Hydrogen fuel-cell heavy duty trucks for long haul transport in the EU; conditions for a successful implementation

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Glossary

BEV – Battery electric vehicle
BE-HDT – Battery electric heavy duty vehicle
EC – European Commission
EEA – European Economic Area
EU – European Union
FCEV – Fuel-cell electric vehicle
GDP – Gross domestic product
GHG – Greenhouse gasses
HDT – Heavy duty truck
HDV – Heavy duty vehicle
HFC-HDT – Hydrogen fuel-cell heavy duty truck
ICE – Internal combustion engine
LH – Long haul (distances over 400 kilometres)
LR – Learning rate
MHDVs – Medium and heavy duty vehicles
SFF – Success and fail factors
SMR – Steam methane reforming

Summary

Many industries operating with fossil fuels, or fossil fuel-based product, are under great pressure to change from their established and standardized system towards a sustainable and zero-emission alternative. This pressure is exerted by both society and political institutions to ensure a clean, reliable, and sustainable future for upcoming generations. The transport sector is a very big actor in this change as this specific sector is responsible for 17 per cent of worldwide GHG emissions (Statista, 2022). Moreover, within the category of transport emissions, the medium and heavy duty truck are responsible for 22 per cent of this category translating towards roughly 1.6 billion metric tons of CO_2 (Statista, 2021). For this reason, this sector is able to contribute significantly to reducing global emissions and is subject to continuous research. Furthermore, alternative zero-emission technologies are actively being developed and explored to convert the fossil fuel-based transport sector. Especially for long haul transport, the future is still uncertain and a definitive drive train is not yet clear. A potentially promising technology is the hydrogen fuel-cell for heavy duty trucks due to advantages regarding driving range, refuelling time, and energy density over other alternatives such as the battery electric trucks. This thesis therefore focusses on which conditions need to be met in order to successfully implement the use of HFC-HDTs within the European Union. Accordingly, the main research question central in this thesis is:

Under which conditions can hydrogen fuel-cell heavy duty trucks be successfully adopted for long haul transport within the European Union?

The current research available to assess a new technology or innovation such as the HFC-HDTs, is quite general and not specified for particular technologies. An example of this is the framework of Feitelson and Salomon (2004), which is used in this research as a base for developing a success and fail factor framework for the implementation of HFC-HDTs. With this as the base, the sub research questions were developed and answered. These are divided into four main categories, namely: current developments, technological factors, economic and societal factors, and political factors. To answer these sub questions, the main research method was literature research of mostly scientific literature. However, especially for the current developments regarding hydrogen and HFC-HDTs grey literature was used as well. In turn, these were supplemented with case studies on HFC vehicle pilots. Out of the findings from this, a framework is developed. This framework is one of the main products of this thesis and can be used by decision makers as a tool for assessing their options. The eight chapter of this thesis serves as a test for the identified factors and framework, which portrays the most impactful factors on the implementation of HFC-HDTs. It tested this by using the learning curve equation to calculate the course of production cost over a period from 2020 up to and including 2050 in different scenarios.

As mentioned above, a SFF framework was developed as one of the main products of this thesis, this framework can be seen in figure 1. The SFF framework follows the same principles as the sub research question as to the categories mentioned above. These are colour coded within the framework itself; yellow for current developments, blue for technological factors, red for societal, environmental, and economic factors, and purple for the political factors. Within the framework, the blocks represent the factors and the arrows dictate the direction of the relation between the factors. Some of the factors only have an effect on other factors such as environmental awareness, sustainability, and alternative powertrains. These do have significant impact on the implementation of HFC-HDTs but are considered to be indirect. On the other hand, there are also a great number of factors which have a direct effect on the implementation of HFC-HDTs, or a combination of indirect and direct effect. As can be seen in the framework, one factor with a lot of relations is "policies and regulations", the notion that it has a lot of relations shows the importance of policies and regulations on the success of HFC-HDTs.

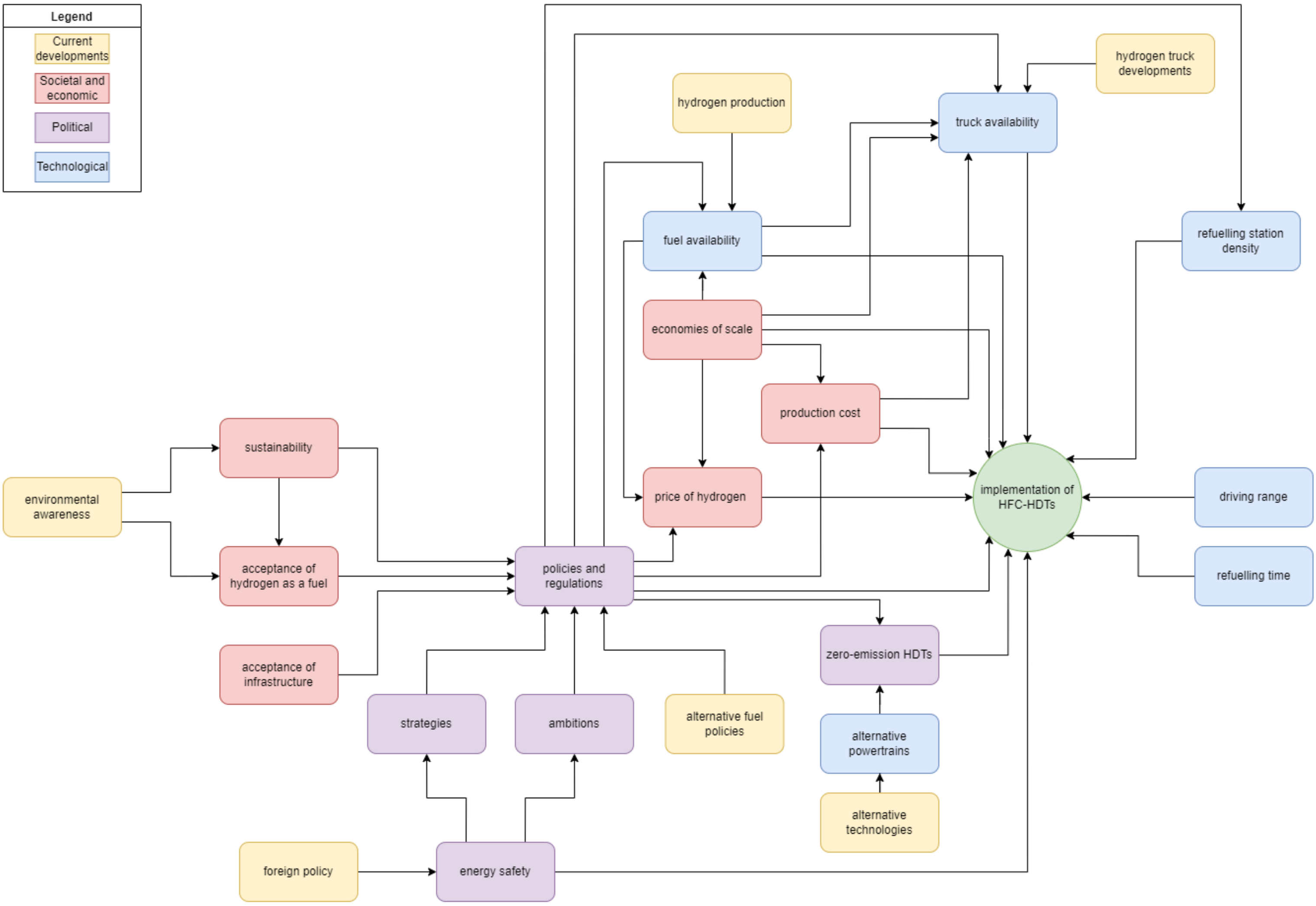

Figure 1 - final SFF framework for the implementation of HFC-HDTs

After the development of the SFF framework, the following chapters focus on the individual categories. Besides the current developments, where the main findings suggest that many facets of HFC-HDTs and the accompanying infrastructure are still being actively researched. One important aspect is the production, where new methods are being developed but are not yet operational on a larger scale. This means that hydrogen production is currently relying on fossil fuel-based steam methane reforming. Regarding the technological factors, the main findings from this chapter are considered to be the trucks themselves and their needed infrastructure together with the availability of fuel and the potential threat of alternative powertrains on the success of HFC-HDTs. When it comes to economic, social, and environmental factors, this thesis identified that the acceptance of a new technology can have a great impact, and that the main drivers for investors are the overall costs of a technology which in this case include the cost of the truck but also the hydrogen itself and other accompanying expenses. Lastly, within the chapter examining the political factors, the main finding is that policies and regulations are incredibly important when it comes to the success of HFC-HDTs.

The framework in figure 1 is tested and used with the help of the learning equation, which is used to calculate the expected production costs of HFC-HDTs in different scenarios and perspectives. The LRs are based on literature and are between 11 per cent and 18 per cent. The perspectives are however based analyses and deductions from the SFF framework which led to the assumptions shown in table 1.

Table 1 – shortened overview of the different assumptions made for the perspectives ranging from very negative (- - -) to neutral (- / +) to very positive (+ + +) in relation to the adoption of HFC-HDTs

Factor	Pessimistic	Neutral	Optimistic
Acceptance of hydrogen as a fuel	- - -	+	+ + +
Acceptance of infrastructure	- -	- / +	+
Policies and regulations	- - -	- / +	+ + +
Hydrogen production	- -	+	+ + +
Fuel availability	-	+	+ +
Economies of scale	- - -	-	+ +
Price of hydrogen	- -	+	+ +
Zero-emission HDTs	- - -	-	+ +
Truck availability	-	+	+ + +
Refuelling station density	- - -	-	+ +

The calculations resulted in the graph from figure 2 which portrays the worst and best case regarding the production cost. Important to note is the grey line at €100k which is the current purchasing price of diesel HDTs and is used as a reference point. Furthermore, the production costs of HFC-HDTs might continue to decrease beyond that mark, the purchasing price of HFC-HDTs will most likely not as it seems that operators are willing to pay this price for HDTs. Furthermore, this competitiveness mark is achieved between 2035 and 2040 for the best case which means a significant period of HFC-HDTs needing strong incentives to be used by operators. This period of not being competitive and need of incentives further emphasise the need for strong policies and regulations promoting the use if HFC-HDTS.

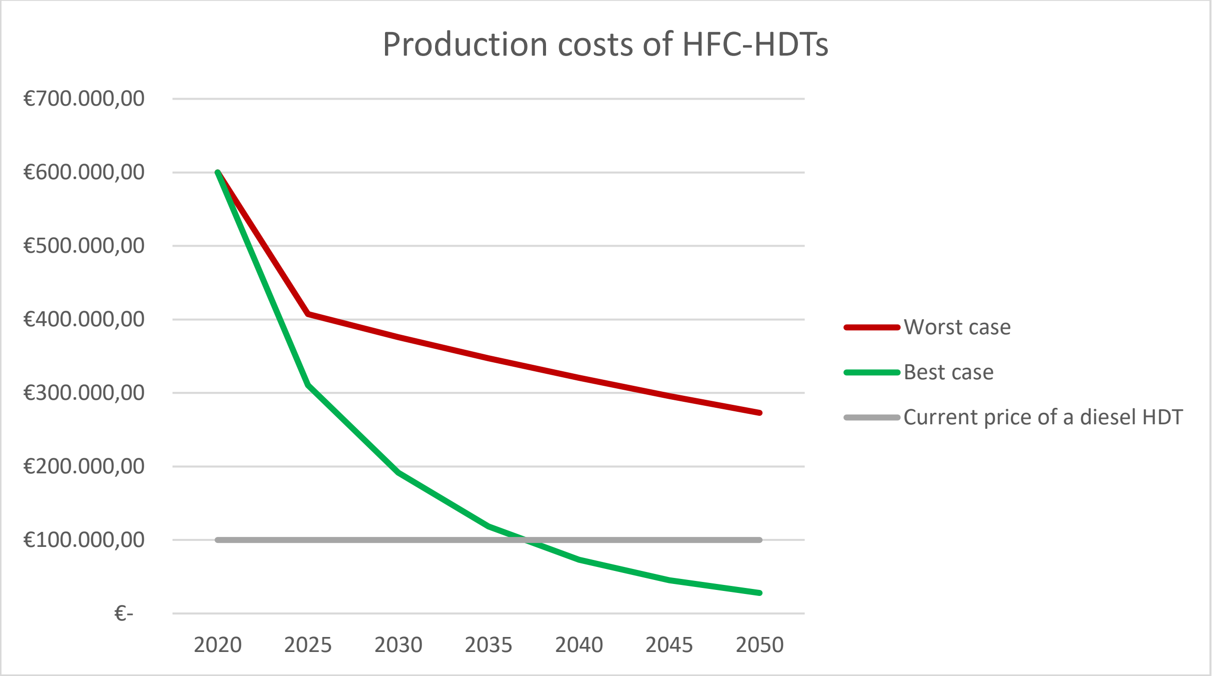

Figure 2 - worst case (LR of 11% and annual growth of 10%) and best case (LR of 18% and annual growth of 40%) for the production cost development of HFC-HDTs

Some of the factors or conditions are absolutely necessary in order to even implement HFC-HDTs, even on a smaller scale. This is the case for most of the technological factors within the framework. For example, the fuel availability, truck availability, and refuelling station density. If any of these three factors are considered very negative, as in there is either not enough fuel, trucks, or HRSs there will not be enough incentive to use HFC-HDTs over other technologies.

All in all, it seems that HFC-HDTs do have a viable future if the conditions of the neutral or optimistic perspective, as described above, are met in the foreseeable future. Furthermore, the EU and national governments of its member states should incentivise the use of HFC-HDTs, especially until competitiveness is reached. The first step towards the implementation of HFC-HDTs is the continuation of pilots and projects backed by the EU and other governmental bodies which aim to test HFC technologies and develop standardized protocols for the use of this technology in HDTs. however, the EU should consider to expand on their current plans and ambitions in order to accelerate the development of HFC-HDTs which would help reach zero-emission transport faster. Additional but necessary incentivisation should be done using different tools such as taxing emission emitting HDTs and coupling the proceeds of these taxes on subsidies for operators purchasing HFC-HDTs. Moreover, additional funds should be allocated to subsidise more aspects of a hydrogen fuel network such as the sustainable production of hydrogen and the construction of a refuelling infrastructure. These measures would in turn ensure sufficient truck and fuel availability which would make it viable for operators to opt for HFC-HDTs instead of other alternatives.

Interesting notions for further research could be conditions which are deemed to be absolutely necessary as mentioned above. This basic infrastructure needs to be researched sufficiently in order to gain momentum and convince decision makers to opt for HFC-HDTs. Furthermore, the developed SFF framework could be limited due to the scope of this research. This could be a great starting point for further researchers to build upon. This can for example be done by empirically testing the framework using a survey among experts or interviews. Another interesting research opportunity is to explore individual relations from the SFF framework. A good example could be the effect that other zero-emission drivetrains have on the implementation of HFC-HDTs. In this case, the BE-HDT can become the dominant technology over HFC-HDTs in the future if its development is more beneficial. In order to ensure proper decision-making, all alternatives should be researched thoroughly.

Contents

1. Introduction

It is clear that the way we live is everchanging, especially major events such as the COVID-19 pandemic have influenced everybody. A sector which underwent a relatively big change was the transportation of goods, as online shopping has increased (UNCTAD, 2020). Furthermore, a shortage of truck drivers within the European Union (EU) has been going on for years and seems to increase every year (Transport Intelligence, 2021). Another driver for change in the transport sector is the threat of climate change, which calls for a shift from established fossil fuel-based transport methods to transport methods which make use of sustainable energy (electric, hydrogen, etc.). With the pressure from societal organisations and governmental bodies, which push towards sustainable transport modes, the relevance of this issue is clear as well. This problem can be regarded as a socio-technical issue as it touches on technical development as well as on societal changes. Furthermore, a lot of different actors are involved for both the development and the operational side.

The transport sector is a big player when it comes to GHG emissions, being the second biggest emitting sector after the energy sector with 17 per cent of worldwide GHG emissions (Statista, 2022). More specifically, medium and heavy duty trucks are responsible for 22 per cent of the worldwide transport emissions, which calculates to roughly 1.6 billion metric tonnes of CO_2 (Statista, 2021). Within the EU specifically, transport emissions should be reduced by 90 per cent by 2050. Hydrogen has been marked as one of the priority areas by the European Commission when it comes to realising this goal (European Commission, 2019). The medium and heavy duty trucks are thus responsible for roughly 3,75 per cent of global GHG emissions and should be considered as an important factor in a more sustainable economy.

Multiple different methods can be used in order to make HDTs more sustainable. In this specific research, hydrogen fuel-cell HDTs will be researched and the factors which influence its success in the EU. Moreover, a lot of developments are happening at the same time in the transport sector which need to be considered, albeit technological, societal, or political. Alternatives for the conventional internal combustion engine trucks, mainly run on diesel, are rapidly developing which all has an influence on the success of hydrogen fuel-cell HDTs.

Problem statement

As mentioned before, one promising innovation regarding truck transport over longer distances are hydrogen trucks, but a lot of different factors influence whether such a new source of fuel will be successfully adopted or not (Peters et al., 2021; Walker, 2021). Many different types of factors play a role as well, Feitelson and Salomon (2004) developed a framework in which technical, economic, social, and political feasibility are the main focal points. This framework displays how adoption of a technology is not simply reliant on how well it performs on a technological level, or how much support there is amongst political actors. It rather states that it is a combination of factors with interconnecting relations towards each other, and a combination of factors can lead to either successful implementation or a failed innovation. Moreover, the technology acceptance model of Davis (1989) looks at the perceived usefulness and ease of use for example. This model states that the more social or even practical components can play a big role in the adoption of a certain innovation. The aforementioned theories and frameworks are great tools to assess new technologies, but they logically are not specified to a single case such as HFC-HDTs. Therefore, these theories and frameworks are used a basis for this particular research. They provide very useful insights into the different perspectives for the evaluation of HFC-HDTs. Furthermore, these theories proof that it is not just technical feasibility which determines the successfulness of an innovation but rather a complicated web of different factors and aspects. Additionally, it is important that the right analyses are performed due to long term effects and the big investments required for a technology shift such as this. It is however the case that for HFC-HDTs there is not a lot of research done on this broader perspective on the adoption of HFC-HDTs. The framework of Feitelson and Salomon (2004), is therefore used as a basis in this research to examine the success and fail factors regarding HFC-HDTs, and thus under which conditions it can be successfully implemented for long haul transport within the EU.

Research scope

As mentioned in the section above, it is currently not possible to give a definitive answer to whether hydrogen trucks will be implemented in the future. Thus, the scope of this research will focus on, which conditions are necessary for hydrogen fuel-cell HDTs to be adopted for long haul transport from a broad perspective. To be more specific, the success and failure factors are examined and weighed against each other and developments in the market. The scope of the research is of great importance as well, as already stated the geographical scope will entail the EU, and the segment of the market will be the long-distance transport. The reasoning for the focus on the EU is that there is a relatively well developed infrastructure regarding the road network, and they have shown extensive ambitions when it comes to new technologies and innovations in, amongst others, the transport sector (European Commission, 2020b).

Knowledge gap

In the current literature there seems to lack a consensus on whether hydrogen fuel-cell HDTs will be adopted in the long-haul transport market. Furthermore, it is also not uniformly clear as to what factors actually are important for the success or failure, and the significance of those factors related to each other as well. Research of certain aspects such as technical possibilities is available, however there does not seem to be analyses focussed on a multi-perspective view. Moreover, it is possible that different technologies, such as hydrogen and all-electric, co-exist in the same system. In the current literature, the technologies are often portrayed as one or the other, whilst a combination of powertrains is possible as well and should be discussed. In the following chapter, the conceptual model, a preliminary literature study is done which enforces the existence of the abovementioned knowledge gap. Furthermore, a framework is developed which entails all the factors found in this research and their relations towards the adoption of HFC-HDTs.

Research question

It is clear that hydrogen has potential to function as a fuel for HDTs, and greatly decrease the emission of GHGs in the transport sector. However, the lack of consensus on whether it will be successful and can be implemented is the cornerstone for this research. This thesis aims to provide a clear answer as to which conditions are necessary for a successful implementation of a hydrogen fuel-cell HDT system for long haul transport within the EU. This translates into the following main research question:

Under which conditions can hydrogen fuel-cell heavy duty trucks be successfully adopted for long haul transport within the European Union?

The main research question is further divided into smaller sub-question, these sub questions assist in making the research more clear and understandable. These sub-questions mainly focus on the main categories of influential factors on the implementation of HFC-HDTs. To do this, in the third chapter, a success and fail factor (SFF) framework will be presented which portrays factors identified in this whole thesis. This framework is a tool to get an overview of all the possible factors, either positively or negatively, which influence the implementation of a new innovation as well as the relation between these factors as well. After this framework, the following chapter will go into further detail for the separate categories, namely: current developments, technological factors, economic and societal factors, and political factors. Lastly, the framework is used in combination with the learning curve equation to calculate different scenarios and perspectives regarding the production costs of HFC-HDTs up to and including 2050.

The first sub research question is focussed on developing an SFF framework as described above. This framework will portray the most important factors found in scientific literature, obtained as described in methods chapter. The SFF framework suggests that it is not a simple cost benefit ratio which determines an innovations success but rather a combination of economic, technical, social, and political feasibility (Feitelson & Salomon, 2004). Therefore, the first sub researched question to be looked into is:

1. Which factors have an effect on the implementation of hydrogen fuel-cell heavy duty trucks?

Secondly, as mentioned above, the SFF framework is divided into different categories. The second sub question is focussed on the current developments when it comes to the HFC-HDT and its alternatives. Therefore, the second sub question is:

2. What is the current state of developments regarding hydrogen fuel-cell heavy duty trucks, and its alternatives?

This sub question is focussed on the current system in place and the possibilities which are offered by making use of hydrogen fuel-cell heavy duty trucks. This includes the readiness of the trucks itself, but also the already existing infrastructure when it comes to hydrogen fuelling stations, hydrogen generation, costs, etc.

The third sub question building on the previous acquired knowledge is:

3. Which technological and technology related factors play a role in success or failure of hydrogen fuel-cell heavy duty trucks, and if the technology will be adopted?

As mentioned before, the SFFs will be divided up in different categories. This sub question will specifically look at possible factors which are of a more technical nature. Findings from the previous sub question will be taken into account and expanded upon when necessary. An important thing to note, it is not just the technical factors directly linked to of hydrogen fuel-cell heavy duty trucks, but also indirect technologies necessary for those trucks to operate.

sequentially, societal, environmental, and economic factors are examined in order to get a complete picture of all the different factors which can influence a technological innovation such as the hydrogen fuel-cell heavy duty trucks.

