only CAPEX support for some early projects, but also a OPEX support for the first five years of operation for example for HRS.

- ***H_2 Expert (2nd interview)***
  - How do you think that municipalities could share knowledge or experience for HRS development, align with hydrogen?

  It is very hard to get things done in bigger cities, too much politics. Front-runners are smaller cities as they could make the cities more attractive and for business possibilities. Bigger cities try to run for good a case instead of a quick case, even though they could be very successful. There must be national level regulation or plan to avoid individual plans in regions and then align at infrastructure level.
  - Does having a national level infrastructure plan reduce the amount of veto from municipalities towards infrastructure development?

  Local veto is a strong democratic tool but is slowing the process too much, but standardisation will help reduce the veto to increase the number of renewables through more participation of the national government and increasing the benefits for the local municipalities.

Taxes is a holy grail topic, cannot be touched, however, it must be more flexible to provide more reimburse to municipalities. More important is job creation, how many jobs are we creating over time with the deployment of renewables and the long-run incomes are not being considered.

- The EU has move forward to develop the gas package, do you think that Sweden would adopt or create a regulatory framework for this purpose?

Sweden is not a gas country yet, however in 2021 they have part of the gas package, beneficial for hydrogen. They do not see (owners) that the existing pipelines are going to be completely refurbished for hydrogen, they believe that new pipelines. Industries need methane, that means you cannot swap directly to hydrogen. The Bothnia project is deploying and not waiting for politicians (hydrogen backbone). Gas packaging is pro-hydrogen, however, there is favouritism towards specific colours of hydrogen.

- About the Delegated Act:

People have not understanded how well Sweden went out with the Delegated Act.

- Bidding process for the HRS subsidy:

Extra incentives to develop HRS in mid-Sweden. There are ~60 stations announced, compared to the 33 required by AFIR. We could use the block exception and 1/3 incentives (3 usd per kilo; 30 SEK / kilo) for hydrogen production to really release the market.

- Companies are avoiding policy gaps and going for project development. Is this the better approach?

The time now is too complicated, too many directives, regulations, etc. external investors are interested in the clean power of Sweden, what is the maximum allowed? Foreign investors are necessary, but it is important to select the right partners. Very few people have the complete vision and could give the right investment decision.

- The most difficult permit for HRS?

The guidelines must be ready for municipalities and approved by authorities for HRS development. Environmental testing is more complicated, however there is very little environmental impact with the construction of an HRS. Education is needed. As the safety issues are managed by different stakeholders, the fire department has not standardised guidelines at a national level, even at municipality level, so there is not efficient communication between institutions.

- ***FCEV End user (H_2 expert) #1***

  - Can you get us through your thinking process when you decided to buy an FCEV? What were your motivations?

FCEV vehicles are more sustainable, therefore, I went for an FCEV rather than a BEV. (He is manager of sustainability at Sandvik, therefore, he really wanted to project sustainability in general.

Still an expensive option.

- Was this your first option vehicle in your house? What other vehicles did you have at that moment?

I own other vehicles, including BEVs and ICE vehicles.

I use my FCEV to move to Stockholm, stopping in Arlanda for refueling.

- How was the experience of being the owner of one of the first FCEVs in Sweden? Do you have any regrets?

No issues with the car, however, I had a minor accident, where Toyota had no problem fixing the vehicle, but the car only has friction tires, instead of static tires for icy winters.
However, in cold weather, it outperforms BEV.

- Tell us about how the experience related to refuelling your FCEV was. Was it an issue with the range of your vehicle to find a refuelling station? Did you have to strategically plan for this?

As an engineer, I know the pros and cons about buying an FCEV, so I was ready to deal with the lack of refuelling stations, therefore, he planned beforehand the refuelling of the vehicle. Going to Stockholm was not an issue as Arlanda station was always available.
HRS stations work better when are used regularly, otherwise, there are issues to start the components as heating is required for this, normally the case in Sandvik station. At Arlanda, I never faced issues.

- Are you making any efforts to incentivize the demand besides the NHC project?

Sandviken Pure Power: Joint Venture between Sandvik, Sandviken, and Linde, to develop the HRS and infrastructure for the city, leveraging Sandvik influence on the municipality. I had the initiative and pushed a Hyundai salesperson to show an FCEV, which then was brought from Malmö to Sandvik, and exposed in Sandviken factory as an event where the municipality and company directives where present, motivating then the development of an HRS, a Kinto renting station outside Sandvik, and the usage of FCEVs at the company.

- Which has been the major bottlenecks or risks in the projects you have developed here in Sweden and other places?

Fear barrier - Education

- ***FCEV End user (H_2 expert) #2***
  - Can you get us through your thinking process when you decided to buy an FCEV? What were your motivations?

The car is for the company, rather than for own usage. It is used for car-pooling and for business purposes. As a company developing hydrogen refuelling stations, we must have a hydrogen vehicle.
Renting a vehicle is fine, but I prefer to own it.

- Tell us about how the experience related to refuelling your FCEV was. Was it an issue with the range of your vehicle to find a refuelling station? Did you have to strategically plan for this?

Easiness to refuel, 3 minutes to refuel, 60 grams / second maximum refuelling capacity.

- How was the service provided by the vehicle manufacturer in terms of after-sales, maintenance, and repairs?

Limited maintenance capacity from vehicle manufacturers in specific cities and with limited personal with the competence to provide maintenance to FCEV.

- Are you making any efforts to incentivize the demand besides the NHC project?

More refuelling stations are needed to accelerate market development.

- Which has been the major bottlenecks or risks in the projects you have developed here in Sweden and other places?

