Modeling a potential hydrogen refueling station network for fuel cell heavy-duty vehicles in Germany in 2050

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DISSERTATION

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Preface

“If I have seen further it is by standing upon the shoulders of giants.”

- Sir Isaac Newton

This thesis was written during my research at the Fraunhofer-Institute for Systems and Innovation Research ISI in Karlsruhe. Whilst working on the problems that cumulated in the present text, I experienced help and support from many sides and I would like to acknowledge the most important ones here.

First of all, I am grateful to my supervisor, Prof. Dr. Martin Wietschel, for the possibility to perform research in his group and his confidence in my work. I would also like to thank him for many suggestions during this whole project and stimulating discussions regarding this thesis and beyond.

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Ebenfalls danke ich meiner Familie, die mir ein sorgenfreies Aufwachsen und eine umfassende Ausbildung ermöglichte, insbesondere meiner Mutter für ihre konstante, selbstlose Unterstützung auch in schwierigen Zeiten.

Die allergrößte und unschätzbare Unterstützung erhalte ich von meiner Frau Jana Rose. Ich kann ihren Beitrag nicht hoch genug würdigen und freue mich auf das, was kommt.

Abstract

Heavy-duty traffic is responsible for about eight percent of global greenhouse gas emissions. A potential solution to reduce these greenhouse gas emissions is to use fuel cell heavy-duty vehicles powered by hydrogen produced from renewable energy sources. However, widespread adoption of fuel cell heavy-duty vehicles would require a new hydrogen refueling station network and would have major impacts on the electricity sector. This thesis aims at evaluating a potential hydrogen refueling station network for the large-scale adoption of fuel cell heavy-duty vehicles in Germany in 2050.

A new model-based approach to developing alternative fuel station networks for heavy-duty vehicles is introduced, which generates the required input data and develops a new optimization model. Vehicle and infrastructure user requirements collected for this thesis allow the determination of relevant framework parameters, e.g. vehicle efficiency, range, and refueling station technical layout. Further, an analysis is conducted of several thousand heavy-duty vehicle traffic kilometers on highways to understand current traffic demand and flows. Subsequently, a Flow-Refueling Location Model, which is extended by a node-capacity restriction, enables the derivation of an optimal hydrogen refueling station network with the fewest stations needed to meet the traffic demand. A link to an open-source electricity model makes it possible to assess what value a flexible hydrogen production for the HDV station network has for the electricity system as a whole.

The results show that hydrogen refueling stations for heavy-duty vehicles are very different in size compared with passenger car stations. The network modeling indicates that a hydrogen refueling station network of about 140 stations with a daily demand capactiy of 30 tons of hydrogen per location could cover all the heavy-duty traffic. This potential station network would cause annual costs of about nine billion euros per year in 2050, including operating and capital expenditures for the stations, electrolyzers and electricity. Coupling this station network with the electricity system could reduce the annual costs by about one billion euros due to the increased flexibility of hydrogen production for the station network, as could the construction and operation of a pipeline network with centralized hydrogen production instead of decentralized production. In sum, this thesis contributes to a better understanding of a large-scale hydrogen refueling infrastructure for heavy-duty vehicles and the potential to reduce its costs by coupling flexible hydrogen production with the electricity system.

This thesis is based on my research conducted at the Fraunhofer Institute for Systems and Innovation Research ISI under the supervision of Professor Dr. Martin Wietschel at the Institute for Industrial Production (IIP) at the Karlsruhe Institute of Technology. It is written in English and submitted for a doctoral degree in engineering (Dr.-Ing.).

Kurzfassung

Schwerlastverkehr ist für rund acht Prozent der globalen Treibhausgasemissionen verantwortlich. Zu deren Reduzierung ist der Einsatz von Brennstoffzellen-Schwerlastfahrzeugen, welche Wasserstoff aus erneuerbaren Quellen verwenden, eine mögliche Lösung. Eine massive Verbreitung von Brennstoffzellen-Schwerlastfahrzeugen würde jedoch ein neues Wasserstoff-Tankstationsnetz erfordern und den Stromsektor beeinflussen. Diese Dissertation zielt auf die Bewertung eines potenziellen Wasserstoff-Tankstationsnetzes für Brennstoffzellen-Schwerlastfahrzeuge in Deutschland im Jahr 2050 ab.