4. What societal and economic factors play a role in the adoption of hydrogen fuel-cell heavy duty trucks?

Fifthly, after having gained technical and societal knowledge, it is important to know how external actors, such as national governments or the EU, can influence the transport system. Therefore, the fifth sub question is focussed on that, namely:

5. How do institutional, political, and governmental bodies affect the success or failure of hydrogen fuel-cell heavy duty trucks?

Sixth and last, with all the gathered knowledge from the previous chapters, and the SFF framework, different perspectives are developed. These perspectives are a set of conditions which are used as a base for learning curve calculations for different scenarios regarding production costs of HFC-HDTs. These calculations will be used to answer the sixth sub question which is as follows:

6. Under which conditions will hydrogen fuel-cell heavy duty trucks be affordable and competitive with conventional trucks in the foreseeable future?

When all of the sub questions are answered, then the main research question can be worked out and the factors influencing the success of hydrogen fuel-cell heavy duty trucks can be determined. This will in turn provide a thorough conclusion regarding the feasibility and future of hydrogen trucks from a system perspective.

Research structure

This first chapter serves as an introduction in which the problem statement the scope, and the research questions are presented. In short, the further research will follow the structure of the sub research questions as mentioned din the section above. However, this section will provide a more detailed overview of the general structure and outline of this thesis.

Firstly, the next chapter is dedicated to the methodology used for the research, which is separated into theoretical research and empirical research. An overview is given as well in a research flow diagram which divides the types of research sources and the sub research questions. Following, in the third chapter the conceptual model is developed. The framework developed in this chapter is one of the main products of this research as the framework will show the factors influencing the adoption of HFC-HDTs. Furthermore, this framework portrays a clear and complete overview of the SFFs for this specific technology. The following three chapters are detailed studies separated into different categories as classified by the sub research questions, namely: technological factors, societal and economic factors, and political factors. Within these chapters, the current developments regarding that specific category is researched and discussed as well. In the conclusions of these chapters a magnified section of the framework is portrayed containing the factors of that category with further explanations. In the seventh chapter “learning curve and scenarios” will focus on one factor in particular namely, the production costs of a HFC-HDT. Within this chapter, perspective analyses are done using the SFF framework as a base. This is supported by different scenarios regarding the potential learning rates. This will result in different possible futures for the course of production costs of HFC-HDTs. These possible futures will be calculated and modelled based on the findings from the previous chapters and the SFF framework.

Consecutively , the findings will be discussed in the conclusions section where the main findings are presented. Lastly, within the discussions section, the main limitations of this research are specified, and further research opportunities are given.

2. Methodology

In this section, the methodology of acquiring data and knowledge in order to answer the abovementioned main and sub research questions. Firstly, a research flow diagram is presented to create a clear overview of the main research methods. After this, a more detailed analysis of the specific methods is given.

Research design

In order to get a clear overview of how this research is set up, a research flow diagram is presented in figure 3. It provides a simplified overview of the steps taken in order to be able to answer the research questions. As can be deducted from the figure, the knowledge flows from each sub question into a well thought out conclusion about the future of a hydrogen HDT system in the EU. The main deliverables are indicated in green and are the main objective of the different chapters in this research. As can be seen in the white boxes, the sub questions form the basis of the deliverables and are the main driver behind this research in general. Underneath the white boxes containing the sub research questions, there are yellow boxes which indicate the main types of data sources which will be used to answer the questions. These types of sources are further explained underneath the figure. The arrows in the figure illustrate the direction of the knowledge flow. This shows that the knowledge acquired within each deliverable is used as a basis for the following deliverables and the empirical adoption scenario calculations. Eventually, this research results in new knowledge about HFC-HDTs from a system perspective, and what is necessary for successful implementation.

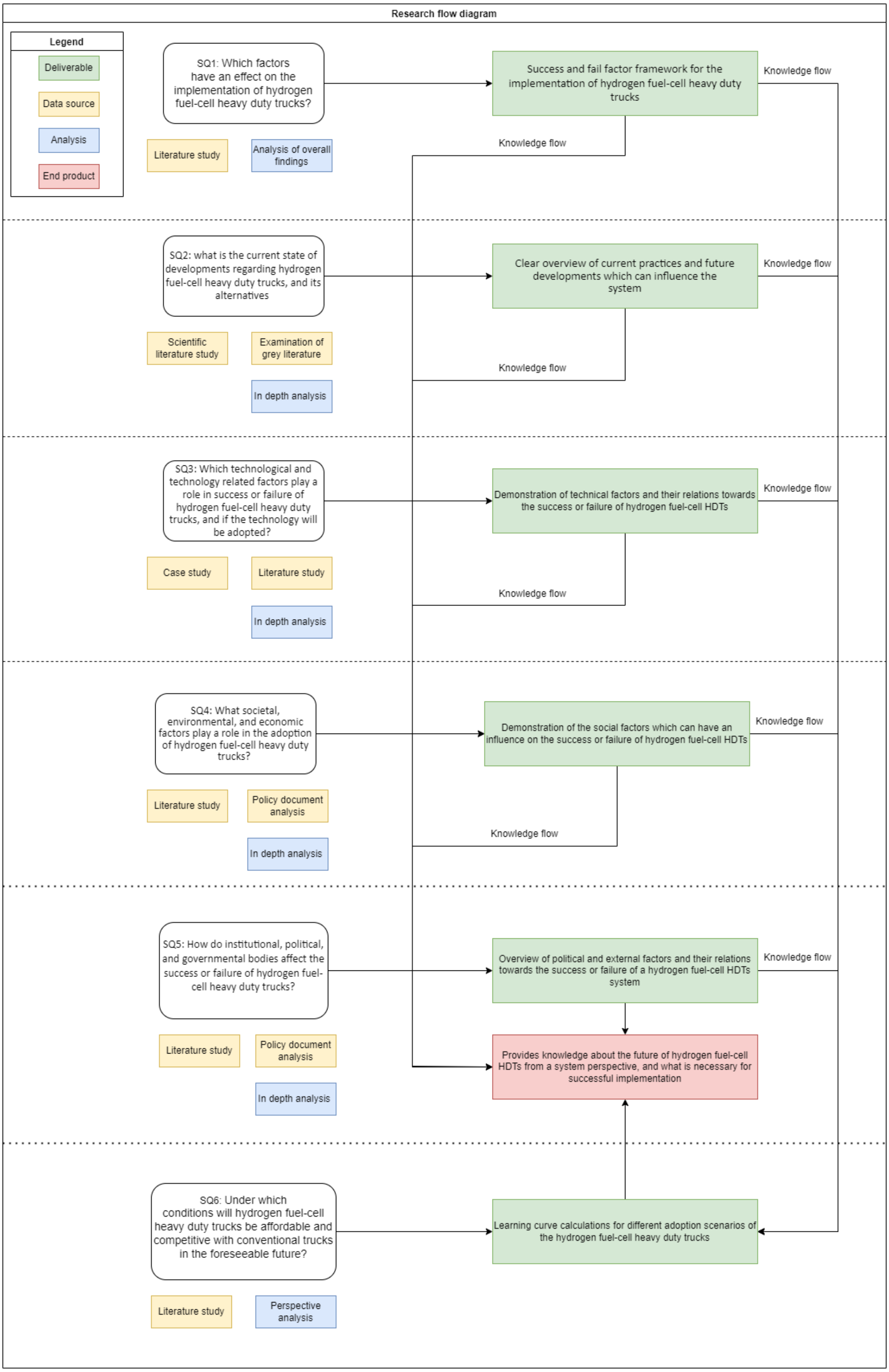

Figure 3 - research flow diagram

Literature research

The main research method in this research is the literature research, this literature consists of either scientific literature or grey literature, discussed in the next section. However, the main bulk will consist of scientific literature. This is literature is peer reviewed and published in scientific journals. Due to the nature of this research and the multi-perspective view, there is no definitive type of journal in which this research is focussed, but rather a multitude of journals from different research fields, e.g., the journal "*Renewable and Sustainable Energy Reviews*" in which research is published focussed mainly on new technologies in renewable energy and sustainability or "*Research Policy*" where studies more related to policy, management, and ecomics of technologies are published. The search queries used for this research range from more general queries to more specific queries containing definitve technologies or aspects. Table 1 displays the used search terms, the corresponding sources, the database where the sources was obtained, a short description of the article, and, if applicable, the relation to the SFF framework developed in this thesis. All the search terms were entered in both ScienceDirect and Google Scholar and were sorted by relevancy. Furthermore, the publishing date of the article was evaluated as well in order to ensure the most up to date knowledge was used to support the argumentation in this thesis, with some exceptions for certain established theories and findings. Not all sources used are in the table due to using the snowballing technique to find more sources. This is a technique in which new sources are found by using the references within an initial source. Furthermore, another tool used to obtain more sources is a function by ScienceDirect, this function recommends new articles based on the current article and reading history.

Table 2 - overview of search terms, entered into ScienceDirect and Google Scholar, with corresponding source, database, short description, and relation to the SFF framework (if applicable)

Search term	Source	Database	Short description	Relation in SFF framework
Decarbonization of trucks	(Nykvist & Olsson, 2021)	ScienceDirect	Feasibility of BE-HDTs, where economic feasibility seems generally underestimated by previous research	U, T, S
Electrolysis hydrogen	(Ursua et al., 2012)	IEEE Xplore	Description of electrolysis process with advantages, drawbacks, and challenges	M
	(M. Wang et al., 2014)	ScienceDirect	Developments in water electrolysis based on renewable sources	A1, C, M
Energy security EU	(Gökgöz & Güvercin, 2018)	ScienceDirect	Vulnerability of the EU regarding energy security, also in relation to renewable sources	F, H1, H2, G, I
	(Matsumoto et al., 2018)	ScienceDirect	Historical development of energy security in the EU and how diversification of sources can assist	G, I , J
	(Jonsson et al., 2015)	ScienceDirect	Increasing prominence of energy security interests in the EU strategies	F, H1, H2, G, I, J, K

Heavy duty trucks	(Anderhofstadt & Spinler, 2019)	ScienceDirect	Delphi study on different factors influencing new powertrains for HDTs including barriers	T, U,
Hydrogen economy	(Bossel, 2006)	IEEE Xplore	Due to the lack of efficiency of HFCs, a hydrogen economy seems unrealistic as it cannot compete with electricity	
Hydrogen economy policies EU	(Bleischwitz & Bader, 2010)	ScienceDirect	Examination of EU policy framework concerning hydrogen, no hinder but also no significant push	L1, L2, L3, L4, L5, L6
	(Demirbas, 2017)	Taylor & Francis Online	Advantages of a hydrogen economy, investment dilemma and implications for policymakers	P1, P2, P3, L6, N1, N2
Hydrogen fuel cell	(Machado et al., 2022)	ScienceDirect	Comparative analysis of BEV, FCEV, and FCHEV, including technology itself and infrastructure	S, T, U, W, X, Y, Z
Hydrogen fuel cell case study	(Coleman et al., 2020)	ScienceDirect	Case study on implementing HFC or BE busses in Germany	
Hydrogen fuel cell trucks	(Çabukoglu et al., 2019)	ScienceDirect	Swiss case study on the potential of HDT-HFCs, showing great potential when using green hydrogen	S
	(Cullen et al., 2021)	Nature Energy	Review of roadmaps concerning the outlooks of using hydrogen in road transport	
	(Cunanan et al., 2021b)	MDPI	Comparison of the three main powertrains and future perspective of HDTs	T, U
	(Lee et al., 2018)	ScienceDirect	Life cycle comparison of HFC-HDTs and the conventional diesel HDTs	U, Y, Z
	(Liu et al., 2020)	Springer	Requirements for a widespread refuelling infrastructure and cost competitiveness of HFC-HDTs	O1, O2, Q1, Q2, R, X

	(Q. Wang et al., 2020)	IEEE Xplore	Comparison of gaseous and liquid hydrogen storage for fuel applications	
Hydrogen fuel economic prospects	(Ajanovic & Haas, 2018)	ScienceDirect	Economic prospects of hydrogen as a fuel, including learning effects and dependency on policies	Q1, Q2, L6
Hydrogen fuel prospects	(Moriarty & Honnery, 2019)	ScienceDirect	Superiority of hydrogen when used for freight transport but not for passenger transport	Y, Z
Hydrogen heavy duty transport	(Farrell et al., 2003)	ScienceDirect	Strategy to introduce FCEVs, HDTs seem to be the best method for technical and environmental gain	C, L2, L5, L6
	(Yaïci & Longo, 2021)	American Society of Mechanical Engineers	Feasibility analysis on HRSs and the cost of the hydrogen fuel compared to diesel	L1, L4, R, O1, X
Hydrogen production	(Dincer & Acar, 2015)	ScienceDirect	Examination of methods of hydrogen production, both renewable and non-renewable, comparison of environmental impact, costs, etc.	A1, C, M, O1, O3,
Hydrogen production costs electrolysis	(Guerra et al., 2019)	ScienceDirect	Cost analysis of hydrogen, produced by electrolysis, under different conditions	A1, C, M, O1, O3
hydrogen production electrolysis	(Chen et al., 2022)	ScienceDirect	Renewable hydrogen electrolysis and the use of catalysts with future perspectives	M
hydrogen production electrolysis percentage	(Cavaliere et al., 2021)	MDPI	Description of the state of water electrolysis technologies	M
Hydrogen storage	(Barthelemy et al., 2017)	ScienceDirect	Hydrogen storage technologies and their performance under different conditions	
	(Rivard et al., 2019)	MDPI	Hydrogen storage methods specific to mobility applications	

Hydrogen storage refuelling stations	(Apostolou & Xydis, 2019)	ScienceDirect	Developments regarding HRSs and infrastructure with necessary investments	X, P1, P2
	(Dagdougui et al., 2018)	ScienceDirect	Book chapter on deployment of HRSs and their supply chain	X, Y
Hydrogen transport Europe	(Tlili et al., 2019)	ScienceDirect	Market entry feasibility for hydrogen in mobility with requirements	
	(Steen, 2016)	ScienceDirect	Book chapter on the deployment of a hydrogen infrastructure in the EU	X
Hydrogen versus battery electric truck	(B. Bree et al., 2010)	ScienceDirect	Multi-level analysis on adoption of HFC or BE HDTs	
Incentives for hydrogen fuel cell trucks	(Staffell et al., 2019)	Royal Society of Chemistry	Role of hydrogen in the future energy system, and the necessity of policies in order to make it competitive	L6
Increasing efficiency hydrogen trucks	(Kast et al., 2018)	ScienceDirect	Examination of specifications and standards of HFC-MHDTs	
	(Gray et al., 2021)	ScienceDirect	Comparison of different potential zero-emission alternative powertrains	S, T, U
Large scale hydrogen production	(da Rosa & Ordóñez, 2022)	ScienceDirect	Book chapter on the different hydrogen production methods	M, O1, O3
	(Navarro et al., 2015)	ScienceDirect	Book chapter on production of hydrogen from biomass	M, O1, O3
Learning rate hydrogen fuel cell	(Ruffini & Wei, 2018)	ScienceDirect	Life cycle cost analysis of FCEV with different learning rates	
Life cycle hydrogen fuel cell	(Ahmadi & Kjeang, 2017)	Wiley online library	Life cycle analysis of FCEVs compared to conventional vehicles when it comes to GHG emissions and costs, and potential FC improvements	A1, C, Q2, R
Rigidity of EU environmental policies	(Deters, 2019)	Wiley Online Library	The course of flexibility in the EU when it comes to decision on environmental policies	G, I

Safety measures hydrogen trucks	(Pagliaro & Iulianelli, 2020) (Ahluwalia et al., 2023)	General Chemistry ScienceDirect	Study on different accidents at HRSs including future safety recommendations On board hydrogen storage specifications based on safety and other requirements	
Social acceptance hydrogen fuel cells	(Oltra et al., 2017)	Utrecht University Repository	Importance of social acceptance of HFCs, and the knowledge among the population about HFCs across multiple countries	A2, B, D, E
Sustainable hydrogen production	(Chen et al., 2022)	ScienceDirect	Developments and advancements in water electrolysis for hydrogen production	O3
Technology acceptance model Davis	(Davis, 1989)	JSTOR	The technology acceptance model developed by Davis on perceived usefulness, perceived ease of use, and user acceptance	D, E
Thermochemical production hydrogen	(Steinfeld, 2005)	ScienceDirect	Technical advances in production of hydrogen from solar thermochemical production	M

Grey literature

In order to get a good overview of "current developments" regarding hydrogen use in transport and HFC-HDTs, grey literature will be used beside the abovementioned scientific literature. This is mainly because the current developments regarding pilots or new technologies are reported by journalists and posted on news sites, blogs, company sites, and other such sources. Furthermore, certain developments, especially ongoing pilots and projects are not necessarily available in scientific literature but are widely reported in different grey sources. This is partly due to the faster publication of grey literature over the more time consuming publication of scientific literature. Moreover, the grey sources have provided further sources by reference, and knowledge on which search terms to use for both new grey sources and scientific sources. Table 2 displays an overview of the most important grey sources with the search terms used, the corresponding sources, a short description, and the relation to the SFF framework if applicable. The search queries were entered in both the regular Google search engine and the Google News search engine. Some report and papers were obtained from Google Scholar as well.

Table 3 - overview of used search term with corresponding source, short description, and relation to the SFF framework (if applicable) (search engine used: Google, Google News, and Google Scholar)

Search term	**Source**	**Short description**	**Relation in SFF framework**
Alternative Fuels Infrastructure Directive	(European Union, 2014)	Document on potential implementation of new infrastructure and their requirements	X
Costs hydrogen heavy duty truck	(Sharpe & Basma, 2022)	Working paper on the costs of different zero-emission trucks	Q2
EU road sustainability ambitions	(European Commission, 2020b)	Strategy report on the future ambitions of the EC concerning sustainable road transport	L1, L2, L3, L4, L5, L6, L7
Global trend environmental awareness	(Lampert et al., 2019)	Report on the increasing trend of environmental awareness	A1, A2
Hydrogen fuel cell trucks economics	(Burke & Sinha, 2020)	Research report on which market is suitable for BEVs or FCEVs regarding technical, economic, and operational factors	
Hydrogen heavy duty transport	(Borbujo et al., 2021)	Conference document on the EU Green Deal and the role of BEVs and FCEVs	L7
	(Hydrogen council, 2020)	Cost perspective study for competitiveness of hydrogen with recommendations for policies and investments	L4, L6
Hydrogen strategy EU	(European Commission, 2020a)	Strategy document on specific steps towards implementing hydrogen in the EU energy market	L1, L2, L3, L4, L5, L6
Hydrogen transport Europe	(Zhou & Searle, 2022)	White paper by the icct on hydrogen costs under different conditions e.g., with a subsidy	M, O3, L6,
Hydrogen truck manufacturer (+brand)	(DAF, 2022; Hyundai Motor Company, 2022; Hyzon, 2021; Toyota, 2022)	Description of developments regarding current and future HFC-HDTs by DAF, Hyundai, Hyzon, and Toyota	V

Hydrogen trucks pilot	(DHL, 2021)	Announcement of first use of HFC-HDTs by DHL in the EU	V
Incentives for hydrogen trucks	(Adler, 2022)	The effect of incentives on the price of HFC-HDTs	L2, L5
Increasing efficiency hydrogen trucks	(Collins, 2022)	Article on benefits of hydrogen over electric trucks	U,T
Long haul transport hydrogen	(Walker, 2021)	Advantages of using hydrogen in LH transport over electric trucks	T, S
Purchasing cost hydrogen trucks	(Cebon, 2022)	Opinion piece from professor Cebon on HFC-HDTs versus BE-HDTs where BE-HDTs are expected to be dominant	U,T
Refuelling time hydrogen trucks	(FuelCellsWorks, 2021) (H2 Mobility, 2021)	Characteristics of HFC-HDTs Report on hydrogen refuelling infrastructure	Y, Z,V X,Z
Transportation emissions	(Statista, 2021) (Statista, 2022)	Statistics on global CO2 emissions by the transportation sector Facts on global transportation emissions	A1, A2
Truck fleet EU	(ACEA, 2021a) (ACEA, 2021b) (ACEA, 2022)	Size and distribution of EU vehicle fleet Fact sheet on trucks in the EU Share of alternatively powered vehicles in the EU	V

Case studies

Within this research, certain case studies will be used to assess the technological advancements. For example, there are certain ongoing projects and pilots within the EU in which certain tests are done on HFC-HDTs or hydrogen production. The insights of these ongoing cases can determine certain technological aspects such as the ideal pressure of the hydrogen to be used as a fuel or the driving range. Other case studies will give insights into the safety, technical feasibility, or social acceptance of this technology. One of the case studies which could provide useful insights is the case study done by Ricci et al. (2008) which gives insights into public perception and acceptance of using hydrogen as a fuel. Another possibly useful study is the article of Aguilera and Inchauspe (2022) which uses the hydrogen industry in Australia to assess technical factors, economic factors, and polices. For more technical insights, the case study on the German Rhine-Main area done by Coleman et al. (2020) can prove to be useful. This study is done on the implementation of hydrogen fuel-cell busses in the area and how the hydrogen production can meet demand and be optimized for the costs. Furthermore, additional case studies will be looked into during the research process in the upcoming chapters.

Policy document analyses

In order to answer the fourth sub research question, "how do institutional, political, and governmental bodies affect the success or failure of hydrogen fuel-cell heavy duty trucks?", policy documents are examined. These are documents mainly published by the EU, EC, or national governments. Within this category different types of documents are used such as directives, regulations, and ambition documents. In this particular case, the bulk of the policy documents consist of directives. Directives are legislative acts which set a goal for all the member states, but it does not state how a member must achieve this goal, member states have to formulate their own laws to ensure they achieve the goal set in the directive. Regulations are often the step after directives, they are binding legislative acts which apply to all the member states and must be abided (European Union, 2023). Ambition documents are way less definitive and as the name suggests ambitions for the future. These often contain goals such as climate neutral transport and consist of preliminary research on methods for reaching a goal without being a concrete legislative tool. Furthermore, these ambition documents are often in cooperation with other institutions or organizations which are active in the required research field.

Learning curve calculation

In order to empirically test the results of this research, the learning curve equation is used to calculate the expected production cost of an HFC-HDT in different scenarios, based on a set of factors found in the research. This equation can be used to examine new technologies and provide empirical insights into cost as a function of cumulative produced units or experience (Ruffini & Wei, 2018). The equation and results will be discussed in chapter 8, "Learning curve and scenarios". The learning curve portrays how, in this case, the HFC-HDTs will decrease in production cost over time. This in turn can be used as an additional factor regarding the successful implementation of HFC-HDTs as the production costs need to be competitive with the current dominant technology and the other future alternatives for heavy duty trucks. Within the chapter, the calculations will be done with certain assumptions. These will be portrayed by scenarios and perspectives, the scenarios are dependent on the learning rate and will be acquired from literature. These scenarios will be combined with three different perspectives, which will be correlated to the annual market growth of HFC-HDTs, a pessimistic, a neutral, and an optimistic perspective. To get these perspectives, a perspective analysis will be done which will result in a set of conditions which define the perspectives. These perspectives will be elaborated on in the chapter itself. The combination of these scenarios and perspectives will in turn provide insight into the potential production and purchasing costs which can be one of the main drivers for some of the truck operators regarding the switch towards zero-emission HDTs. Nonetheless, calculations of future scenarios cannot be completely certain and should be used as indications instead of the complete truth.