Easiness with environmental permitting when developing HRS. Safety permitting is more complicated as there is no rulebook to follow for a risk assessment.
Bus or trucks are needed to ramp up the value chain. 2027-2028 trucks are going to be available from Scania and Volvo.
Vehicle manufacturers don’t want to sell vehicles in Sweden as there is no place to refuel the vehicle.
Fossil fuels are heavily supported by subsidies.

- Why consider on-site production for some HRS solutions?

HRS are mostly out of order in Europe (30%) and California (35%). Therefore, it is required at least 2 stations per location. The lack of low-carbon hydrogen is the reason why the stations are out of order. Production on site of the HRS for robustness, the goal is to always have hydrogen at the station, it is cheaper and cleaner as there is no need to transport the hydrogen. 0.5 MW electrolyzer in each station equal 200 kg/day.

- How do you obtain financing for the projects you develop in the mobility sector? (Expanded to what is required to reach an FID for an HRS

CAPEX subsidy has a positive impact on the FID for HRS, as we receive 70% CAPEX subsidy. By 2025, when the HRS are built, it will take 3-5 (2028-2029) years to get enough money to at least cover the costs. Producer and offtaker at the same time is the goal. 1 or 2 trucks per day (120 – 160 kg/day) for business profitability per HRS.
Klimatklivet money will come after the HRS is developed, with no money upfront.

- ***FCEV End user #3***
  - Can you get us through your thinking process when you decided to buy an FCEV? What were your motivations?

  First, he didn’t want to drive any more petrol or diesel. When buying the FCEV, he was looking for options that require less expenses than usual vehicles (road taxes, VAT, etc). Battery was an option, however, due to low range and charging time, vs cost, compared to hydrogen, it was not a benefit. He also needed space for his dog.

  - How was the experience of being the owner of one of the first FCEVs in Sweden? Do you have any regrets?

  He was not expecting to be one of the first in Sweden, as he bought the vehicle in Norway. The FCEVs he sees on the streets are normally from companies or the municipality.
  He has been in the media to show his experience with the vehicle.
  Since he owns the car, only 1 more HRS has opened, something that worries him, so he highlights the need for more HRS.

  - Was this your first option vehicle in your house? What other vehicles did you have at that moment?

  He has an FCEV, and his girlfriend has a petrol car, but mostly they use the FCEV.

  - Tell us about the experience related to refuelling your FCEV. Was it an issue with the range of your vehicle to find a refuelling station? Did you have to strategically plan for this?

He drives a lot with the car. It is more convenient when he drives along Germany, Austria, Switzerland, Belgium, etc, because of more refuelling stations on those countries.
He lives in Mariestad, where there's availability of one HRS, if not, he wouldn't have bought his car.
There are technical issues with the HRS. He considers it's something that must step up for this technology to work. Sometimes the station runs out of fuel, so he is in very close contact with the refuelling station owners/operators to know when the station is working properly.
It is more expensive to refuel in other places, the cheapest he knows is in Mariestad. In Norway, the price has increased a lot (he does not know why).

- Did you feel safe when refuelling your vehicle? What was your perspective towards hydrogen in terms of safety?

No safety concerns. He knows the vehicles are safe, he knows that the vehicles have been crash tested and they work perfectly.

- How likely are you to continue to be part of the FCEV market as a vehicle owner based on the current conditions?

He would recommend this vehicle to friends and others, and he will stay as a FCEV user as long as the station is there. People do not know FCEVs.

- How was the service provided by the vehicle manufacturer in terms of after-sales, maintenance, and repairs?

Very good relationship with Automaker. The first three services are covered. Education of car mechanics is necessary, as there are very few specialized people today.
The services are in Oslo since he bought the car over there. However, it is not a problem for him, because he drives several times there.

- ***FCEV End user #4***
  - Can you get us through your thinking process when you decided to buy an FCEV? What were your motivations?

He is passionate about hydrogen and could afford himself. He is well aware of the benefits of the technology. The only used FCEV available in Sweden by that time, was a Nexus. Other brands could give the vehicle in his expected period.

- How was the experience of being the owner of one of the first FCEVs in Sweden? Do you have any regrets?

Still owner. Car is amazing, he likes it, is quiet, smooth, looks nice, and clients like it. He normally talks to people about hydrogen. 99% of the people he drove are interested in hydrogen. He is proud of being one of the first owners.

- Was this your first option vehicle in your house? What other vehicles did you have at that moment?

Only hydrogen vehicle, no other option in his house.

- Tell us about the experience related to refuelling your FCEV. Was it an issue with the range of your vehicle to find a refuelling station? Did you have to strategically plan for this?

He always drives to Arlanda to refuel, but he felt that the price was increasing rapidly in the last year. Only one time was worried because of the low fuel range, getting closer to Gavle.

Normally he communicated by phone with the HRS to go and refuel, because several times the station wasn’t working, due to problems with the compressor or lack of fuel.
He thinks that redundancy of HRS is better, and crucial for using the technology.

- Did you feel safe when refuelling your vehicle? What was your perspective towards hydrogen in terms of safety?

Easy process to refuel, a friend of his showed him.
He knows that hydrogen is highly flammable, however, he also knows that it dissipates fast and remember the Hindenburg accident.

- How likely are you to continue to be part of the FCEV market as a vehicle owner based on the current conditions?

He really likes FCEV; he would change to another FCEV. However, it is expensive and there are few HRS to recommend the vehicle right now.

- How was the service provided by the vehicle manufacturer in terms of after-sales, maintenance, and repairs?

Maintenance fine. Agreement with automaker for maintenance as they were interested in keeping the vehicle.
Maintenance in Uppsala, however, for more complicated stuff they must move the vehicle to Gavle or Sandviken which has more specialized maintenance. It is fine the maintenance time.