3. Conceptual model

In this chapter, a preliminary literature review is conducted in order to grasp the different factors which can have an influence on the adoption of HFC-HDTs. After this, a simplified conceptual model is presented which serves to give a quick and clear overview of the general idea behind the eventual framework. The starting point of the framework for this research is the already established framework of Feitelson and Salomon (2004). In the feasibility framework of Feitelson and Salomon, different categories of factors are depicted in a web in which the eventual outcome is the adoption of a certain innovation. Central in this framework are the technical, social, and political feasibility. This research will follow the same structure when it comes to those main "categories". However, the abovementioned framework is quite generalised in order to apply it to almost all new technologies. In this thesis a framework will be formed based on the findings of the research which is specified to HFC-HDTs within the EU. After the mentioned simplified conceptual model, the full and detailed framework for the factors specifically influencing the adoption of HFC-HDTs is presented, which is based on the findings from the upcoming chapter which will go into great detail on the different factors.

Preliminary literature review

Central to this research are the success and failure factors (SFF) which can contribute to the future of hydrogen fuel-cell HDTs. The factors most important to this research are related to logistics and infrastructures, due to the nature of the subject. An important framework to determine SFFs is the framework of Feitelson and Salomon (2004), which considers technical, political, and social feasibility and their interrelations. By combining this framework with other key elements of other frameworks, an overall framework for this specific case can be constructed. For example, the theory behind the framework of Geels and Kemp (2007) can be used to describe the trajectory from technical niche to successful innovation with the help of similar factors as the Feitelson and Salomon (2004) framework. Within the research itself, further factors connected to the mentioned "main" categories will be examined and elaborated upon.

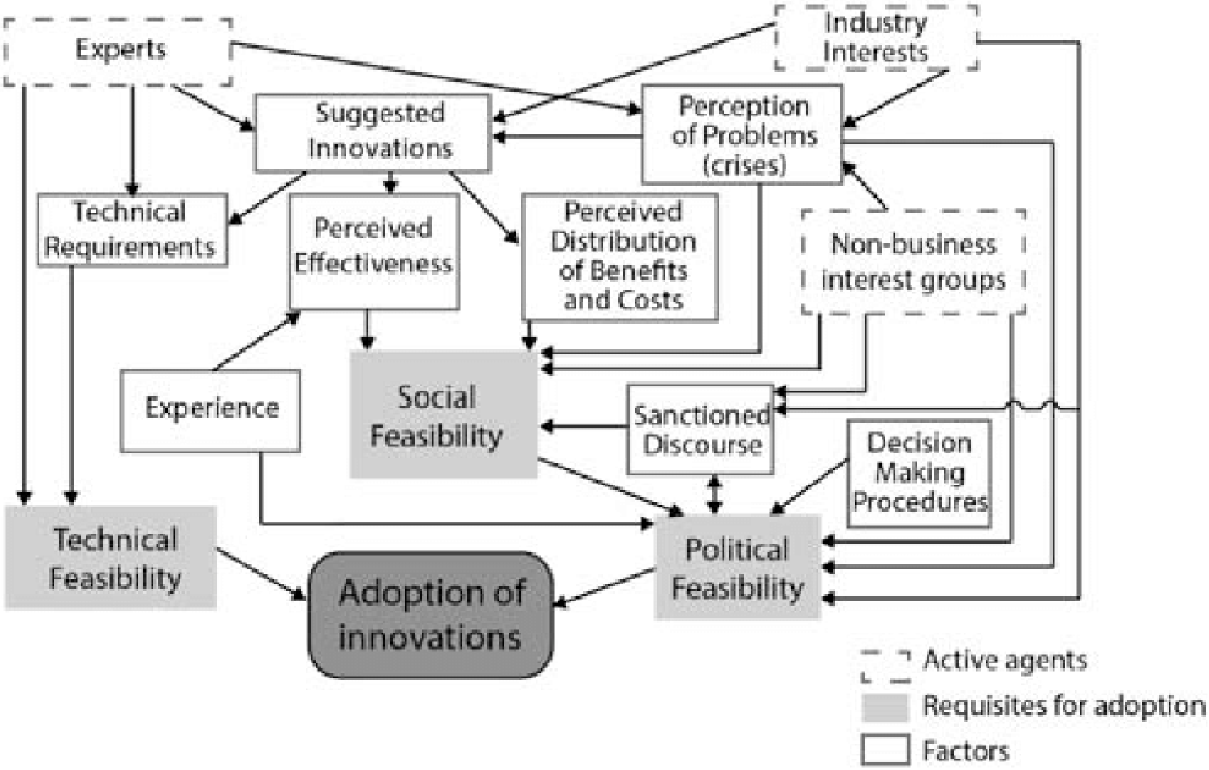

Figure 4 - feasibility framework of Feitelson and Salomon (Krabbenborg et al., 2021)

The shift towards sustainable modes of transport within Europe is a certainty, as investments and subsidies are mostly focussed on new zero-emission transport modes or making existing transport modes or infrastructures more sustainable (European Commission, 2020b; Schroten et al., 2019). This is paired with ambitious global climate goals such as the Paris Agreement (United Nations, 2021). The transport sector itself was accountable for 27% of the greenhouse gas (GHG) emissions of the EU in 2017 (European Environment Agency, 2020), meaning that it is necessary to make changes within that sector to reach the set climate goals. This because the current HDTs make use of combustion engines based on fossil fuel, mostly diesel, which is of course a finite and polluting resources.

Besides the abovementioned ambitions regarding substantial environmental factors and reasons behind a shift towards more sustainable transport modes, there are other aspects which influence the success of hydrogen fuel-cell HDTs. A reason why hydrogen fuel-cell driven HDTs might have an upper hand on other technologies is the high energy density of hydrogen, the relatively fast refuelling time, and the relatively low weight of the combustion system, compared to lithium-ion battery driven trucks for example (Cunanan et al., 2021a). There is however, still uncertainty regarding the infrastructure and hydrogen production methods necessary for HDTs based on hydrogen combustion (Forrest et al., 2020; Tsakiris, 2019). The issues regarding the infrastructure can be seen as an example of network effects, the better the refuelling infrastructure, the more companies and organisations will be willing to use hydrogen fuel-cell HDTs. Moreover, the impact of available complementary goods (e.g. refuelling stations, mechanics, hydrogen storage, etc.) will increase the indirect network effects (Murmann & Frenken, 2006).

Furthermore, other than infrastructure and energy density issues, the investments needed for the development and purchase of the trucks itself is very important as well, especially for the logistic service providers. Due to the uncertain and relatively new technologies available it is difficult to make a decision on which powertrain to use. This is paired with path dependencies, which these are characterised by people or organisations making decisions based on past decisions (Murmann & Frenken, 2006). It cannot be said with certainty whether this is definitively positive or negative for the case of hydrogen fuel-cell HDTs. This phenomena can be paired with the potential switching cost as well (Baral et al., 2021), which discourage companies from changing their main form of powertrain (e.g. from lithium-ion battery to hydrogen fuel-cell). All of the abovementioned factors have a great influence on the success, or failure, of the hydrogen fuel-cell HDTs. This results in different perspectives and thoughts about the future of long-haul road transport.

Influential factors

As mentioned above, different factors might influence the success of hydrogen fuel-cell HDTs. In order to get an overview of potential factors, a table is presented below depicting findings from scientific literature. Table 3 shows in a quick glance what factors should be taken into account when considering the future of HFC-HDTs. These factors range from technological factors such as driving range and refuelling time to economic factors such as required investments, and societal/political factors such as the social acceptance. The factors in the table are however preliminary and will be researched further in their respective chapter in order to examine their influence and relations towards the successful implementation of the HFC-HDT.

Table 4 - initial exploration of influential factors on a hydrogen transport system according to scientific literature

	Driving range	**Refuelling time**	**Infrastructure**	**Investments/costs**	**Tank/Well-to-wheel efficiency**	**Energy density**	**Zone entry/pollution reduction**	**Hydrogen production/supply chain**	**Social acceptance**	**Policies and regulations**	**Alternative powertrains**
(Liu et al., 2020)	X	X	X	X							X
(Anderhofstadt & Spinler, 2019)	X	X	X		X		X			X	X
(Apostolou & Xydis, 2019)	X	X	X	X		X		X			X
(Lee et al., 2018)	X	X			X			X			
(Yaïci & Longo, 2021)			X	X							
(Scovell, 2022)				X				X	X	X	
(Steen, 2016)			X	X	X	X		X		X	X
(Borbujo et al., 2021)	X	X	X								
(Moriarty & Honnery, 2019)	X	X	X	X						X	X
(Viesi et al., 2017)	X		X	X	X		X	X	X	X	X
(Larsson et al., 2015)	X		X		X		X			X	
(Tlili et al., 2019)		X	X	X	X			X		X	X

Simplified conceptual model

The framework of Feitelson and Salomon, shown in figure 4, is quite convoluted but generalized and cannot be easily examined in one look. It is however, clearly visible that the factors used in the framework are connected to one another via different routes, which end in the adoption of a new technology. As a steppingstone towards the eventual product of this research; an SFF framework for HFC-HDTs, a simplified model is developed which can provide basic insights into the basic variables in a quick overview.

A conceptual model can have different types of variables, with different relations to other. The two main types of variables are dependent and independent variables, other variables are moderating, mediating, and control variables. In this thesis, the main examined "categories" are identified as the variables. Hence, the variables are current developments, technological factors, societal factors, political factors, and lastly the implementation of HFC-HDTs.

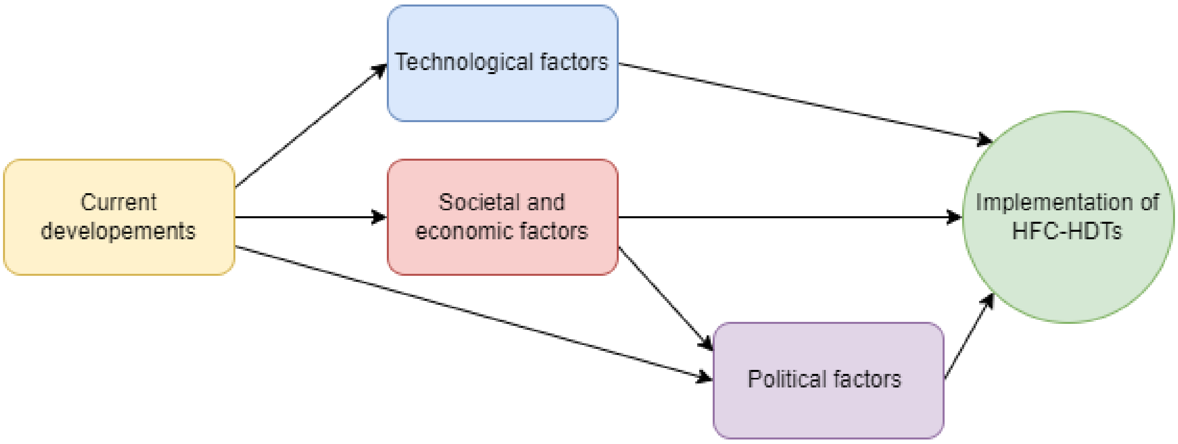

Figure 5 - Simplified conceptual model of main research focusses

Figure 5 shows the main variables examined in this particular research namely, current developments, technological factors, societal factors, and political factors. This result in the outcome which is characterized as the implementation of HFC-HDTs. In this simplified model, "current developments" is seen as an independent variable, "technological factors" and "societal factors" are defined as dependant variables, and "political factors" is classified as a mix of dependent and mediating variable. As mentioned before, this model is quite simplified as all the different aspects within the categories is not taken into account.

The starting point of this particular research are the current developments regarding the hydrogen sector and the HFC-HDT industry. These will mostly be independent from the other variables, but is not completely detached as developments do have a big impact on the technological, societal, and political factors. Regarding the relations to technological factors, current advancements in for example the production of hydrogen or the on-board storages tanks of HFC-HDTs will influence the technological factors which in turn will influence the adoption and implementation of HFC-HDTs. On the other hand, certain developments currently made will often not be implemented on a large scale on short notice, in some cases developments will not be implemented at all. A similar example but for societal factors could be the sustainability of hydrogen production or the costs of the needed infrastructure. When examining the political factors, there are more dependencies due to the nature of politics. Besides the developments of the technology, the input of society is very influential as well. As some development can have a direct effect on politicians and their decisions such as energy security and international relations, other factors are mediated by society. This is because politicians are representatives of society itself and are chosen by the residents of the, in this case, EU. Eventually, the end deliverable of this research is formulated as factors which influence the implementation of HFC-HDTs, this is therefor the resulting dependant variable of the conceptual model.

Even though the feasibility framework of Feitelson and Salomon is the base for the conceptual model of this research, it is significantly more detailed than the formulated conceptual model. Furthermore, in the feasibility framework, the social feasibility does not have a direct relation towards the adoption of an innovation but only via political feasibility. This is of course a very important relation, and social factors definitely influence politics, but for this research social factors will be examined and will influence both politics and the adoption of HFC-HDTs directly. An example of this could be the social acceptance of using hydrogen as a fuel for HFC-HDTs which could both influence politicians in their decision, but also the public debate regarding the technology itself. Moreover, during the research different factors will be examined in much detail which will almost certainly cause some factors to have a correlation to the different categories. However, this will be discussed in more detail in the upcoming chapters.

Specified framework

Arguably the most important product of this research is the SFF framework developed specifically for the adoption of HFC-HDTs. This framework contains the factors found in this research. However, in order to keep the framework clear, not every single factor could be included in this framework. As mentioned in the section “research structure”, the SFF framework in figure 6 is the end product of this research whilst the upcoming four chapters, chapter four trough seven, will go into greater detail regarding the factors and dissect the framework into smaller frameworks focussing on the individual categories. These separate SFF frameworks contain more factors than the framework below, but these have either direct or indirect effect on the factors in the final framework. The eighth chapter will use the learning curve equation and the SFF framework to calculate the course of the production costs of a HFC-HDT in different scenarios, but this will be elaborated on in the chapter itself.

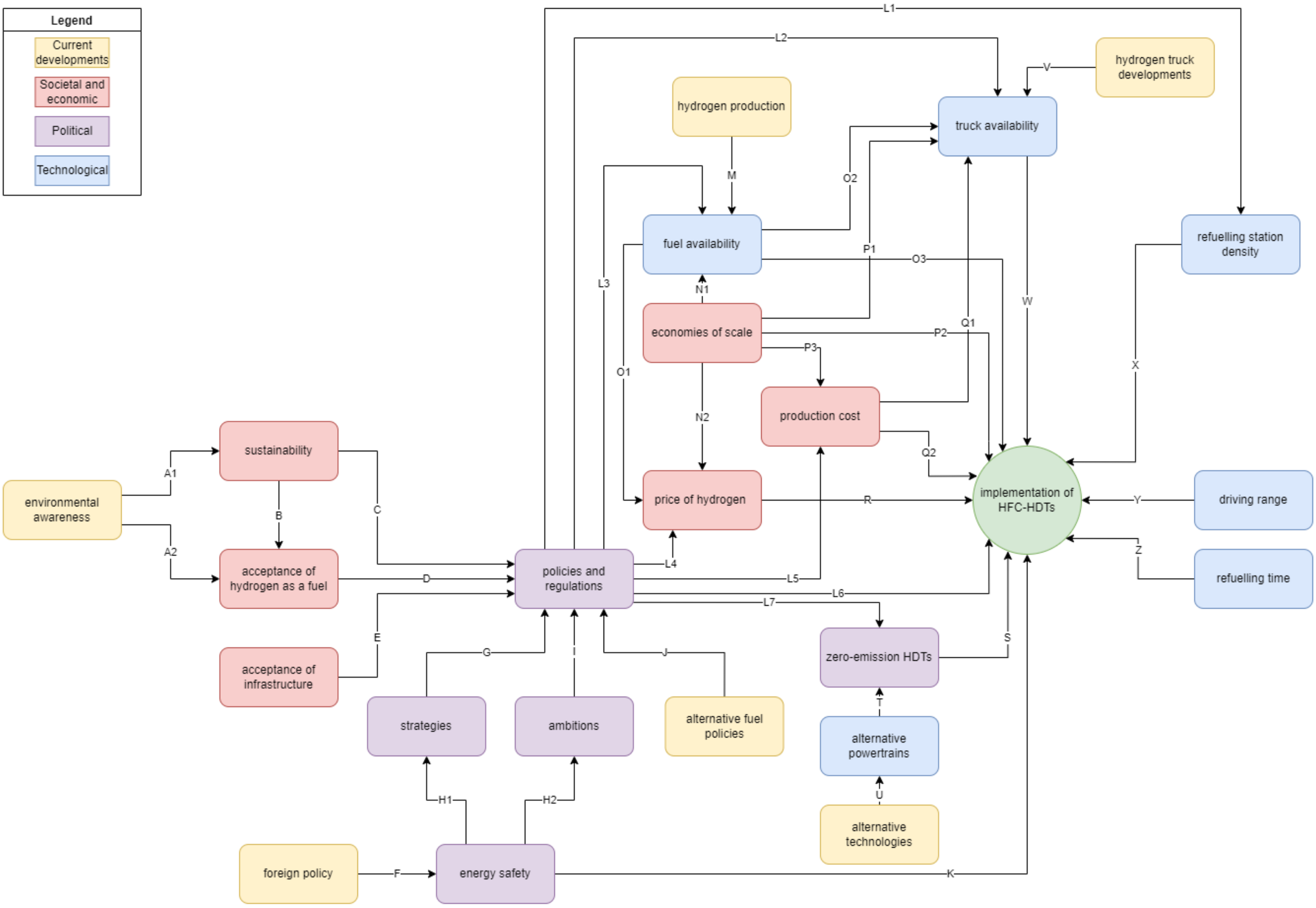

Figure 6 - final SFF framework for the implementation of HFC-HDTs (with relations referenced from table 1 and table 2)

The colours in the SFF framework, figure 6, follow the same principle as the simple conceptual model earlier in this chapter, yellow is for current developments regarding hydrogen and HFC-HDTs, blue is for technological factors, red is for societal and economic factors, and purple is for political factors. As can be seen in the figure, it is still quite complicated but that is to be expected with the introduction of a new technology where the old technology is very embedded in society and business. Regarding the yellow current development factors, these do not have a direct effect on the implementation of HFC-HDTs but do have indirect effects due to their impact on other factors in the other categories. These developments are not tied to a single category like other factors but are a broad view on ongoing events which are not necessarily played out yet, e.g., the factor “hydrogen truck developments” refers to the developments which are not yet in active production such as a truck which operates on liquid hydrogen. This and the other factors regarding current developments will be elaborated on in the next chapter. When it comes to the technological, societal and economic, and political factors, these do have both direct relations to the implementation of HFC-HDTs but also relations between each other. In particular, the societal and economic factors can also have a great impact on political decision making especially on policies and regulations. On the other hand, the technological factors are often not dependant on society or politics as most of the developments are driven by researchers or companies venturing into the zero-emission HDT market.

As mentioned before, the factors will be explained in great detail in the upcoming chapter, accompanied with SFF frameworks specified to the category central in the chapter.

4. Technological factors

In this chapter the following sub question will be answered; *Which technological and technology related factors play a role in success or failure of hydrogen fuel-cell heavy duty trucks, and if the technology will be adopted?* Thus, technological and technology related factors are discussed and examined to have influence on the success or failure of using hydrogen in a HDT transport system. Furthermore, challenges and barriers are defined, examined, and discussed as well. Comparisons will be made to the current standard for long-haul transport by HDT, which is the diesel powered truck. Moreover, the most prominent alternative, the lithium-ion battery electric truck, will be used for specific comparisons as well.

Trucks

The foremost requirement of using hydrogen in the transport sector is the availability of vehicles which can use hydrogen as a fuel. Within this research, the long haul HDTs are examined for use in the EU. Thus, the availability of said trucks which run on hydrogen is a necessity. for this a FCEV is used, a FCEV operates similarly to a BEV, but instead of using a large and limited battery it uses a hydrogen fuel-cell to convert the energy stored in hydrogen to electricity, which is stored in an intermediary battery, in order to power the electric motor (Cunanan et al., 2021a). The advantage of a FCEV is that there are zero tailpipe emissions when it comes to GHGs, the only “emission” is water.

At the moment, the amount of hydrogen fuel-cell HDTs on the road in the EU are very limited. Different projects across the EU are currently operating on, and testing hydrogen fuel-cell HDTs. An example of this are the current operating ten hydrogen fuel-cell HDTs by Hyundai which run on gaseous hydrogen (350 bar) and have a range of roughly 400 kilometres and a refuelling time of 15 minutes. Besides Hyundai, other established companies such as DAF, Toyota, and others are either investing, testing, or producing similar hydrogen fuel-cell trucks (DAF, 2022; FuelCellsWorks, 2021). Whilst Mercedes-Benz and other companies like Hyzon Motors Inc. and Chart Industries Inc. are working on a next generation hydrogen truck run on liquid hydrogen which could have a range of approximately 1.000 kilometres and enter the market in 2027 (FuelCellsWorks, 2021; Hyzon, 2021). Here the significant difference between hydrogen in its gaseous form and in its liquid form is clearly seen. These different methods of hydrogen use could influence the success of the trucks greatly, as driving range is considered to be very important and a reason as to why lithium-ion battery electric HDTs might not be successful (Staffell et al., 2019).

It seems that HDTs running on liquid hydrogen are more efficient and able to deliver more power, range, and have a higher load capacity than HDTs running on gaseous hydrogen (Q. Wang et al., 2020). However, the first trucks of that type are expected in 2027, whilst a European consortium of companies want to have 100,000 hydrogen trucks operatable by 2030 (FuelCellsWorks, 2021). This suggests that a larger part of these trucks will run on gaseous hydrogen. The current standard for operating HDTs is gaseous hydrogen at a pressure of 350 bar (Hyundai Motor Company, 2022).

The efficiency of these types of trucks is a point of attention as using hydrogen as a fuel is not the most efficient path. For the production of hydrogen, it is highly dependent on the route of production. When considering electrolysis, as this has the potential to be sustainable, it then depends on even more factors such as scale, type of electrolyser, etc. but the efficiency of converting electricity into hydrogen is roughly 65-80 per cent (Yoo et al., 2018). This can be improved over time, but the overall efficiency of hydrogen is questionable as only 20-25 per cent of the source energy to produce hydrogen is left for end use by efficient fuel-cells (Bossel, 2006).

Additional features which increase the overall efficiency of the hydrogen fuel-cell HDT could benefit the driving range and reduce fuel consumption. One interesting feature could be the addition of regenerative breaking which would generate energy and store it in the batteries when the trucks use their breaks (Ahmadi & Kjeang, 2017). Optimizations of the on-board hydrogen storage to make the overall weight lighter could also increase efficiency (Collins, 2022).

Furthermore, there is the possibility of retrofitting existing diesel trucks so they can operate on hydrogen instead. This can be done by removing the diesel engine and gear box, adding an electric motor and accompanying hardware, adding a battery and fuel-cell, and replacing the diesel tank with a tank which can hold hydrogen instead (Çabukoglu et al., 2019). Retrofitting existing trucks could function as an intermediary for companies to use hydrogen fuel-cell HDTs without replacing their trucks completely and reduce investment costs. This way, the number of hydrogen fuel-cell HDTs could increase significantly and the principle of economies of scale comes into play.

Moreover, the trucks need to have the space in order to fit on-board storage of hydrogen without impacting the space for cargo and driving range too much. Although there are a lot of different types of MHDVs, it seems that it is possible to arrange the hydrogen storage in such a way that the MHDVs can still accommodate 90 per cent range operations with respect to the current diesel trucks (Kast et al., 2018). This is different for the electric alternative which would need a very large battery to accommodate the same driving range capabilities as the common diesel truck.

Hydrogen as a fuel

When considering a fuel for transport means, its energy density has a big influence on the adoption of said fuel. The specific energy (kWh/kg) of hydrogen is very high, namely 33.3 kWh/kg. This is significantly better than diesel which has a specific energy of 12.6 kWh/kg. However, hydrogen is also the lightest element on the periodic table, meaning that the energy density of hydrogen is relatively low compared to the specific energy. Current HDTs use diesel which has an energy density of 10.6 kWh/dm^3, whilst liquid hydrogen has an energy density of 2.37 kWh/dm^3 and gaseous hydrogen (350 bar) has an energy density of 0.77 kWh/dm^3. Alternatively, lithium-ion batteries have a specific energy of 0.55 kWh/kg, and an energy density of 1.69 kWh/dm^3 (Edwards et al., 2008; Sheffield et al., 2014).

Table 5 - specific energy and energy density of different powertrains (Edwards et al., 2008; Sheffield et al., 2014)

	Specific energy (kWh/kg)	**Energy density (kWh/dm^3,)**
Diesel	12.6	10.6
Hydrogen (liquid)	33.3	2.37
Hydrogen (gaseous, 350 bar)	33.3	0.77
Lithium-ion battery	0.55	1.69

As mentioned before, there are not many operating hydrogen fuel-cell HDTs but the ones currently on the road operate on gaseous hydrogen under a pressure of 350 bar. There are also trucks in development that run on liquid hydrogen which would greatly increase the range and thus reduce the need for refuelling. Furthermore current personal vehicles run on gaseous hydrogen under a pressure of 700 bar such as the Toyota Mirai (Toyota, 2022).

As mentioned before, the current hydrogen trucks make use of a fuel-cell, but there is also the possibility to make use of internal combustion engines, similar the current standard engine for almost all fossil fuel based vehicles, which run on hydrogen instead (DAF, 2022). This technology is less dependent on the purity of the hydrogen and might be more familiar to the truck operators as ICEs are a tried and proven technology for decades (TNO, 2020). However, it seems that these types of truck are still in the development stage and are not yet available for HDTs. Nonetheless, Cummins Inc. and

Daimler made a partnership in which they will develop hydrogen ICE trucks for use in North America, expected in 2027 (Robinson, 2022).

The specifics of the fuel used in the HDT impacts the successfulness directly, as it correlates with the driving range, the necessary density of refuelling stations, storage, and transport. The current HDTs on the road and the planned projects make use of hydrogen fuel-cells combined with gaseous hydrogen under a pressure of 350 bar. Moreover, fuel-cell trucks that use liquid hydrogen are under development as well. The question then arises if these different technologies will compete with each other or if they will enhance the overall position of hydrogen in the future. It can be argued that this is actually beneficial as it promotes the use of hydrogen as a fuel, and it can help increase the overall production and adoption of hydrogen in general (Cummins Inc., 2022).

All the abovementioned findings suggest a certain level of versatility of using hydrogen as a fuel in the heavy duty transport sector. This could be seen as a positive factor relating to the success and use of hydrogen. The use of hydrogen in other industries and sectors can also have a positive influence as the demand might be higher, but that encourages the production of hydrogen as well. The versatility does however also come with more challenges as production and infrastructure should be adaptable to meet the specific demand.

Production

There are multiple routes for producing hydrogen at the time, and it is important to understand which options are currently feasible for a larger scale production. The large scale hydrogen production via the chemical route, starting with fossil fuels, is a mature technology which is currently used for the production of ammonia (da Rosa & Ordóñez, 2022). This is done via a process called steam methane reforming (SMR). This method can also be used to produce hydrogen as a fuel for hydrogen fuel-cell HDTs, however as it still uses a fossil fuel it is not considered completely zero-emission (Song et al., 2022). For a lot of stakeholders it is important that hydrogen will be zero-emission on the long term. This means that different production option should be further developed. This is already happening in smaller scale projects and is still researched actively. A well-known technique to produce hydrogen is electrolysis, which is the process of splitting water into hydrogen and oxygen by using an electric current (Ursua et al., 2012). This technique has great potential as it can be completely sustainable when electricity from a renewable source, such as solar or wind, is used (M. Wang et al., 2014). However, as of 2019, only 4 per cent of the hydrogen used originated from water electrolysis using renewable sources (Cavaliere et al., 2021). The electrolysis path is rather versatile as there are many different forms of generating electricity, such as fossil fuels, nuclear plants, and renewables which could all be used for electrolysis. Moreover, the electrolysis path can make use of fossil fuels as long as the transition towards complete sustainability is not yet reached.

A very promising technique of producing hydrogen is with the help of solar energy, which can be done in multiple different ways. One of them is the abovementioned electrolysis, but it can also be done by using heat (thermochemical) or light (photocatalytic) which are more efficient than electrolysis (Navarro et al., 2015). One of the fossil fuel free thermochemical paths is thermolysis, which require extraordinary hight temperatures of around 2500 K and is a single step dissociation of water shown in equation 1.

$$(1)\ H_2O \rightarrow H_2 + 0.5O_2$$

The other option is to use thermochemical cycles which uses metal oxide redox reactions in order to lower the required temperatures. This is done in two steps, as shown in equation 2 and 3 where M indicate a metal and M_xO_y its metal oxide.

(2) Step 1: $M_xO_y \rightarrow xM + y2O_2$
(3) Step 2: $xM + yH_2O \rightarrow M_xO_y + yH_2$

The net reaction of this process is still the same as equation 1, but is considered more efficient due to the lower temperature requirement of below 1200 K (Steinfeld, 2005). The other thermochemical path is photocatalytic splitting of water which uses a photo-semiconductor in order to absorb solar energy and split the water in the same manner as equation 1 of the thermolysis path (Navarro et al., 2015).

There are also other paths including the use of biomass. The biomass could be sourced from residual agricultural mass, so it does not compete with food production. An important note with biomass form residual agricultural mass is the availability however, which is difficult to ensure (Posso et al., 2020). Another option is to use algal biomass which seems to be promising but is still in early development (Show et al., 2018).

The capacity for production of hydrogen within the EU was 10 Mt per year as of 2018, which was based on fossil fuels for 90.6 per cent. For the hydrogen fuel-cell HDT to be successful, it is necessary to produce significantly more hydrogen as the current demand is 8.3 Mt hydrogen, mostly from refineries and ammonia production. Moreover, less than 0.1 per cent of the produced hydrogen was used for the transportation sector (Pawalec et al., 2020). Worldwide, the production of hydrogen was roughly 90 Mt of which around 80 per cent was made from fossil fuel sources without emission reduction. The worldwide demand industries for hydrogen is similar to the demand in the EU, being refineries and ammonia production (International Energy Agency, 2021). When comparing the capacity of hydrogen production with the demand for the most common HDT fuel in Europe, diesel, it is a mere fraction of the fuel demand. Specifically, the total demand for diesel in the EU in 2020 was 275.2 Mt, despite a decrease of transport demand due to the COVID-19 pandemic, making it the by far most used oil product, for fuel, in the EU (FuelsEurope, 2021).

Moreover, the production of hydrogen should be fully sustainable in the near future, meaning that the most common methods of hydrogen production should also be replaced by new technologies. This would further increase the need for “new” sustainably produced hydrogen. In the future this could be done with the help of all the new methods, but they are still under development. It is the case that hydrogen fuel-cell HDTs are getting traction and the use will be upscaled in the near future. This would mean that the demand for hydrogen will increase, faster than new methods are capable of large scale production, whilst production should increase parallel to the demand.

The electrolysis process is a mature and proven technology to produce hydrogen and in combination with sustainable energy sources it is very promising for the future (El-Emam & Özcan, 2019). it is argued that this specific technology might be the potential solution regarding sustainable hydrogen, instead of the polluting SMR process (Maggio et al., 2019). This because the production of hydrogen via the SMR route, even with CCS, is not very viable as it would defeat the purpose of sustainable production (Dincer & Acar, 2015). Electrolysis is the process of decomposing water and forming hydrogen and oxygen in the process, in which electrodes are responsible for conducting electricity through the water and forming the gasses (dos Santos et al., 2017). There are some challenges to overcome when it comes to using this technology. For example, the availability of electrolysers within the EU is not adequate enough for large scale use of hydrogen as a fuel as only small scale projects are operating in the EU right now (Fuel Cells and Hydrogen, 2019). It is however a mature technology and possible to use in larger scale production in the near future. Furthermore, a problem with electrolysis is that the efficiency of the process is significantly restrained by the anodic oxygen evolution reaction (OER) due to sluggish kinetics (Chen et al., 2022). This issue can be partially solved as different types of new electrolysers are developed. These newer types of electrolysers are classified by the nature of the electrolyte, the three foremost and proven types for near term large scale production are polymer electrolyte membrane (PEM) electrolysers, alkaline electrolyser, and solid oxide electrolysers (El-Emam & Özcan, 2019). Firstly, PEM electrolysers are promising as it is a proven technology which can produce high purity hydrogen within a compact design. The materials needed however are valuable and rare which makes it challenging to commercialise this specific type of electrolyser (Millet, 2015). Secondly, Alkaline electrolysers are also a mature, reliable, and safe technology producing high purity hydrogen. This methods is used in commercial scale but it is slower due to the OER and research into catalysts is needed to improve the process (Bodner et al., 2015). Lastly, solid oxide electrolysers do have a higher theoretical efficiency, but operate on a higher temperature. Furthermore, they have higher levels of degradation of the electrodes and overall long term durability is poor. If these problems are solved however, with further research and development, this technology could be very promising (Zheng et al., 2021). Furthermore, it is important to note that it could be argued that electrolysis in general can only be genuinely sustainable when there is a surplus of sustainable energy which is currently not yet the case (Maggio et al., 2019).

Another route for hydrogen production is via thermochemical processes. It is possible to obtain hydrogen from biomass when using this technique, with high energy efficiency. However, there are still problems regarding high production cost and tar generation as an unwanted by-product (Pandey et al., 2019). When using thermochemical pyrolysis, there are GHG emissions such as methane, carbon monoxide and carbon dioxide. It is however possible to produce more hydrogen from the methane by the SMR process, reaction 4, and the water-gas shift reaction, reaction 5 (Ni et al., 2006).

(4) Steam methane reforming reaction: $CH_4 + H_2O \rightarrow CO + 3H_2$
(5) Water-gas shift reaction: $CO + H_2O \rightarrow CO_2 + H_2$

Further challenges with these techniques are the fact that it makes use of biomass which is highly distributed and that it should not endanger the food chain. Moreover, a carbon capture system should also be in place when zero-emission is a necessity (Dou et al., 2019).

Consequently, this is currently one of the biggest disadvantages when it comes to using hydrogen as a fuel for the transport sector, there is simply not enough production at this moment. Furthermore, the production of hydrogen roughly matches the current demand. This suggests that all the hydrogen that is potentially needed for transport needs to be produced on top of the current production. However, the demand for hydrogen regarding transport is currently not high. This suggests that this disadvantage might not be the biggest barrier, if the production is upscaled in the near future.

The abovementioned lack of hydrogen production might not be a very big problem yet. However, as the amount of operating hydrogen fuel-cell HDTs will increase in the future, the production should rise in parallel to this demand. This growth in hydrogen demand does not mean that the development of alternative production methods is a prerequisite, as the electrolysis path is sufficient when enough investments are made. It does seem however that electrolysis will be the biggest technique regarding hydrogen production in the short and mid-term future due to its versatility, scalability, and maturity of the technology.

The option of hydrogen production via the SMR route with CCS is not very viable as it would defeat the purpose of sustainable production (Dincer & Acar, 2015). Furthermore, it could be argued that the production of hydrogen is genuinely sustainable when there is a surplus of sustainable energy which is not always the case, but is an opportunity for unpredictable energy sources such as solar, wind and hydro (Maggio et al., 2019; Thapa et al., 2021).

Infrastructure

In order to have an effective and complete hydrogen transport system, a refuelling infrastructure is necessary. This could be seen as one of the biggest hurdles for FCEV as it takes significant investments, but that will be discussed in a later chapter. Technologically speaking, an infrastructure of hydrogen relies on factors such as transportation and storage of the fuel as well. Firstly, the refuelling stations themselves are examined as they function as the backbone of the road transport system. Furthermore, it is argued that a reliable infrastructure of refuelling stations is one of the biggest barriers, if not the biggest, to overcome in order for hydrogen HDTs to be implemented successfully (Melendez, 2006).

The foremost argument for hydrogen over the most favourable other alternative, the battery electric HDT, is the down time regarding the refuelling or recharging. Where the battery electric HDTs will have to charge over night over a period of 10 hours or fast charge over 2 hours (Engdahl, 2021), the refuelling time for HFC-HDTs is roughly 10 to 15 minutes which is similar to current diesel heavy duty trucks (Cunanan et al., 2021a; H2 Mobility, 2021). Taken this into account, this is a very positive advantage of the HFC-HDT due to very low down time and having the same working method as the current standard.

Regarding the HRSs themselves, it is still unclear to which type of hydrogen will be widely used in the future, this depends on the pressure and temperature of which the HFC-HDTs and other vehicles will operate. Furthermore, different types of hydrogen engines are still under development as mentioned in the previous chapter. Therefore, it is important that the HRSs that are currently being developed or planned, are versatile and can accommodate in different specifications of hydrogen fuel in order to prevent unnecessary costs.

One possibility is to produce the hydrogen on-site with the help of either the SMR process or electrolysers and compressors as a method for eliminating the need to transport hydrogen, for the SMR process the on-site production rate would be roughly 250 kg/day (Dagdougui et al., 2018; Rahimipetroudi et al., 2021). This seems to lead directly to a significant problem regarding these types of HRSs, the current hydrogen fuel-cell HDTs have 7 storage tanks with a capacity of 32 kilogrammes each, resulting in a total capacity of 224 kilogrammes of hydrogen (FuelCellsWorks, 2021). Thus, these types of HRSs would not be suitable for a hydrogen fuel-cell HDT transport network. Furthermore, when a newer generation of trucks, which use liquid hydrogen, come to the market the capacity would need to be even higher.

Consequently, the abovementioned findings conclude that for HDTs, larger HRSs are necessary and that the hydrogen needs to be produced off-site and transported to those locations. This of course comes with a new set of challenges and barriers to overcome, as the hydrogen needs to be transported over long distances and safely stored at the locations of the HRSs. Figure 7 portrays the different possibilities regarding the supply chain of HRSs.

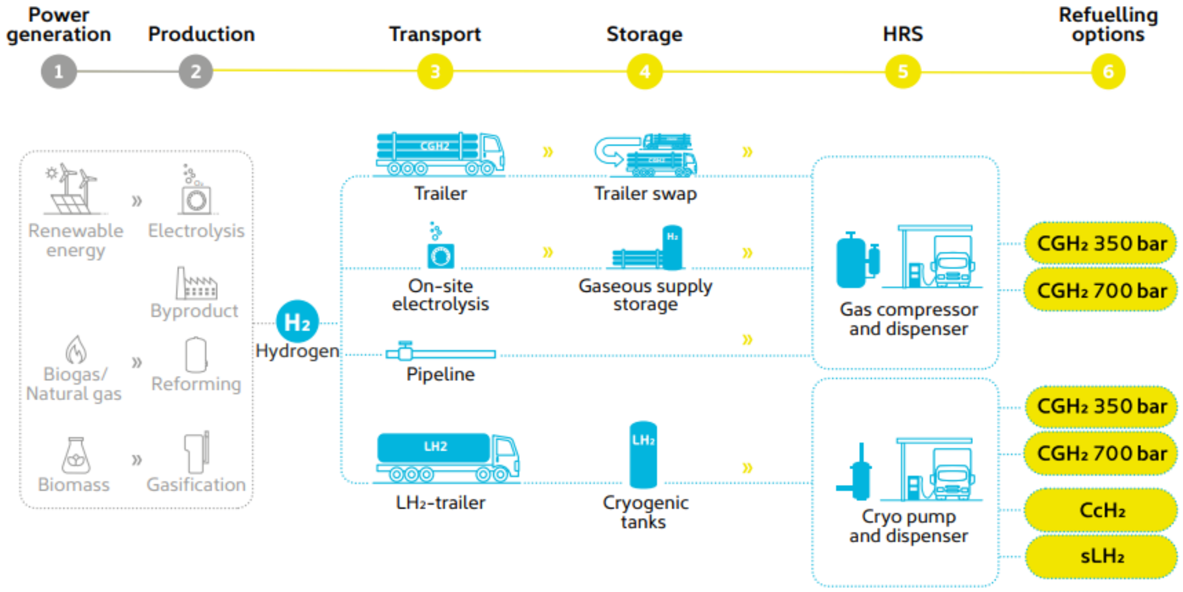

Figure 7 - different hydrogen supply chain options for HRSs (H2 Mobility, 2021)

Transport and storage

As mentioned above, the hydrogen for HFC-HDTs has to be produced off-site and transported to the HRSs. The transport and storage can either be done in the gaseous or liquid state of hydrogen. Both options come with advantages and disadvantages as they have different requirements and costs. When it comes to hydrogen in its gaseous state, the main challenges relate to the lower density of hydrogen when compared to fossil fuels. This can be combatted by either using larger storage vessels or using newer technologies which use high pressure, cold temperature or materials that attract hydrogen molecules (Moradi & Groth, 2019). These are however newer technologies and are not yet used on a larger scale. In simulations done by Mayer et al. (2019), both options are viable but liquid truck supplied stations are more inexpensive in the future than gaseous truck supplied stations. However, the liquefication of the hydrogen is significantly more expensive and requires extremely low temperature of around -253 °C, which can cause issues with boil-off losses and impracticality when it comes to mobility means (Rivard et al., 2019).

The options for transportation include making use of either compressed tube trailers, cryogenic liquid trucks, or compressed gas pipelines (Singh et al., 2015). In the beginning stages and for different demand types, a combination of these methods is of course possible. For example, before a widespread pipeline network the tube trailers and trucks can be used. Furthermore, for locations with a higher demand a compressed gas pipeline could be used to meet the demand.

Together with the refuelling stations and transport, the actual storage of hydrogen itself can be seen as one of the major challenges which need to be faced as well in order to adopt a hydrogen economy (Singh et al., 2015). It seems that the most important factor for the type of storage at HRSs is the capacity required for the vehicles. In this case, for HFC-HDTs it would suggest that the liquid storage at HRSs could be seen as a requirement as this type of storage has a capacity of more than 1000 kilogrammes of hydrogen a day while gaseous storage have a range of 100 to 520 kilogrammes of hydrogen per day when looking at the current stations (Apostolou & Xydis, 2019). This however, also means that the stored hydrogen needs to be converted to gaseous hydrogen in order to accommodate the current HFC-HDTs.

Safety measures

Another important aspect is the safety of the hydrogen fuel-cell vehicle when that vehicle is in an accident. One argument being made is that these types of vehicles should be safer than natural gas or gasoline vehicles when a collision occurs in open space (Najjar, 2013). Hydrogen as a gas is however highly flammable as it has an extensive flammability range, 4 per cent to 75 per cent in air, combined with a low ignition energy and low molecular weight which increase leakage (Pagliaro & Iulianelli, 2020). Together with the notion that hydrogen cannot be smelt when there is a leakage, it is a requirement that the chance of a leak is as minimized as possible. This means that certain measures need to be taken in both HFC-HDTs and HRSs, especially regarding the storage of the hydrogen. Moreover, when it comes to the storage of the hydrogen, the emissivity of the storage, the effectiveness of emitting energy as thermal radiation, should be lower than 0.2 whilst the distance of the storage to the actual fuel dispenser should be greater than 8.5 meter at the HRSs (Sakamoto et al., 2016). Regarding on-board hydrogen storage, a promising material for both the liner and shell of the tank is aluminium 2219 which has a low density but has a good strength and toughness. This material allows for a size of usable hydrogen of 86.8 kilogrammes which has an average range of 1057 kilometres which is sufficient for HDTs (Ahluwalia et al., 2023). Furthermore, it is important that the equipment used to fuel the HFC-HDTs are simple as well and easy to use by the end users.

The transportation of hydrogen, as mentioned above, can be done by different means. The overall safest option would be to transport the hydrogen with the help of pipelines as there is little to no need for people to handle the hydrogen when it is outgoing or incoming (Markert et al., 2007). This would minimize the chance of leakage when switching from storage vessel. However, the transport of hydrogen by truck is not a new occurrence and should therefore not be a big challenge. The overall consensus is that there is a need to gain experience in a fast pace regarding the safety performance of HRSs and HFC-HDTs so standards can be developed and deployed over all stations and trucks (Markert et al., 2007).

Alternative technologies

The rise of alternatives besides hydrogen will also influence the success of hydrogen trucks, lithium-ion battery driven vehicles are already used in a larger scale and is used in trucks on a smaller scale as well. However, it is technologically feasible to use battery electric trucks at this moment, but a negative aspect of these types of trucks is the energy density. The range and payload of battery electric trucks is considerably lower when compared to the current standard diesel trucks (Gray et al., 2021). It could be argued that there is a technology battle for a dominant design between lithium-ion battery trucks and hydrogen fuel-cell trucks (Kaa et al., 2017). As both of the technologies are not yet fully adopted and only a relatively small part of the overall market is taken by lithium-ion battery trucks and even fewer by hydrogen fuel-cell trucks, it seems that the battle is taking place in phase 3, creating a market when considering the different phases described by Suarez (2004) (Suarez, 2004). This phase is characterized by a growing number of operational trucks of both technologies and the beginning of a market for them (Suarez, 2004). Important to note, it does not mean that the technologies are fully developed yet.

The share of alternatively powered trucks can also be important due to the effects of economies of scale. currently, it is clear that the biggest share of trucks by far is the internal combustion engine, mostly diesel powered (96.3%). But when looking at alternative powertrains, the biggest players are battery electric or alternative fuel trucks (ACEA, 2022).

Overhead truck charging and induction charging lanes are also an upcoming technologies which are piloted in some countries at the moment (Porter, 2019; Radu, 2021). For these technologies, a relatively small adaptation is needed to the current trucks so they can use electricity as a powertrain. However, these types of truck often still use internal combustion engines as a main source which means that zero-emission is not guaranteed. Furthermore, they require an enormous amount of new infrastructure, either above the road or within the road itself which is very costly and not realistic in all places.

Results

A lot of developments are not yet ready for the implementation of a hydrogen fuel-cell HDT network across the EU. Furthermore, some technologies are simply not developed yet, liquid hydrogen HDTs for example. That does not mean that hydrogen fuel-cell HDTs are technologically unfeasible. There are multiple projects which prove the concept of HFC-HDTs being used in the transport sector. Even though the trucks themselves are in full development and the specifications of the hydrogen differ between truck types. It is a certainty that the current developed HFC-HDTs are advantageous over the battery electric HDTs when it comes to driving range, refuelling time, and the possibility of retrofitting diesel trucks. However, using hydrogen as a fuel brings a lot of challenges as well as the production and infrastructure are not yet in place. On top of that, the alternative technologies are under full development as well and it could be argued that especially the BE-HDT is a more mature technology. Nonetheless, the alternatives are not fully adopted yet which means that there is still a possibility for HFC-HDTs to become the dominant technology. Regarding the production, the current produced hydrogen is almost exclusively for the ammonia industry and makes use of the fossil fuel based SMR reaction. The only current developed mature technology is electrolysis which would need to be upscaled significantly in order to serve the transport sector. There are however other promising production paths based on other sustainable energy technologies such as solar energy, specifically thermochemical or photocatalytic which are more efficient than the conventional electrolysis. Furthermore, the sustainable production via electrolysis is dependent on a potential surplus of sustainable energy which is not the case yet. The solution to these issues with the production of hydrogen itself are a hard prerequisite for the use of hydrogen as a fuel. Especially the availability of hydrogen is a must as the HFC-HDTs would otherwise be useless. It could be argued that the sustainability aspect however can be solved over a longer period.

Regarding the infrastructure it is essential that the HRSs and the transport and storage are in order before HFC-HDTs can be extensively used in the EU. The conclusions from the abovementioned findings suggest that the hydrogen cannot be produced on-site at the HRSs as the capacity is simply too low for HFC-HDTs. This directly correlates to the storage, as the hydrogen almost certainly needs to be stored in a liquid form as this greatly increases the capacity of the HRSs. Furthermore, the transport to the stations will need to be in liquid form as well when done in trucks. However, when making use of hydrogen pipelines the situation would change as this would decrease the need for high storage capacity. The technological aspects regarding safety measures are already developed for the HFC-HDTs trucks themselves, where the most important aspect is the on-board storage tank. Regarding the HRSs, and the notion that the hydrogen is produced off-site, the storage and transfer to the storage need to be completely leakproof due to the volatility of hydrogen. Furthermore, it is important that the experience gathered from pilots and projects is shared and used across hydrogen applications in the transport sector.

Figure 8 is a schematic overview of the relations between the factors regarding the technological aspects of implementing HFC-HDTs. This portrays the factors examined in this chapter and is somewhat simplified in order to keep a good overview of the factors whilst still being understandable.

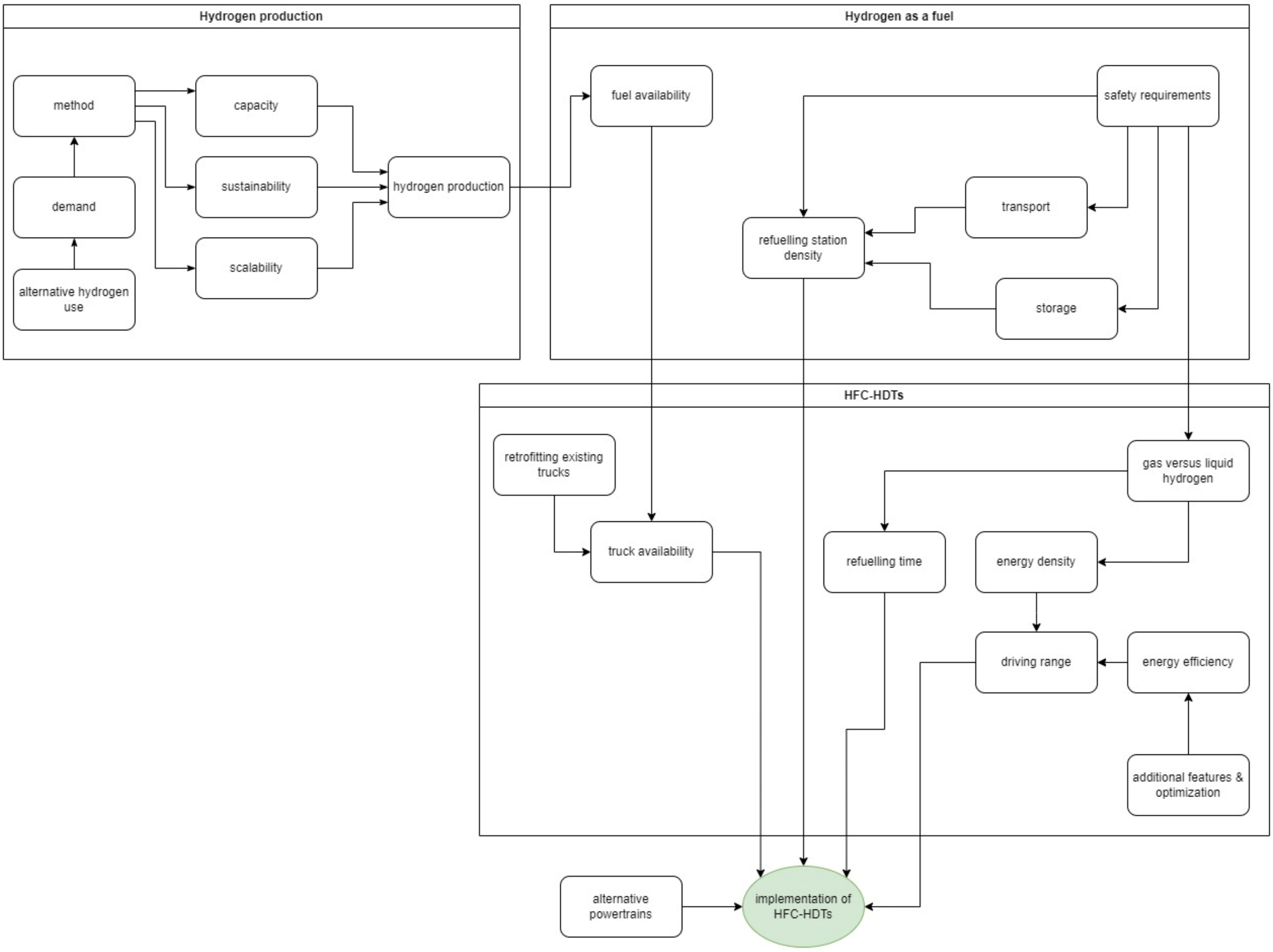

Figure 8 - schematic overview of influential technological factors

5. Economic and societal factors

In this chapter the following sub question will be answered; *What societal and economic factors play a role in the adoption of hydrogen fuel-cell heavy duty trucks?* Instead of the technological factors discussed in the previous chapter, this chapter will focus on societal factors such as the public opinion, economic impact, and overall perception of a hydrogen fuel-based road transport system. It is known that the opinions on hydrogen as a fuel is very widespread across society, but it has an important influence on political actors, discussed in the next chapter, and the rollout of a new road transport system.

Transport demand

Within the EU, there has been a steady increase in the online ordering of goods (and services) as can be seen in figure 9. This increase in bought or ordered goods or services is paired with an increase of internet users as well (Ecommerce Europe, 2021), portraying a very large and fast increasing market which is dependent on the transportation of goods across Europe.

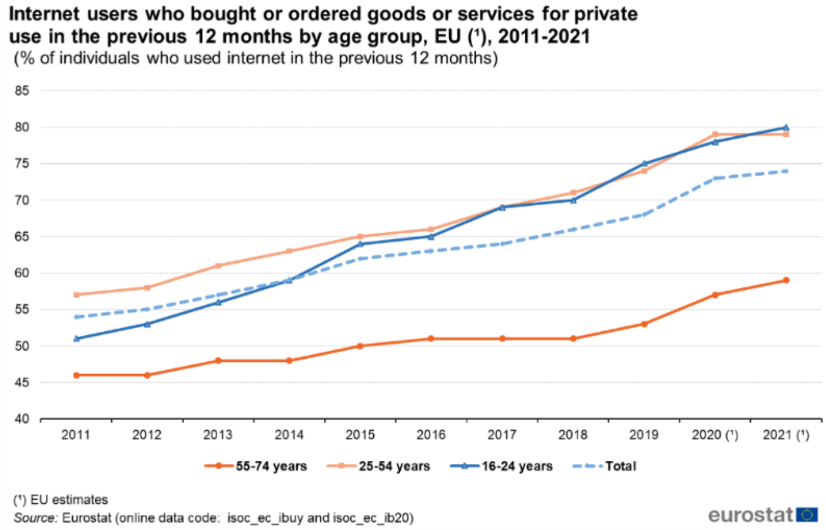

Figure 9 - internet users who bought or ordered goods or services for private use in the previous 12 months by age group (Eurostat, 2022)

This growing consumer market has led to a steady incline in the need for transportation as well, this need transcends a single modality or distance and is thus often a combination of different modalities and shorter and longer distances.

The demand for inland freight transport within the EU has consisted of mainly road transport, over the past years it has been around 75.8 per cent of the total inland transport (Nowakowska-Grunt & Strzelczyk, 2019) . With a fleet of roughly 6.2 million medium and heavy commercial vehicles, of which only 0.7 per cent are alternatively powered (ACEA, 2021a). This comes down to roughly 43,400 alternatively powered trucks. This provides a lot of room for an expansion of sustainable trucks like hydrogen fuel-cell trucks. It is important to note however, that for hydrogen fuel-cell trucks it is important that the hydrogen is also produces sustainably without the use of fossil fuels. Moreover, the question of how to sustainably transport goods across the EU has been a big driver on developments over the past years and multiple different option arose from this, of which hydrogen fuel-cell HDTs is one. However, with hydrogen it is very important as to how it is produced and stored as this is the biggest contributor to whether it is sustainable or not.

Economic

It is no surprise that the rollout of a completely new fuel and transport infrastructure is paired with significant investments and overall economic impact. Investments are a big part of changing an existing transport system and replacing it with another technology. This includes investments made by truck manufacturers, operators, but also governments and institutions such as the EU. The question however rises which party is responsible for certain investments. An example for this, the manufacturers can invest in the HFC-HDTs but are still dependent on the production of hydrogen and the refuelling infrastructure across the EU. Therefore, businesses can be hesitant to purchase and use HFC-HDTs without the certainty of proper infrastructure. Additionally, the fuel cost will also play a role in the adoption of HFC-HDTs as it needs to be competitive with the current diesel prices and the costs of electric HDTs. A study done in the United States of America, demonstrates that hydrogen can already be competitive with diesel prices, including hydrogen production and transport, but not in all cases. To solidify the competitiveness, different regulatory and policy efforts are suggested (Guerra et al., 2019).

When it comes to the production of the hydrogen itself via electrolysis, its costs mainly depend on the price of the energy used, the capital cost of the electrolyser itself, and the load factor of it (Longden et al., 2022). The production of hydrogen using fossil fuels is roughly $1.66-184 per kilogramme without carbon capture and storage, however when this is taken into account the price increases to $2.09-2.23 per kilogramme. This further increases when a carbon penalty of the EU is taken into account, to $2.24-2.70 per kilogramme. Whilst the production of hydrogen with electrolysers is roughly $3.64 per kilogramme and expected to lower to $1.85 per kilogramme when capital and electricity costs lower in the future (Longden et al., 2022). Figure 10 shows the average fuel cost of diesel and hydrogen when hydrogen is produced for less than 4 dollar per kilogramme in different areas, the last two columns are specifically for HDTs and show that the prices are relatively similar (Guerra et al., 2019).

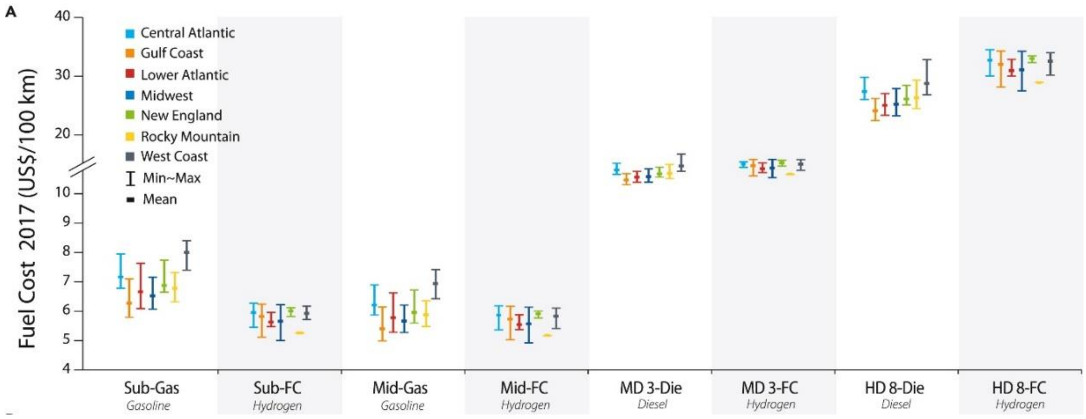

Figure 10 - fuel cost comparison of gasoline, diesel, and hydrogen (produced for 4 dollars per kilogramme) for different vehicle types (Guerra et al., 2019)

Another option for cost optimization could be to use local hydrogen production at HRSs and integrate them with the power grid. As this system is also in need of investments and restructuring due to a shift towards sustainable energy, synergy can be obtained by coupling these sectors and costs can be reduced. The coupling of these sectors, the heavy duty HRSs and the power system, and investing symbiotically can reduce the costs with around seven billion euros per year (Rose & Neumann, 2020). An example where this could be very beneficial is the Netherlands where multiple problems have occurred when it comes to capacity and demand and investments are necessary to anticipate future sustainability goals (NOS Niews, 2022). This issue does however also spread across the EU due to the more variable nature of sustainable energy (Pleßmann & Blechinger, 2017). However, as mentioned in the previous chapter, this option is most likely not viable when it comes to HFC-HDTs as these trucks require more hydrogen and the HRSs with on-site hydrogen production lack the capacity to provide enough hydrogen with the current technology. It can however be considered in certain cases or when electrolysers are improved in the future.

A study done by Wietschel et al. (2006) suggested that for a scenario in which hydrogen market penetration has a 5 per cent share in the stationary and transport energy consumption by 2030, needs an investment 0.07 per cent of the EU-25 GDP, roughly 13 billion euros. The bulk of the costs come from production infrastructure and transport infrastructure, the refuelling infrastructure only has minor impact (Wietschel et al., 2006). This study is however does not focus on hydrogen fuel-cell HDTs specifically, but all hydrogen fuel-cell vehicles. This would mean that investments might be less than the aforementioned amount, but due to the high energy demand of HDTs it could suggest similar needs.

Furthermore, the development of hydrogen fuel-cell vehicles in general would greatly benefit hydrogen fuel-cell HDTs due to the principle of economies of scale. The economies of scale principle would suggest that the overall development of the hydrogen economy, or the general use of hydrogen as a transport fuel, would greatly increase the likelihood of a successful system as costs go down and efficiency increases in the different aspects of such as a system, e.g. production of hydrogen and hydrogen fuel-cell components (Ajanovic & Haas, 2018). This is specifically examined for different scenarios of the production cost of HFC-HDTs from 2020 to 2050 in the “Learning curve and scenarios” chapter later on. On the other hand, for electrolysers, it is shown that economies of scale can obtain capital cost reduction up to 60 per cent when processes are optimised correctly (Morgan et al., 2013).

In order to make hydrogen, both its production and infrastructure, economically competitive it is almost certainly a necessity for the EU and national governments to provide subsidies, but this subject will be examined and discussed in the next chapter.

Social acceptance

A well-established theory on social acceptance of technologies is the technology acceptance model (TAM) of Davis (1989). In this theory, perceived usefulness and perceived ease of use influence the intentions to use a technology which in turn influences the actual use of the technology. Moreover, it has taken a leading role in explaining the behaviour of technology users (Marangunić & Granić, 2015). This theory can be applied to the use of hydrogen as a fuel as well. When examining the TAM from the perspective of the users; the truck operators and drivers, the perceived usefulness can be categorized in terms of sustainability and usefulness in achieving sustainable road transport. This will mainly be a concern for the operators as company image is often seen as important and environmental friendly management helps improve this (Oberhofer & Fürst, 2012) furthermore, environmental concern is growing within society as well (Lampert et al., 2019). Secondly the perceived ease of use should not be a concern to the actual truck drivers as driving range, refuelling time and overall driving experience is similar to their current diesel trucks. For operators this can be a point of concern as accompanying infrastructure is mostly lacking and available trucks are scarce.

However, this research focusses on HDTs which narrows the number of users. On the other hand, when examining hydrogen as a fuel for transport in general, the potential user basis grows significantly as personal vehicles can be counted as well. When this is taken into account it could change the perspective on those types of vehicles as it seems that the argument of sustainability is not enough for people to make sacrifices when it come to the introduction of new technologies (Ricci et al., 2008). A study done across seven countries in Europe shows that the technology itself is not very well known except for the idea that is more sustainable. Consequently, the initial attitude towards hydrogen fuel-cell electric vehicles (HFCEVs) is positive and in favour of accepting and adopting the technology (Oltra et al., 2017).

Due to time constraints and scope, it is not possible to include all types of HFCEVs in this particular study. Furthermore, as this research focusses on hydrogen fuel-cell HDTs, most people will not have to sacrifice anything at all. Moreover, truck drivers also have limited hindrance as refuelling time and driving range are similar to conventional trucks. As discussed in the section above, the owners and operators of the trucks will experience the most hindrance in the form of investments and uncertainty. The foremost initial idea that people in society will have in relation to hydrogen fuel-cell HDTs, is that they are more sustainable than conventional trucks, which is generally perceived as a positive aspect.

When it comes to using hydrogen as a fuel, it seems that there is a lack of concerns about the safety of this technology (Ricci et al., 2008). This could be considered odd as a study for hydrogen fuel-cell busses in Stockholm suggests that safety is one of the most important factors when considering this transportation technology (Haraldsson et al., 2006). Overall, it seems that the positive attitude is due to limited public awareness and positive public information about hydrogen. Furthermore, it seems that people perceive safety as a pre-requisite for hydrogen technologies which enter the market (Ricci et al., 2008). Besides sustainability, safety has an important role in forming opinions. A well-known psychological trait of people is the availability heuristic which states that people can more easily think of an event if it has happened before or if it is easy to imagine (Jones-Lee, 1990). This phenomenon can be applied to safety risks, when an accident or other negative events happen with a new technology such as HFCEVs in their earlier stages, then people will remember this and perceive the technology to be unsafe. It is important that the safety of the HDTs is ensured before they enter the market on a larger scale in order to prevent major accidents and influence the perceived safety negatively.

Besides the technology itself, the acceptance of the infrastructure is important as well. The concerns regarding refuelling stations for HDTs will not be significant as they will most likely not be placed near residential areas and safety measures, as examined in the previous chapter will be in place. However, the transportation of hydrogen could be a concern when making use of pipelines which most people would not want near them, the so called “not in my backyard” argument (Park et al., 2017). When considering the transportation of hydrogen via trucks, this should not be a major concern for the public as different dangerous fluids are already being transported and safety standards for these fluids are sufficiently in place.

Climate impact

There are a lot of ongoing developments influence the transport sector and which technology might be used in the future. However, it is certain that within the EU there will be a change towards sustainable road transport rather than the traditional diesel trucks (European Commission, 2021). This is due to a trend in general which suggests more environmental awareness (Lampert et al., 2019), and thus more need for sustainable technologies across different sectors. Furthermore, transportation is the second biggest emitter of GHGs after the power sector with 17 per cent of all GHG emissions (Statista, 2022). Of that, medium and heavy trucks are responsible for 22 per cent of the transport emissions worldwide which calculates to be roughly 2 billion metric tonnes of CO_2 (Statista, 2021). This portrays the necessity of change within this sector, which is the reason for multiple developments in this area, and thus also in a hydrogen-based system. The impact of the transportation sector on GHGs and climate change in general might well be the biggest driver behind the move towards sustainable modes of transport. Consequently, using sustainably produced hydrogen in this sector could help reduce GHGs in the EU. Whilst the use of green hydrogen in hydrogen fuel-cell HDTs result in zero-emissions, whether the entire supply chain is fully sustainable is dependent on multiple factors such as production method, material use, and transportation/storage of hydrogen (Wulf et al., 2018). Even though the sustainability of hydrogen is dependent on the method of production, the current production capacity is not yet ready for large scale use of hydrogen as a fuel. As an intermediary the SMR process can be used to compliment electrolysis capacity. This is however based on fossil fuels, nonetheless it is proven to emit less GHGs to use hydrogen via this production method than using conventional gasoline or diesel vehicles (Guerra et al., 2019).

It is important for the EU and its citizens to move towards a sustainable method of goods transportation as this is a big contributor to climate change which consequences can be disastrous for the whole continent. The EU and the European Commission are key political actors in this, but they are chosen by the citizen of the EU. This means that for these political institutions to make a change, their voters need to speak out on this issue. Fortunately, awareness for climate change and sustainability increase yearly (Lampert et al., 2019). On the other hand as mentioned before, when people have to make sacrifices to use a new sustainable technology, the sustainability argument alone is not enough (Ricci et al., 2008).

A study done in the Beijing-Tianjin-Hebei-Shandong (BTHS) region in China found that replacing currently operating diesel powered HDTs with hydrogen fuel-cell HDTs could reduce the GHG emissions with 32.7 per cent in that region (Lao et al., 2021). This study portrays the possibility that hydrogen fuel-cell HDTs offer when it comes to reducing GHGs, even though the BHTS region and the EU cannot be directly compared due to different aspects such as geography and economy. This potential of hydrogen fuel-cell HDTs should be taken into account when policymakers and operators make decisions on potential investments.

Results

In this chapter, different societal and economic factors have been examined. These factors influence the different parties related to the adoption of HFC-HDTs, such as the manufacturers, operators, and governmental bodies. Firstly, the economic factors influencing the successful implementation of HFC-HDTs mainly relate to the cost which will have to be made by manufacturers and operators. The operators of the trucks will only invest when HFC-HDTs are competitive with the conventional trucks and other alternatives. The first aspect is the price of hydrogen itself when it is used for fuel. Currently there are regions where it is similar with diesel prices and thus competitive, this is however not yet the case everywhere and possible regulatory and policy efforts are necessary to solidify the competitiveness. It is also projected that prices of hydrogen will be lower in the future which could be very beneficial for the implementation of HFC-HDTs. Regarding the production and refuelling infrastructure, it seems that significant investments need to be made, mostly likely from the EU and other governmental bodies within the EU, in order to have a sufficient network of HRSs to cover the EU and incentivize the use of HFC-HDTs. However, besides the investments needed by governmental bodies, it is a requirement that manufacturers of the trucks themselves make investments as well. These investments are necessary to set up a production line for HFC-HDTs and invest in improving their models with up-to-date technologies. It seems that overall, the economies of scale can greatly influence the use of hydrogen as a fuel in vehicles in general. The same goes for the production as more electrolysers are taken into use, costs can drop up to 60 per cent of the current costs. Furthermore,

Secondly, the social acceptance of hydrogen and HFC-HDTs seems to be sufficiently and should not lead to any negative impact on the implementation of HFC-HDTs. Examining the TAM, the perceived usefulness relates to the sustainability and has a positive relation to HFC-HDTs as the operators and society value sustainability increasingly over the past years and is expected to continue to grow. The perceived ease of use is similar to the conventional diesel truck and should thus not have a negative effect, in contrast to the electric HDTs which have significantly longer refuelling time. It is however the case that people in the EU on average are not very knowledgeable about hydrogen at all, which can actually have a positive effect as negative aspects are not known either. This reasoning continues in the same line regarding the safety, where most people seem to assume that the HFCEVs are safe before they are widely adopted. A potential negative factor could however be the acceptance of the hydrogen infrastructure itself, production and HRSs.

Significantly intertwined with social acceptance is the environmental impact of a new technology such as the HFC-HDTs. It could also be seen as the biggest driver of moving to sustainable transport modes, such as hydrogen fuel based vehicles. Due to HFC-HDTs being more sustainable than conventional diesel HDTs, even with SMR produced hydrogen and possibly reaching zero-emission with sustainable electrolysis produced hydrogen, HFC-HDTs provide an optimistic perspective for the adoption of the technology. Furthermore, it is proven that exchanging current diesel trucks with can reduce GHG emissions significantly.

In figure 11, a schematic overview is given of the relations between the factors regarding the societal and economic aspects of the research. It gives an uncomplicated overview of the findings of this chapter without it being too confusing.

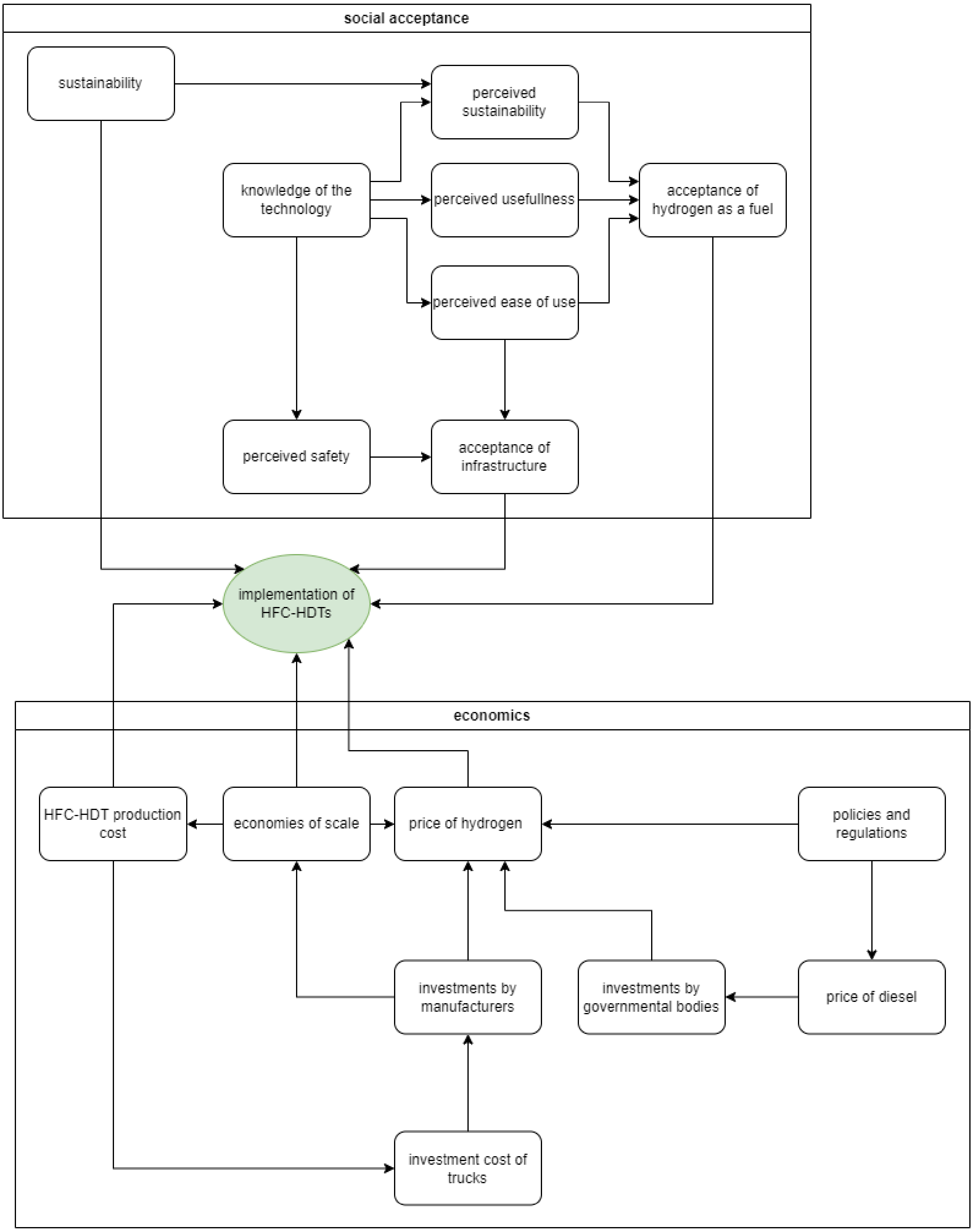

Figure 11 - schematic overview of influential societal and economic factors

6. Political factors

In order to change the current dominant technology, the diesel ICE trucks, the political bodies active in the EU can play a major role. It could even be argued that these actors can tip the scales for a certain technology such as hydrogen fuel-cell HDTs. These factors heavily depend on the factors examined in the previous chapters, the technological, economical and societal factors. One of the bigger and more important steps and concrete commitment towards combatting climate change is the Paris Agreement of 2016 in which 196 parties, one of which the EU, agreed to tackle global warming and GHG emissions (United Nations, 2021). Furthermore, when it comes to promoting zero-emission transport technologies, the EU has certain ambitions as it aims to halve all GHG emissions by 2030, and be completely climate neutral in 2050 (Tsiropoulos et al., 2020). Within this particular research, the EU can be seen as the most important political actor together with the national governments and their institutions (Machado et al., 2022). However, lobbying by certain pro- or antihydrogen organisations can greatly influence the stance on hydrogen as well. A more simple “solution” sometimes proposed is to, for example, subsidize the use of HFC-HDTs over other technologies can be seen as favouring certain technologies which would interfere with the free market and thus is not a viable option and more neutral measures should be taken.

Political shifts

The European Commission is actively forming different ambition documents, directives, and policies when it comes to the more sustainable future of transport. an example of an important directive by the EU is the “Directive on Alternative Fuels Infrastructures” (DAFI) which requires the member states to develop policy frameworks for the implementation of alternative fuels and their accompanying infrastructure (European Union, 2014). Since then, the EU and the different governments within the EU have focussed on developing an infrastructure for electric passenger vehicles for example, albeit mainly in the western and northern regions of the EU.

The war in Ukraine has also put a shift towards sustainable energy within the EU in an acceleration to become less dependent on Russian oil and gas. The necessity of being less dependent on Russian products, specifically oil products, will most likely have a very positive effect on the development of alternatives of which hydrogen fuel-cell vehicles is one. This, in turn, can accelerate new research and development in the fuel and energy sector. The long-term consequences are not yet known and difficult to predict but it does seem that the transitions towards sustainable energy has gained significant momentum and hydrogen as a fuel is part of this transitions.

Energy dependency and security

An important aspect to energy policies is the security aspect. The concept of energy security is however rather abstract. In this specific case, the aspects are as follows: diversification of supply, distance to source, method of transportation, and relations with country of origin. Furthermore, the price of the energy or fuel source is important as well (Lazarczyk et al., 2022). Hand in hand with security is of course the dependency on outside parties. As described in the abovementioned definition of energy security, the source of the energy plays a large role. If this source of energy is within the internal market of the EU, it could be assumed that, for example, the relations with the country of origin is reliable.

For future policies and strategies, the EU might look to enhance its independency and overall security of its internal energy market. It could be argued that the internal energy market of the EU is currently significantly dependent on outside parties and its security might therefore be nonoptimal. This dependency is partly due to the gap between energy production and energy usage which is rather sizeable as it is around 54 per cent, this gap is bridged by using oil and natural gas imported from other countries (Gökgöz & Güvercin, 2018). This reliance on outside parties and lack of security suggests a certain vulnerability which is not desirable for the future renewable energy market. One option which has been explored and somewhat used over the past years, is the diversification of energy sources (Matsumoto et al., 2018). By doing this, the EU could compensate the loss of one source with another and thus increase the security. The abovementioned findings prove that the EU is looking to increase its energy security. However, it could be argued that the EU does not have a wide enough definition of energy security and is too focussed on import dependency and security of supply. Especially regarding the move towards zero-emission energy, the scope of security needs to be broadened to also include availability, affordability, demand and geopolitical security (Jonsson et al., 2015). When considering availability, hydrogen is quite advantageous as its main source, water, is available in abundance and is mostly geographically independent and can thus be seen as a driving force for a hydrogen economy when there is a surplus of energy to produce the hydrogen (Demirbas, 2017).

The EU has an overall well developed infrastructure, but there is a lack of potential when it comes to natural resources and land availability. There are however some countries within the EU, e.g. Spain and France, do have access to sufficient renewable resources to serve the region (Pflugmann & De Blasio, 2020). Due to the well-developed infrastructure within the EU, the countries with the renewable resources for larger scale production could be important as it could potentially supply a large part of the EU demand for hydrogen and thus have a positive influence on the energy security of the EU.

Another possibility for the EU is to engage in a partnership with North African countries when it comes to hydrogen production, as there are more opportunities when it comes to for example solar energy (van der Zwaan et al., 2021). If such a partnership is formed, it does mean that the EU will be dependent on outside parties and will not achieve full energy autonomy. It is however the question whether it is possible for an entity such as the EU to be completely independent from outside parties. It is highly unlikely this will ever be the case as production capacity needed for the production methods should be in the EU as well, which is not the case as the EU mostly depends on China for solar panels and turbines for example (Pinto, 2022).

Hydrogen economy

There is a lot of speculation regarding the potential of the hydrogen economy in the future. Besides the benefits of economies of scale, the increased use of hydrogen across different sectors can entice governments to promote the use of hydrogen in general. However, there are significant challenges when it comes to the beginning of a so-called hydrogen economy. Governmental bodies such as the EU and national governments are critical actors in the overcoming of certain challenges and hurdles. This would however require investments and policies to be made and executed, which can prove to be difficult as governmental bodies tend to be rather rigid when it comes to change, especially the EU is known for certain institutional rigidity. However, the EU has shown to be rather dynamic when it comes to environmental policy (Deters, 2019). If this flexibility were to be properly used to promote the hydrogen economy or the HFC-HDTs more specifically it could have a positive effect on the implementation of the technology.

In turn, governmental bodies are influenced by the public and values hold by society, as they are generally a representation of society itself which has been discussed in the previous chapter. However, political actors are not only influenced by society, but other institutions can also play a big role as well. Furthermore, lobbying parties which can influence in a pro-hydrogen or anti-hydrogen manner can serve different interests as well if done successfully. It is however hard to predict which parties will lobby in either a positive or negative manner and it can thus have a positive or negative effect on the implementation of HFC-HDTs. It would mostly depend on the EC or individual member states on whether they are susceptible to lobbyists and their intrinsic values regarding the hydrogen economy. Moreover, if the EU would implement the concept of a hydrogen economy in some format, it would have a beneficial impact on technologies using hydrogen such as the HFC-HDTs due to economies of scale as examined in the previous chapter. It would however take significant policies, regulations, investments etc. from the EU to set up a European wide hydrogen economy.

Another beneficial aspect of a hydrogen economy is the concept of economies of scale which is examined in the previous chapter as well. It does however also have benefits from a political perspective, as the decisions made by the EU have a big impact on the internal market and thus the magnitude of benefits. This can in turn create a positive feedback loop which policymakers need to take into account when making their decisions on the matter. The concept of a hydrogen economy is a great example of the potential of economies of scale as more widespread production and use of hydrogen can have positive influences on multiple sectors such as the transport sector but also energy storage and other industrial processes in which the EU aspires to be more sustainable.

Policies and regulations

The EU has taken concrete steps towards forming policies regarding its energy market, which influences the possibility of a hydrogen economy. A tool set up to do this is the Energy Union which was founded in 2015. This energy union has five main aims in its energy policy, namely: diversification of energy sources to increase security, enabling a fully integrated internal energy market, improve energy efficiency, decarbonise the economy, and promote research in low-carbon and clean technologies (European Parliament, 2021). It is however the case that individual member states are still in charge of their own energy infrastructure and supply, the Energy Union cannot force certain measures on member states. The Energy Union does offer some positive outlook on the future of hydrogen and thus HFC-HDTs. A hydrogen economy could provide the EU with achieving the five abovementioned aims of the Energy Union. These aims are not necessarily specified for the transport sector but for the energy market as a whole, it does show the intent of the EU and the willingness to alter the energy usage in general and thus in the transport sector as well.

More specifically, the EU also has policies for the mobility and transport sector, a specific strategy developed by the EC is the Sustainable and Smart Mobility Strategy which states that the whole transport system will have to cut the emissions by 90 per cent by 2050 by transforming the current system into a more resilient and sustainable system (European Union, 2021). This strategy is a very ambitious document with many different aspects, but the focus will be the specific strategies regarding the use of hydrogen in the road transport sector. The strategy states that the EU is supporting manufacturers in the investment of HFC vehicles, more specifically, they are supported under the EU energy system integration and hydrogen strategies. Furthermore, in the strategy, the EU sets the aim to build 500 HRSs by 2025 and have 1000 HRSs in 2030 across the member states (European Commission, 2020c). In the “hydrogen strategy for a climate-neutral Europe” the EC specifically sets aims to increase the capacity of electrolysers within the EU and a projected increase of general hydrogen use in the energy mix of the EU from less than 2 per cent at this moment to roughly 14 per cent in 2050 (European Commission, 2020a). These specific strategies and policies portray the attitude towards HFC-HDTs within the EC and EU which seems to be rather positive for transport over longer distances where current electric vehicles are not currently sufficient.

Moreover, even more distinct projects have been initialized by the EU such as the PHRYDE project, protocol for heavy duty hydrogen refuelling. As the name suggests, this project was initiated to standardize and develop certain protocols for refuelling HFC-HDTs. The results of this project has led to concepts which could decrease the fuelling time and provided a framework for HRSs to standardize their fuelling system for the heavy duty segment (Hart et al., 2022). The current energy policies in place have functioned as a push factor for HFC vehicles but tend to be insufficient on their own to make a significant difference due to the lack long term investments. Regulatory policies also tend to have a positive impact on HFC vehicles albeit rather weak, the positive effects are mainly due to the tax exemption for hydrogen which does not apply to electricity or other fuels. Moreover, another type of policy has the great potential to have a positive impact on the adoption of HFC vehicles are the spending policies as they can channel funds to certain technologies. On the other hand, these policies are regional and thus often limited (Bleischwitz & Bader, 2010).

It could be argued that the EU should move from funding separate projects to becoming a global leader in regulations regarding the use of hydrogen as a fuel. This would in turn lead to explicit standards and policies which would benefit the adoption of the technology. Successively, this would incentivise investors and promote cross-border investments (Machado et al., 2022). One example is the notion that hydrogen has the potential to store excess energy as well, which is a great asset when it comes to very fluctuating renewable energy sources. This is a specific example for which the EU would need to develop regulations regarding this aspect of hydrogen. Furthermore, developing such regulatory frameworks, setting objectives, and taking actions could further incentivize investments (Astiaso Garcia, 2017).

Zero-emissions

In its goal to achieve a zero-emission future, the EU can use different tools to promote or even force the use of certain technologies and ban on other technologies. The most prominent options at hand are to subsidise hydrogen fuel, or to enforce a tax on the emission of GHGs. The first option, to subsidise hydrogen as a fuel, can be seen as somewhat controversial as this would suggest that the EU favours this technology over, for example lithium-ion battery electric HDTs. This is due to the argument that political institutions should not choose which technology is preferred, this should be left to the qualities of the technology and the free market. It is however proposed by some that a 3 euro per kilogramme subsidy is introduced in order to make hydrogen competitive enough and ensure lower prices at the HRSs (Zhou & Searle, 2022). A more neutral and honest measure would be to go for the second option, a tax on GHG emissions in transport could be argued to bet better as the operator of the HDTs is enticed to abandon the ICE HDTs but is not inclined to favour one technology over another by the EU. The first option, to subsidise hydrogen HDTs, would certainly help with achieving zero-emission transport within the EU. But as mentioned before it would favour hydrogen as a power train in general. This in turn will most likely cause businesses and organisations to invest in hydrogen rather than lithium ion battery electric HDTs. The second mentioned option, to tax GHG emissions, would suggest a similar move towards achieving zero-emissions, but it would rely more on the technology itself and market mechanisms to get to a dominant technology.

Other manners of achieving near zero-emissions could include the use of carbon capture and storage (CCS), but this technology is rather expensive at the moment. Furthermore it is not 100 per cent effective and the emission of carbon is not prevented but it is captured on later date in certain locations (Longden et al., 2022). Moreover, this specific technology would not be the solutions to make transportation fully sustainable as the aim is to make use of zero-emission vehicles within the EU (Tsiropoulos et al., 2020). This aspect has two sides when it comes to HFC-HDTs, on one hand, hydrogen has the potential to be zero-emission when produced sustainably. On the other hand, current production capacity for hydrogen is not sufficient when only looking at sustainably produced hydrogen. The option to produce hydrogen via the SMR method is currently more widespread and CCS could be added to this process. Therefore, true zero-emission hydrogen is not possible on short term notice and the SMR with CCS might be needed to suffice in the demand but this would result in HFC-HDTs that are not zero-emission. On the longer term, hydrogen has greater odds to be zero-emissions when investments are made in electrolysis based on sustainable energy.

Results

The EU has a very important role in the adoption of HFC-HDTs, being one of the major actors when it comes to investments and infrastructure development. The overall attitude of the EU and the individual member states towards using hydrogen as a fuel is positive, but this is largely due to the move towards sustainability and not necessarily because hydrogen is the best alternative technology. Furthermore, the EU should maintain a certain level of neutrality when it comes to alternative technologies as to not interfere with the free market.

Firstly, the EU has taken steps towards more energy independency and security which is defined by aspects such as the diversity of supply, distance to source, method of transportation, relations with the country of origin, and the price. Enhancing the overall energy independency and security of the EU would suggest that new policies and regulation need to be developed. Moreover, hydrogen has beneficial aspects regarding energy security as it can be not only store energy, but can also be produced within the EU and would thus be independent from outside parties. Complete independency is not super realistic as other regions such as Nort Africa have geographical benefits over Europe and sustainable energy production methods are dependent on production facilities in for example China.

One specific option to enhance energy security is the concept of a hydrogen economy in which hydrogen is used as the general energy carrier. This has positive effects on the adoption of HFC-HDTs as economies of scale are applied in the production, distribution, and storage. The concept of a hydrogen economy would however require significant and drastic measurements on short term notice and might be too dependent on the attitude towards hydrogen by society and governments. Overall, the change towards a hydrogen economy is not very likely due to the abovementioned reasons.

When it comes to policies and regulations, the EU does have certain ambitions and has formulated policies and regulations to achieve those. But as mentioned earlier, the EU has to have a neutral attitude towards new technologies. This is the case for most policies and regulations currently in place. Most policies which explicitly speak of promoting or funding hydrogen are much broader and apply to other technologies as well. But they do portray the willingness of the EU and EC to support and invest manufacturers of HFC vehicles and the necessary infrastructure. Furthermore, the EU has explicitly mentioned that they see an opportunity for HFC-HDTs for longer transport in the EU. On the other hand, they are mostly funding projects, and it is argued that this should shift from individual projects to policy frameworks and standards in order to further promote the use of HFC-HDTs. If this is done successfully, it would incentivize investors to invest more in the technology.

Lastly, the overall move towards a zero-emission could be a big drive for the success of HFC-HDTs as it has the possibility to be a completely emission free if done correctly. It is however not likely to be completely zero-emission on short term notice as the production capacity for hydrogen is mostly reliant on the fossil fuel based SMR route. For the long term it does have great potential when sustainable hydrogen production is more abundant.

Figure 12 portrays a schematic overview of the factor and their relations to each other examined in this chapter. Similar to the previous chapters, it is slightly simplified to keep it clear and understandable in one overview.

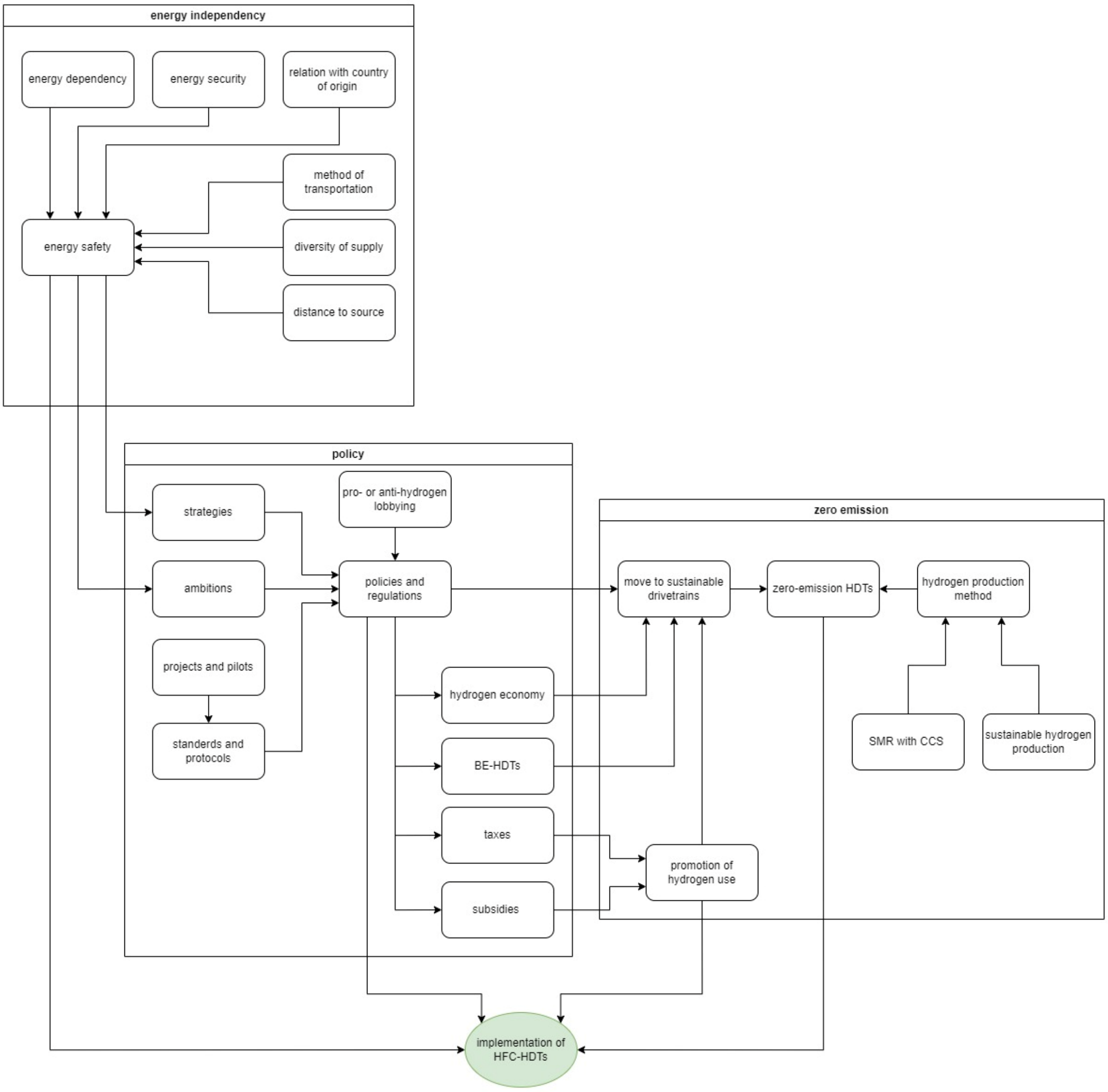

Figure 12 - schematic overview of influential political factors

7. Learning curve and scenarios

As concluded from previous chapters, the implementation of a new technology is not only dependent on whether it is technologically feasible, but it also depends on societal, economic, and political factors. However, one of the most important factors is the production cost of a HFC-HDT. This is because the costs will be one of the main drivers for businesses to decide which powertrain they will use. Furthermore, if another alternative such as the BE-HDT is significantly cheaper they will opt to use that technology. Therefore, this chapter will focus on the course of the production costs of HFC-HDTs over a period of multiple years. These calculations can be used by truck operators to evaluate their possibilities and make a well-studied decision when it comes to their investments. Furthermore, it could be argued that for some actors such as transport operators, the purchasing cost of a HFC-HDT is the most important factor. The purchasing cost is in turn directly related to the production costs. In the previous chapters, different types of factors which can influence the success of HFC-HDTs were identified. These insights are used to further investigate different scenarios regarding the number of HFC-HDTs and their corresponding production cost. However, whereas this research is focused on the EU, the production cost and cumulative experience regarding HFC-HDTs are global. Due to the global economic market, it is possible to purchase the trucks from anywhere, which will be beneficial for pricing as competition can drive prices down. Moreover, supportive infrastructure and technologies will be highlighted in this chapter as well, these aspects are more specific to the EU. The calculations will be done using the learning curve equation which will be explained below.

This chapter serves to apply the factors from the final framework presented in chapter three "conceptual model", and on the premise that certain circumstances are met. In particular, for any of the calculated learning rate scenarios to be viable, there needs to be ample availability of trucks, hydrogen, and infrastructure. furthermore, within the learning rate scenarios three perspectives are assumed based on certain conditions explained below.

Learning curve

When examining new technologies, the learning curve can give empirical insights into costs as a function of the cumulative produced experience or units (Ruffini & Wei, 2018). This curve can be expressed in the following equation:

$$C_t = C_0 * \left(\frac{Q_t}{Q_0}\right)^{-b}$$

In this equation C_0 and Q_0 are the initial cost and cumulative production, and C_t and Q_t are the cost at time t and the cumulative production at time t. The parameter b is the experience index, however to further simplify this can better be expressed in the progress ratio (PR) or the learning ratio (LR). When using these terms, the following equations can be used:

$$PR = 2^{-b}$$

$$LR = 1 - PR$$

The LR for HFC-HDTs specifically can be found in different reports and papers, and is similar to other renewable energy technologies such as solar panels (International Renewable Energy Agency, 2020). The learning curve equation itself can also be further simplified as $\left(\frac{Q_t}{Q_0}\right)$ is related to the number of doublings (ND), namely:

$$ND = \frac{\log\left(\frac{Q_t}{Q_0}\right)}{\log(2)}$$

When the abovementioned simplifications are put into the original equation the following result is obtained:

$$C_t = C_0 * \left(\frac{Q_t}{Q_0}\right)^{-b} = C_0\,(ND)^{-b} = C_0(PR)^{ND} = C_0(1 - LR)^{ND}$$

This equation is used in this research to calculate different scenarios when it comes to adoption of HFC-HDTs and their price over the coming years up until 2050. These scenarios are based on the different examined learning rates, and the global amount of sold HFC-HDTs.

Learning rates

As mentioned before, the learning rate of hydrogen fuel-cells for vehicles are similar to that of solar panels. This is estimated to be between 11 and 18 per cent (Anandarajah et al., 2013; Hydrogen council, 2020; International Renewable Energy Agency, 2020; Körner, 2015). The overall consensus is that the learning rate is most likely around 18 per cent. However, to get a better and more inclusive overview, different scenarios will be calculated with the help of the equation from the previous section. Three different scenarios will be calculated based on the different learning rates estimated in the literature. Within these three scenarios, three perspectives will be examined based on the adoption of HFC-HDTs; a more pessimistic, a neutral and a somewhat optimistic perspective. These will, in turn, be examined and discussed based on how likely they would be able to penetrate the transport sector using the production costs necessary of the HFC-HDTs. As explained in appendix 12.1, the global number of commercial vehicles of 335 million is used for the calculations.

In order to get a better insight into the current transportation market, the purchasing cost of the conventional heavy duty diesel truck is around €100k (Durabak, 2021; Statista, 2020). Consecutively, to be competitive with the current diesel truck, the production cost of the HFC-HDTs should be considerably lower as the manufacturer has a profit margin as well. Regarding the profit margin, in the argumentation and explanations of the scenarios, a margin of 5 per cent is considered (CSI Market Inc., 2023). In practice, this percentage can fluctuate significantly due to the economic situation and many other factors. However, for simpler calculations the abovementioned 5 per cent is used. Furthermore the current production costs of HFC-HDTs are assumed to be around €600.000 in 2020, but do differ significantly between models and manufacturers (Adler, 2022; Cebon, 2022; Sharpe & Basma, 2022).

SFF framework and perspectives

Besides the learning rates, each of the three scenarios is divided into three perspectives as well. These perspectives are related to the annual growth of the market segment of the HFC-HDTs in the LH transport sector. In contrast to the learning rates which are, as argued in the section above, moderately predictable and researched in scientific literature, the perspectives used in the calculations are more dependent on the factors from the SFF framework formulated in this research. Regarding the perspectives, the pessimistic perspective assumes an annual growth of 10 per cent, the neutral perspective assumes 25 per cent annual growth and the optimistic perspective assumes 40 per cent annual growth except for the years until 2025 as there are different pilots and tests done with HFC-HDTs and the vehicle count is set at a 1,000 for 2020 and 10,000 for 2025. The annual growth as mentioned above, is kept at a steady annual growth over the calculated period in order to anticipate on the factors of the SFF framework and prevent incremental changes which can happen from year to year to complicate the calculations too much. Table 6 portrays the assumptions for the development of the three perspectives with a short description/explanation of the assumption. These factors range from very negative (- - -) to neutral (- / +) to very positive (+ + +) in relation to the adoption of HFC-HDTs. These assumptions are based on findings from this thesis and are based and deducted from the literature and analyses within this research.

Firstly, the pessimistic perspective is the least beneficial for the adoption of HFC-HDTs. This perspective assumes an annual growth rate of 10 per cent from 2025 onwards. Within this perspective, it is assumed that the alternative zero-emission vehicles besides HFC-HDTs are dominant over the hydrogen based technology (e.g., the BE-HDT). It is also assumed that this is mainly due to the lack of acceptance of the use of hydrogen as a fuel and the necessary infrastructure. This in turn goes hand in hand with the lack of supportive policies and regulations for HFC-HDTs. Furthermore, due to the dominance of other zero-emission HDTs, the availability of HFC-HDTs is lower as well which relates to the production of hydrogen and the availability of fuel. Moreover, the lack of HFC-HDTs also means that the refuelling station density is only sufficient on major transport corridors which result in less routes having enough HRSs to support a larger number of HFC-HDTs.

Secondly the neutral perspective assumes an annual growth rate of 25 per cent from 2025 onwards. Within this perspective, it is assumed that most factors tend to be neutral towards the adoption of HFC-HDTs. It is however assumed that the absolute necessities for the introduction of HFC-HDTs are met. This means that there is availability of hydrogen fuel, the trucks themselves, and the refuelling infrastructure along the most used transport corridors of the EU. Furthermore, it is assumed that there is sufficient acceptance of hydrogen as a fuel and its infrastructure. however, it is also assumed that the policies and regulations in place are not beneficial enough for businesses to completely commit to HFC-HDTs over other more known technologies such as the BE-HDTs.

Lastly, the optimistic perspective assumes an annual growth rate of 40 per cent from 2025 onwards. This perspective assumes a moderate acceptance of the infrastructure and a high acceptance of the use of hydrogen as a fuel. It also assumes that multiple policies and regulations are in place which favour the use of HFC-HDTs over its alternatives, an example of this this could be a subsidy of 3 euros per kilogramme of hydrogen as suggested by Zhou and Searle (2022). Furthermore, there are multiple hydrogen production paths which can be used for larger scale use which result in more than sufficient fuel availability and a lower price of hydrogen. Moreover, due to the beneficial circumstances, it is assumed that the HFC-HDT availability is good, and the refuelling density can accommodate higher amounts of trucks along the major and minor transport routes within the EU.

Within each scenario, an example of the costs for truck operators will be done in order to get a better understanding of the costs needed to switch to HFC-HDTs. It is however not known what the average truck fleet size is within the EU due to it not being examined and reported. However, the average fleet size within the USA is six or less for 90 per cent of the operators (Lytx, 2023), and in Great Britain the majority of the operators had a fleet of two to five trucks in 2015 (Statista, 2016). Therefore, the calculations will be done with five trucks in order to show the differences between the scenarios, perspectives, and time. Furthermore, the current average purchasing price of a diesel HDT is around €100k (Durabak, 2021; Statista, 2020) which suggests that operators are willing to pay that price. This means that the production costs as calculated can be lower than that, but the purchasing costs is assumed to not decrease below €100k.

Table 6 - overview of the different assumptions made for the perspectives ranging from very negative (- - -) to neutral (- / +) to very positive (+ + +) in relation to the adoption of HFC-HDTs with explanation

Factor	Pessimistic	Neutral	Optimistic	Assumption / explanation
Acceptance of hydrogen as a fuel	- - -	+	+ + +	Assumption based on concerns of safety and risks due to negative media coverage for the pessimistic perspective, and a more positive media image as a sustainable future-proof fuel for the optimistic perspective.
Acceptance of infrastructure	- -	-/+	+	Based on the not-in-my-backyard principle, which does not affect the pessimistic perspective due to lower infrastructure density, but has more negative impact on the optimistic perspective due to higher infrastructure density.
Policies and regulations	- - -	- / +	+ + +	Assumption based on either very few to no positive policies for the pessimistic perspective, and a multitude of policies in favour of HFC technologies for the optimistic perspective.
Hydrogen production	- -	+	+ + +	The EU does not have the current capacity to produce hydrogen in abundance for fuel usage. The EU is not able to produce more in the near future for the pessimistic perspective. For the optimistic perspective, quick investments and upscaling are assumed to realise an abundance of hydrogen.
Fuel availability	-	+	+ +	In the pessimistic perspective, the availability of hydrogen fuel is ensured for limited use on certain transport routes. For the optimistic perspective, the fuel is in sufficient for use on most transport routes in the EU but it is not available at all refuelling stations.
Economies of scale	- - -	-	+ +	For the pessimistic perspective, there is less production of hydrogen and HFC-HDTs which mean a negligible effect of the economies of scale principle. The optimistic perspective assumes more production of hydrogen and HFC-HDTs meaning greater effects but not optimal due to not using HFC technology in private vehicles.
Price of hydrogen	- -	+	+ +	The pessimistic perspective assumes a decrease in the price of hydrogen but still relatively high compared to alternatives such as diesel and electricity. For the optimistic perspective, the price is assumed to decrease faster nearing the price of diesel and other alternatives but still slightly more expensive.
Zero-emission HDTs	- - -	-	+ +	In the pessimistic perspective, the use of zero-emission HDTs is mainly based on BE-HDTs or other alternatives instead of HFC-HDTs. In the optimistic perspective the use of HFC-HDTs is more widespread but there are still other alternatives in use as well.
Truck availability	-	+	+ + +	It is assumed that in the pessimistic perspective the trucks are more expensive and thus less demand but enough to meet that demand. The optimistic perspective assumes that multiple manufacturers produce trucks on larger scale resulting in a diverse and large offer of HFC-HDTs.
Refuelling station density	- - -	-	+ +	In the pessimistic perspective the refuelling stations are few and far between on very limited amount of transport routes. Regarding the optimistic perspective, the HRSs are sufficient on most transport routes in the EU but are not in abundance outside of the transport routes.

The first scenario

As mentioned above, different learning rates are used to calculate and examine different scenarios. In the first scenario, a learning rate of 11 per cent is used as referenced from the Hydrogen council (2020), this report argues that the learning rate specifically for commercial vehicles is lower due to the lower amount of produced vehicles in comparison to private vehicles. The first five years of the calculations are the same for the three perspectives, this is due to the assumption that there will be a set number of trucks due to different pilots and projects is set at 1,000 trucks for 2020 and 10,000 trucks for 2025.

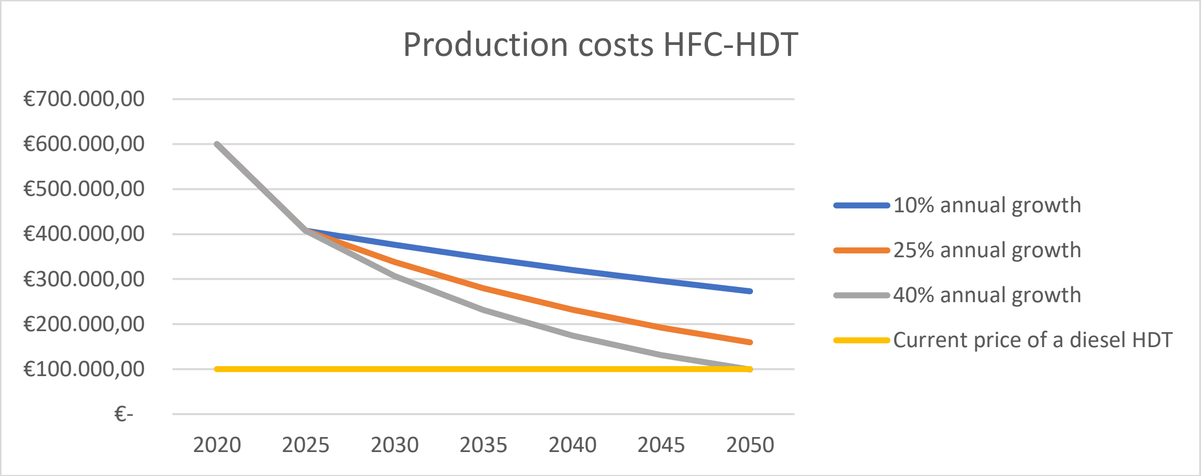

Figure 13 - production costs over time of HFC-HDTs with a learning rate of 11 per cent

The graph in figure 13 shows the learning curve in which the production cost of an HFC-HDT is plotted against the time. The three different lines are representative of the annual growth of the HFC-HDTs and show the clear impact of a higher cumulative production of the trucks. Regarding the pessimistic perspective it seems that the production cost stays incredibly high compared to the conventional diesel HDT at more than 272 thousand euros in 2050, almost three times the price of the diesel truck. The neutral perspective reaches a cost of roughly 159 thousand euros in 2050 and the optimistic perspective drops just below 100 thousand euros in 2050. These calculations would suggest that in this scenario the costs of HFC-HDTs would remain too high, even in 2050, to be competitive with diesel trucks without any external incentives such as subsidies. Table 7 displays the specific calculated prices over the years. For comparison, in 2030 the pessimistic perspective would need an investment of

Table 7 - production costs HFC-HDTs until 2050 with a learning rate of 11 per cent (x1.000)

Year	*10% annual growth*	*25% annual growth*	*40% annual growth*
2020	€ 600	€ 600	€ 600
2025	€ 407	€ 407	€ 407
2030	€ 376	€ 338	€ 307
2035	€ 347	€ 280	€ 231
2040	€ 320	€ 232	€ 174
2045	€ 296	€ 192	€ 131
2050	€ 273	€ 159	€ 99

Within this first scenario, the expected purchasing costs for a HFC-HDT fleet of five trucks is calculated and shown in table 8. This assumes a profit margin of five per cent for the manufacturers and a minimum of €500k as that is assumed to be the amount that operators are willing to pay. However, within this scenario, the purchasing price of HFC-HDTs is not expected to drop below this number. This suggests that the HFC-HDTs would need to be heavily incentivized for a very long term, even till after 2050.

Table 8 - expected purchasing cost of a fleet of five HFC-HDTs in the first scenario, accounting for a minimum of five per cent profit margin for manufacturers (x1,000)

year	*Pessimistic*	*Neutral*	*Optimistic*
2030	1,974	1,775	1,612
2040	1,680	1,218	914
2050	1,433	835	520

The second scenario

In this scenario, the learning rate is 15 per cent which is the average between the 11 per cent argued to be specifically for commercial trucks, and the most common 18 per cent learning rate found in the literature. Logically, with a higher learning rate the price decreases faster and more than the 11 per cent scenario. This can be seen in figure 14. As in the first scenario, from 2020 to 2025 the amount of HFC-HDTs is set to a fixed amount of 1,000 and 10,000 HDTs for all the perspectives. Furthermore, the line for the current price of diesel HDTs is set at €100k which the production costs can drop below, but the purchasing price of HFC-HDTs will most likely not drop below this mark.

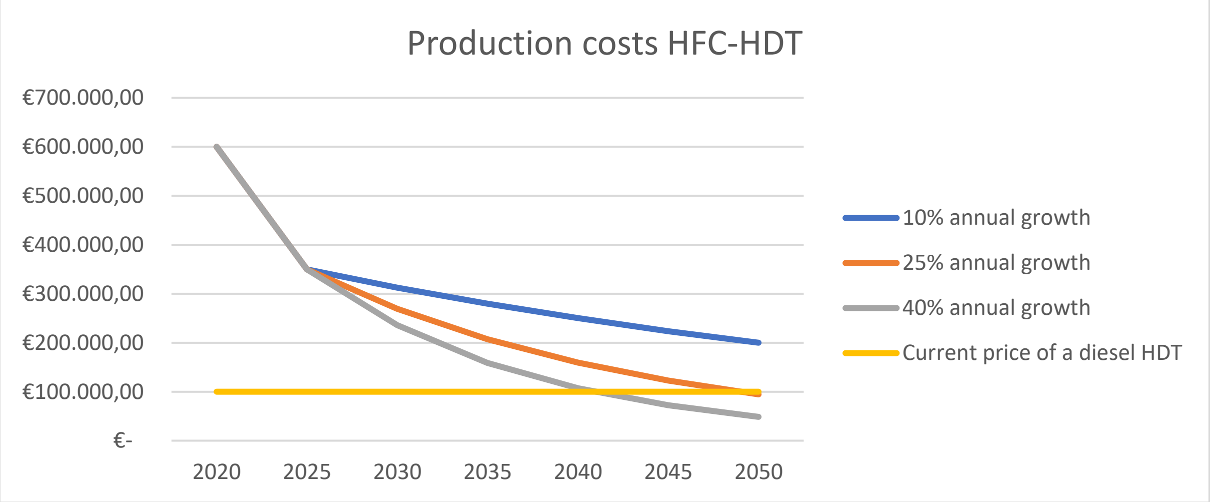

Figure 14 - production costs over time of HFC-HDTs with a learning rate of 15 per cent

With a learning rate of 15 per cent the production costs of HFC-HDTs change considerably faster and portray a steeper slope which suggest a better position regarding the competitiveness of these trucks compared to the diesel trucks or other alternatives. However, as can be seen in table 9, the production cost only drops significantly below the €100k in the optimistic perspective with an annual growth of 40 per cent. With a learning rate of 15 per cent and annual growth of 40 per cent, the HFC-HDT could be a competitive alternative around 2045 whilst still considering profit margins of at least 5 per cent for the manufacturers.

Table 9 - production costs HFC-HDTs until 2050 with a learning rate of 15 per cent (x1.000)

Year	10% annual growth	25% annual growth	40% annual growth
2020	€ 600	€ 600	€ 600
2025	€ 350	€ 350	€ 350
2030	€ 313	€ 269	€ 236
2035	€ 280	€ 207	€ 159
2040	€ 250	€ 160	€ 107
2045	€ 224	€ 123	€ 72
2050	€ 200	€ 95	€ 49

For this second scenario, the expected purchasing price of a fleet of five HFC-HDTs is more positive regarding competitiveness. However, this is on the very long term, namely around 2050 for the neutral perspective and around 2045 for the optimistic perspective. It could be argued that this is very late and the investments portrayed in table 10 will be too much for operators without subsidies or other incentives to lower the price on short term notice to bridge the gap to the expected competitiveness.

Table 10 - expected purchasing cost of a fleet of five HFC-HDTs in the second scenario, accounting for a minimum of five per cent profit margin for manufacturers (x1,000)

year	Pessimistic	Neutral	Optimistic
2030	1,643	1,412	1,239
2040	1,313	840	562
2050	1,050	500	500

The third scenario

In the third scenario the learning rate is set at 18 per cent, and therefore is the most viable scenario of the three. This learning rate is most commonly found in the literature but is mostly concerning the hydrogen fuel-cell itself instead of a hydrogen fuel-cell for HDTs specifically. However, this can be considered to be the main component of the HFC-HDTs due to the other components being effectively the same as competitive technologies, e.g., the necessary battery which is also being developed for electrical HDTs or the storage tank which is not exclusive to vehicles. This means that this learning rate could be argued to be optimistic when it comes transferring the data from the literature to the calculation of the production costs of HFC-HDTs. As in the previous scenarios, from 2020 to 2025 the amount of HFC-HDTs is set to a fixed amount of 1,000 and 10,000 HDTs for all the perspectives. Moreover, the same principle of the production costs dipping below €100k but the purchasing price will most likely not drop below that mark.

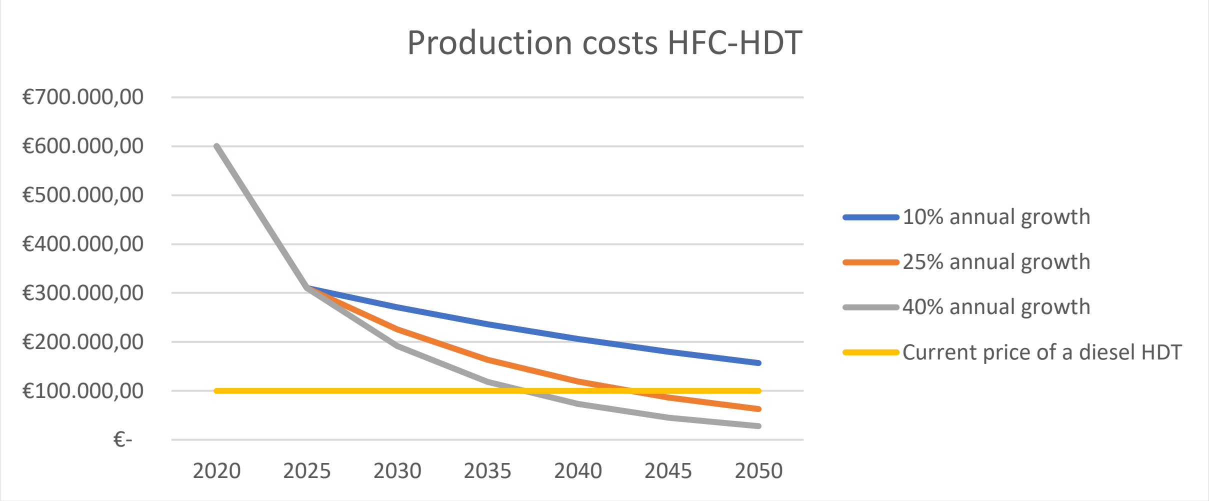

Figure 15 - production costs over time of HFC-HDTs with a learning rate of 18 per cent

In figure 15, the slope logically decreases significantly faster than the previous figures of this chapter. Together with the data from table 11, it can be deducted that even with the high learning rate of 18 per cent, the pessimistic perspective with 10 per cent annual growth might not be viable due to the hight production costs. On the other hand, with 25 per cent annual growth the costs drop below 100 thousand euros between 2040 and 2045. When the HFC-HDTs market grows with 40 per cent annually, the costs drop below 100 thousand euro between 2035 and 2040. These figures suggest that the HFC-HDT might be competitive by that time even when considering the minimum of 5 per cent profit margins for the manufactures.

Table 11 - production costs HFC-HDTs until 2050 with a learning rate of 18 per cent (x1.000)

Year	10% annual growth	25% annual growth	40% annual growth
2020	€ 600	€ 600	€ 600
2025	€ 310	€ 310	€ 310
2030	€ 271	€ 225	€ 192
2035	€ 236	€ 164	€ 118
2040	€ 206	€ 119	€ 73
2045	€ 180	€ 86	€ 45
2050	€ 157	€ 63	€ 28

The third scenario is by far the most beneficial for the potential purchasing costs of HFC-HDTs. However, still in the most beneficial scenario in combination with the optimistic perspective, the purchasing price of HFC-HDTs is expected to not be competitive on short term and is expected to be competitive around 2040. This suggests that a lot of incentives are still necessary for operators to opt for HFC-HDTs and bridge the gap until competitiveness in even the best case scenario.

Table 12 - expected purchasing cost of a fleet of five HFC-HDTs in the third scenario, accounting for a minimum of five per cent profit margin for manufacturers (x1,000)

year	*Pessimistic*	*Neutral*	*Optimistic*
2030	1,423	1,182	1,008
2040	1,082	625	500
2050	825	500	500

Results

The calculations within this chapter are an examination of one of the most important factors when it comes to successfully implementing HFC-HDTs within the EU for LH transport. The perspective analyses done in this chapter in combination with the learning rate scenarios present a forecast of the future production cost of HFC-HDTs. In order to have a good reference point, the conventional diesel ICE-HDTs are used for comparison. The most important reference point in this case is the purchasing costs of this type of truck which is set at an average of €100k. This number is mainly used to refer to the affordability or competitiveness of a potential replacement technology which is the HFC-HDT in this case.

The chapter is divided into three separate scenarios, these scenarios are based on different learning rates. These learning rates are acquired from scientific literature but there is no certain uniformity within the literature. This is the reason to use three scenarios where the learning rates are: 11 per cent, 15 per cent, and 18 per cent. Furthermore, these scenarios are enriched with different perspectives which are based on the annual market growth of HFC-HDTs. These perspectives are categorized as a pessimistic, a neutral, and an optimistic perspective. The pessimistic perspective assumes an annual growth rate of 10 per cent, the neutral perspective assumes an annual growth rate of 25 per cent, and the optimistic perspective assumes an annual growth rate of 40 per cent. Important to note is that these calculations cannot be limited to the internal EU market as learning rates and annual HFC-HDT market growth are inherently part of the global economic system. To re-iterate, the perspectives are defined by the following assumptions:

Pessimistic – enough HRSs on major transport routes but not in abundance, not enough hydrogen production to meet de demand, other drivetrain become dominant, and policies are not sufficiently promoting the specific use of HFC-HDTs.

Neutral – sufficient HRSs on most transport routes but not in remote areas, in theory enough hydrogen production but competing with other uses and industries, no single drivetrain is necessarily dominant over the others , and policies are neutral towards the different alternative zero-emission drivetrains.

Optimistic – abundance of HRSs for HDTs as well as for private vehicles, abundance of hydrogen production to meet demand across all industries, dominant over other drivetrain for LH transport, and policies promote the use of hydrogen for LH transport over other alternative zero-emission drivetrains.

For the first scenario with a learning rate of 11 per cent is not particularly competitive when compared to the current standards. The scenario is up until and including 2050 not profitable for manufacturers even when the market has an annual growth of 40 per cent. Regarding the second scenario, with a learning rate of 15 per cent, has potential to be competitive and profitable for manufacturers between 2040 and 2045 in the optimistic growth or around 2050 for the neutral growth. The third scenario portrays a somewhat more promising outcome due to competitiveness and profitability between 2040 and 2045 for the neutral growth and between 2035 and 2040 for optimistic growth. Within the calculations, the first years, up to 2025, are not particularly important when it comes to the perspectives because it is assumed that these years a set number of trucks are introduced in projects and pilots. However, these first few years might me the most important years due to the knowledge acquired within these projects and pilots. Furthermore, investments made by governmental bodies and other actors do not have a direct effect and might require some years to materialize, an example is the construction of a well-developed hydrogen production and refuelling infrastructure.

Even though the third scenario seems to be quite hopeful for the HFC-HDT market, it still needs to be incentivised heavily in the early stages without the knowledge whether this technology is truly superior to other emerging technologies such as the BE- HDT which are being developed as well. Furthermore, the uncertainty of the HFC technology in HDTs might have a negative reaction on potential manufacturers and buyers if they are risk averse. Furthermore, even in the best case scenario, the competitiveness of HFC-HDTs is a development for the long term. This would suggest that there is a need to incentivize the HFC-HDT even more than is described in the optimistic perspective. Moreover, it suggests that the governmental bodies should incentivize the HFC-HDT greatly, especially on short term.

All in all, this chapter shows that the adoption of the HFC-HDT shows a feedback loop where more manufactured trucks mean less cost and thus better adoption of the technology. These conclusions can therefore be seen as an additional very influential factor regarding the successful implementation of HFC-HDTs in the transport sector in the EU. This potential feedback loop can be positive when the implementation of HFC-HDTs is well incentivized, but it could also result in a negative feedback loop if the cumulative amount of HFC-HDTs is not sufficient enough. This potential feedback loop has a very big potential when it comes to successfully implementing HFC-HDTs within the EU. It could therefore be argued that this factor, the affordability or competitiveness of HFC-HDTs, is one of the most important factors to determine its success. This is especially the case for the decision makers of the operators tasked with the decision whether to invest in HFC-HDTs or other zero-emission drivetrains for HDTs in the near future.

8. Conclusions

Within the previous chapters, the sub research questions were answered and separate SFF frameworks were developed and explained. The research question to be answered in this research is an accumulation of these answers, together with the empirical findings of the learning curve calculations. To re-iterate, the main research question is:

"Under which conditions can hydrogen fuel-cell heavy duty trucks be successfully adopted for long haul transport within the European Union?"

Chapter four through six provided very useful insights in the different categories of factor or conditions which can influence the adoption of HFC-HDTs. This is shown in the developed SFF framework. This framework has been used as a tool to further examine one of the factors, namely the production costs of HFC-HDTs. The results from these calculations have provided further insights into which conditions would be necessary or helpful for the successful implementation of HFC-HDTs.

Firstly, there are certain conditions which are an absolute necessity, it would otherwise be nearly impossible to use HFC-HDTs at all. These mainly relate to the technological feasibility and are: **truck availability, hydrogen fuel availability,** and a basic **refuelling infrastructure**. However, to just have the bare necessities is not enough to fully adopt the use of HFC-HDTs. Furthermore, there are still huge steps to be made when HFC-HDTs are to be fully used in the transport sector. It is mainly the upscaling of the abovementioned factors which is important for larger scale use, e.g., higher density of HRSs. Another technological condition is the sustainable **hydrogen production** method, this should be based on an abundance of sustainable energy as fast as possible in order to ensure HFC-HDTs to be genuinely zero-emission.

When it comes to societal factors, there are certain conditions which could notably increase the potential of HFC-HDTs to become successful. These are mainly connected to political factors as well. But one particular condition is the **acceptance of using hydrogen as a fuel** for HFC-HDTs. When the overall acceptance is high, the use of hydrogen as a fuel can become higher as well. This goes hand in hand with the overall **environmental awareness** within society which has been increasing over the past years. This trend could accelerate the move towards zero-emission HDTs but does not guarantee the success of HFC-HDTs over other alternatives. To ensure that there is sufficient acceptance of HFC-HDTs, the image of this technology in the media should be positive. This can be done by governmental bodies setting up information campaigns which highlight the advantages of using this technology whilst also addressing and resolving concerns.

As mentioned above, the societal factors have influence on political factors. Furthermore, political factors play a key role in the adoption of HFC-HDTs, this can also be seen in the SFF framework, where policies and regulations are central to a lot of relations. The main driver behind implementing HFC-HDTs are therefore **policies and regulations**. These have the possibility to promote this particular technology over its alternatives or discourage it. When it comes to particular conditions for implementing HFC-HDTs successfully, it is important for policies and regulations to promote the use of them or at least accommodate it. Firstly, the EU should have regulations and standardized protocols which enable the hydrogen production and infrastructure, this would facilitate the necessities for implementing HFC-HDTs. However, the scenario calculations proof that this is not enough as the **production costs** and thus the purchasing costs remain high relative to the diesel HDT. Therefore, in order to successfully implement HFC-HDTs within the EU, far more policies and regulations should be put into place by the EU and member states which promote this specific technology. Firstly, the EU should continue funding several hydrogen projects which will help in developing the abovementioned standardized protocols. Secondly, the EU should put a tax on emission emitting fossil fuel based transport modes. The proceeds of this tax measure can be directly coupled with a subsidy for the purchase of HFC-HDTs, which would lower the purchasing costs for operators and incentivize the use of HFC-HDTs. However, the proceeds will most likely not be enough and other aspects such as hydrogen production and infrastructure would greatly benefit from subsidization. This means that the EU and its member states should use money from their sustainability budgets to promote sustainable hydrogen production and its infrastructure. Lastly, where it is common to put tax on fossil fuels, the national governments should subsidize hydrogen fuel to lower its price and incentivize the use of it. These conditions would most likely need more money than the current budget would allow but the EU needs to allocate more resources in order to quickly mitigate the effects of climate change.

Lastly, besides the policies and regulations, the **productions costs**, as briefly mentioned above, is one of the most important factors. This is because it is directly tied to the purchasing cost and thus the investment needed by operators. This factors is examined in three different scenarios based on learning rates (11%, 15%, and 18%), and three perspectives within each scenario based on different assumptions which resulted in different annual market growth rates (10%, 25%, and 40%). Within each scenario and perspective, the competitiveness of HFC-HDTs is a long term prospect with the best case scenario suggesting competitiveness between 2040 and 2045. These findings further underline the necessity of the conditions described in the previous section, and the reliance on policies and regulations.

All in all, even though it is still uncertain whether or not the HFC-HDT has a definitive future in the transport sector, some condition can have a considerable impact. The most important condition is the use of **policies and regulations** to tax fossil fuel based transport and subsidize multiple facets of the HFC-HDT system. Moreover, this is also connected to the **production costs**, which is a crucial factor for operators. Without the described measures, the successful implementation of HFC-HDTs is unlikely but with enough supportive policies and regulations, the HFC-HDT has the potential to be competitive over time. These supportive policies will also ensure truck manufacturers and operators that the use of HFC-HDTs is viable and their investments are worthwhile.

9. Discussion

During the process of this particular research, different assumptions had to be made regarding certain aspects of the adoption of HFC-HDTs in the EU. This has also been done to properly scope the research to ensure a useful end deliverable and basis for future research. In this chapter reflections on the research will be examined, and limitations will be discussed. These findings will be discussed and can be the foundation for future research. Firstly, the limitations of this specific research will be discussed, after which future research recommendations will be made.

Limitations

Due to the nature of this research and the scope, there are certain limitations. First of all, the technology and sector examined, HFC-HDTs and the transport sector in general, are currently subject to a fast changing technology landscape. This because it can be argued that the overall transport sector is forced to change from its current dominant technology, based on fossil fuels, to zero-emission drivetrains. This push towards new technologies means that developments and changes in the availability, assumptions, and research findings of the technology are very rapid. HFC-HDTs and the accompanying hydrogen infrastructure are no exception to these rapid new insights. Because of this, certain cut-off points had to be made when researching new developments, this is especially present in the findings where current developments are the focal point of the research. Furthermore, the scope of this research does not allow for every single factor to be discussed, as this is an ever increasing web of factors which are interwoven. This means that findings on influential factors were analysed on their relation to the implementation of HFC-HDTs and included or not based on their significance.

This means that certain decisions had to be made regarding which factors to include or not, which are discussed in the research itself. A good example is the final SFF framework presented in the third chapter and the conclusion, which does not include all the factors from the separate chapters and SFF frameworks, this is done due ensure readability and clarity.

Another limitation of this research are the calculations done in the seventh chapter. This chapter is based on future scenarios and makes use of the learning curve equations. The scenarios are based on learning rates found in scientific literature, there is however no consensus on the exact learning rate. The learning rates used in this study should therefore be considered as possibilities and not certainties. The same principle applies to the perspectives. These perspectives are based on assumptions, explained in the chapter itself, made through analysis and deductions of findings in this research. These scenarios and perspectives should therefore be the subject of future research as well, this will be discussed in the next section.

One of the primary limitations of this thesis is the lack of empirical research done in the thesis itself. This has led to extensive reviewing of the used literature but does mean there might be a lack verification from sources such as experts. This has probably limited the extent of the findings from this thesis, but as mentioned before, has been supplemented with more extensive literature research. Future research should therefore be more focussed on obtaining empirical evidence for the findings of this thesis, but this will be discussed in more detail in the next section. When this thesis is used as a foundation for future empirical research, this weakness can be turned into a strength as certain findings do not need to be discussed with experts, but more on this in the next section.

Future recommendations

The limitations of this research related to the scope can be translated to opportunities for future research. Furthermore, as mentioned above, the sector is fast changing and future research has to acknowledge and anticipate on sudden changes.

As mentioned in the last section under limitations, one of the main limitations is the lack of empirical research. This can however be turned into a strength by focusing on the importance of this research and the future focus of research. Firstly, one of the findings of this thesis is that HFC-HDTs are technologically possible. This means that it is not necessary to conduct a large number of interviews regarding the technological feasibility. However, the immense importance of policies and regulations is concluded as well. This would be the best starting point for future research, where empirical research should be done via interviews, surveys, or Delphi studies among experts in that field. This would empirically test the effect of the measures mentioned in the conclusions. These methods could contain discussion surrounding questions such as: “Is it feasible for the EU to subsidize operators when purchasing HFC-HDTs? How high can and should these subsidies be according to policymakers?” or “Is it realistic for national governments to invest in a refuelling infrastructure for HFC-HDTs or would they need to be incentivized by the EU?”. Another interesting possibility could be to consider a more niche use of HFC-HDTs and discuss the possibilities of using HFC-HDTs only on certain big transportation routes and how this would affect factors such as the production costs and the role of policies and regulations in such as scenario. Lastly, the scenarios and perspectives used in this thesis should be subject to future empirical research as well. The learning rates can be examined by interviewing manufacturing experts and how they expect the costs to go down. Furthermore, the assumptions made for the perspectives can be discussed with expert to get other input from what they think would lead to certain annual market growth rates. These are just a few interesting notions for future research to focus on which use this thesis as a foundation.

As concluded from this research, there are certain conditions which are an absolute necessity for a HFC-HDT transport network to be put into place. These conditions, such as sufficient hydrogen production and refuelling infrastructure, are therefor essential and need to be well researched and established as well. For example, the production of hydrogen is the subject of much research, and new production methods are developed and optimized constantly, if these developments are adequately researched they can influence the future course of HFC-HDTs and the transport sector in general. Of course, the same goes for competing technologies such as the BE-HDTs and their course of developments. In future research and discussions about the dominant technology, the comparison has to be made between all possible zero-emission drivetrains in order to ensure the right course of action.

A good step towards researching whether HFC-HDTs are actually viable in real life applications is to actually test the technology on a larger scale. There are multiple projects and pilots currently in place but they are mostly on a smaller scale. It could be very beneficial for institutions such as the EU to test it on a larger scale over a longer period to see which specific aspects of the technology are viable in the current system. This is of course not limited to the EU and researchers should always consider findings from all actors.

When it comes to concrete recommendations for actors and truck operators when it comes to implementing HFC-HDTs, it is most important that governmental bodies create a clear vision and ambitions in order to ensure truck operators of their decisions. The clarity will greatly encourage or discourage the operators which would benefit the overall market. Regarding the actors itself, it can be very beneficial to cooperate with one another or with governmental bodies to gain as much knowledge as fast as possible. This can range from making investments to sharing knowledge and concerns among all the actors.

Contributions

The contribution of this research is mainly the SFF framework for the implementation of HFC-HDTs. This is developed for all different actors to help in their decision making regarding investments, policies, regulations, etc. This SFF framework can be used for different means by different actors. It can be used by economic motivated actors, such as investors and manufacturers, to see whether certain requirements they deem to be necessary are met. An example could be whether the EU has a sufficient infrastructure for refuelling and production of hydrogen, or certain policies or subsidies are instated or granted for their projects. Accordingly, the framework can be used as a checklist upfront as well as a checklist over time to see if HFC-HDTs are viable for a future LH transport sector within the EU.

Furthermore, the findings from this research show that there is a need to make a decision regarding the future of the LH transport sector within the EU. Currently, it can seem that, in particular, the political institutions seem to be indecisive, which makes the future of potential investments uncertain and can cause investors to be sceptical about technologies. The perspectives discussed in the scenario calculations also show that it is important that the production costs of the HFC-HDTs go down to make them competitive and profitable, which is possible if the market has a significant annual growth. In order to ensure this, the conditions discussed in this research need to be considered by all actors. Therefore, this research clarifies the urge for decision makers to act quickly and be decisive when it come to the move towards a zero-emission transport system within the EU.

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11. Appendices

11.1. Input data – number of trucks

Regarding the input data for the different calculated scenarios, the learning rates are discussed in the chapter itself, but for the cumulative amount of HFC-HDTs are more detailed explanation is provided in this appendix. Especially the starting point of the input data and as mentioned in the chapter itself, the data for the calculations is global due to the free universal economic market. One of the most important data points is the estimated number of global commercial vehicles, Regarding the data, it is estimated from the global number of commercial vehicles, which was roughly 335 million commercial vehicles in 2015 (SCMO, 2022). This of course, includes more than just the heavy duty trucks which this thesis focusses on. However, the scaling and learning effects are not only limited to heavy duty trucks. The implementation of hydrogen fuel-cells in all commercial vehicles will benefit the production costs of heavy duty trucks greatly, as the cumulative number of vehicles would be much higher. Therefore, the input data used for this thesis makes use of the estimated global number of commercial vehicles as mentioned above.

According to Cullen et al. (2021) the EU plans a market penetration of 45,000 HDVs by 2030 and 1.7 million HDVs by 2050. These numbers can be used as a reference when it comes to annual growth for the perspectives used but are not definitive for the calculations as these numbers are predictions and apply to the EU alone. Whereas the calculations are done on the notion that the global number of HFC-HDVs would be significantly larger. Furthermore, in order for HFC-HDVs to even make a small introduction into the transportation sector, there needs to be accompanying infrastructure for production, transport, storage, and refuelling of hydrogen. The specifics on the factors from the SFF framework are however discussed in the chapter themselves.

Regarding the growth of the market, different sources state a CAGR of between 4.2 and 5.2 per cent until 2028. These estimates are related to the monetary value of the market instead of the actual vehicle count. For that reason, the number of commercial vehicles is kept at 335 million for the calculations of this thesis. Moreover, estimates regarding market growth on a global scale are quite uncertain. Besides that, the calculations make use of all commercial vehicles instead of only HDTs, which can be argued to be beneficial as mentioned above. Furthermore, the market growth of zero-emission HDTs will mostly likely grow at a much more rapid pace than the growth of the sector, this is due to the fact that there is a global trend to switch towards sustainable drivetrains instead of the conventional diesel ICE HDTs. All of the reasoning above and the arguments within the eight chapter are why the perspectives are set at an annual growth rate of 10 per cent, 25 per cent, and 40 per cent. These percentages are set at a fixed annual growth rate as to keep the calculations manageable within the scope of this research, as it will be fluctuating in real life from year to year.