Für die Entwicklung alternativer Tankstationsnetze für Schwerlastfahrzeuge wird ein neuer Ansatz vorgestellt, welcher erforderliche Eingangsdaten generiert und ein neues Optimierungsmodell entwickelt. Die für diese Dissertation gesammelten Fahrzeug- und Infrastrukturnutzeranforderungen ermöglichen es, relevante Rahmenparameter wie Fahrzeugeffizienz, Reichweite und Tankstationsauslegung zu bestimmen. Weiterhin wird eine Analyse von mehreren tausend Schwerlastkilometern erstellt, um aktuelle Verkehrsnachfragen und -ströme zu verstehen. Anschließend ermöglicht ein Flow-Refueling-Location-Modell, erweitert um eine Standortkapazitätsbegrenzung, die Ableitung eines potentiellen Wasserstoff-Tankstationsnetzes mit den wenigsten Stationen zur Versorgung des Verkehrs. Eine Verknüpfung mit einem Open-Source-Strommodell erlaubt es, den Flexibilitätswert einer dezentralen Wasserstofferzeugung über flexibel einsetzbare Elektrolyseure für das Tankstationsnetz zu bewerten.

Dass Wasserstofftankstationen für Schwerlastfahrzeuge hinsichtlich ihrer Größe sehr unterschiedlich im Vergleich zu Pkw-Stationen sind, zeigen die Ergebnisse. Die Netzwerkmodellierung resultiert in einem Wasserstofftankstationsnetz von rund 140 Stationen, welches den gesamten Schwerlastverkehr bei einer täglichen Bedarfsobergrenze von 30 Tonnen Wasserstoff pro Standort abdeckt. Dieses potenzielle Stationsnetz würde im Jahr 2050 jährliche Kosten von rund neun Milliarden Euro pro Jahr verursachen, einschließlich Betriebs- und Kapitalkosten für Stationen, Elektrolyseure und Strom. Die Kopplung dieses Tankstationsnetzes mit dem Stromnetz könnte durch eine erhöhte Flexibilität der Wasserstofferzeugung für das Stationsnetz rund eine Milliarde Euro an den genannten Ausgaben reduzieren, ebenso wie der Bau und Betrieb eines Pipelinenetzes mit zentraler Wasserstofferzeugung anstelle dezentraler Erzeugung. Insgesamt trägt diese Arbeit zu einem besseren Verständnis einer großen Schwerlastfahrzeug-Wasserstofftankinfrastruktur und deren Flexibilitätswert bei der Wasserstofferzeugung durch Kopplung mit dem Stromsektor bei.

Diese Dissertation wurde im Rahmen meiner Forschungsarbeit am Fraunhofer-Institut für System- und Innovationsforschung (ISI) erstellt und von Prof. Dr. Martin Wietschel am Institut für industrielle Produktion (IIP) am Karlsruher Institut für Technologie (KIT) betreut. Der angestrebte Abschluss ist Dr.-Ing.

Contents

List of Abbreviations

AF	Alternative fuels
AFP	Alternative fuels and powertrains
AF-HDV	Alternative fuel heavy-duty vehicles
AFS	Alternative fuel stations
BEV	Battery electric vehicle
BIO	Biofuels
CAD	Computer aided design
CAPEX	Capital expenditures
CAT	Catenary electric vehicle
CCGT	Combined-cycle gas turbines
CNG	Compressed natural gas
CO_2	Carbon dioxide
DMS	Demand side management
EAC	Equivalent Annual Cost
eMET	e-methane
eSYN	e-synfuel
EU	European Union
FC	Fuel cell
FCEV	Fuel cell electric vehicle
FC-HDV	Fuel cell heavy-duty vehicle
FCH JU	Fuel Cell and Hydrogen Joint Undertaking
FILP	Flow interception location problem
FOM	Fixed operating and maintenance cost
FRLM	Flow refueling location method
FRLP	Flow refueling location problem
GH	Gaseous hydrogen
GHG	Greenhouse gas emissions
GVW	Gross vehicle weight
HDRSAM	Heavy-Duty Refueling Station Analysis Model
HDV	Heavy-duty vehicle
HEV	Hybrid and plug-in hybrid electric vehicle
HP	High pressure
HRS	Hydrogen refueling stations
HV-AC	High-voltage alternating current lines
HV-DC	High-voltage direct current links
ICE	Internal combustion engine
LCOE	Levelized cost of electricity
LCOH	Levelized cost of hydrogen
LDV	Light duty vehicle
LH	Liquefied hydrogen
LMC	Locational marginal cost

LMP	Locational marginal price
LNG	Liquefied natural gas
LP	Low pressure
LOHC	Liquid organic hydrogen carriers
LPG	Liquefied petroleum gas
MCLP	Maximal covering location problem
NC-FRLM	Node-capacitated flow refueling location method
NEP	German network development plan
NIP	Network interdiction problem
NSP	Network sensor problem
NUTS	Nomenclature of Territorial Units for Statistics
OCGT	Open-cycle gas turbines
OD	Origin-destination
OEM	Original equipment manufacturer
OPEX	Operational expenditures
PEM	Polymer electrolyte membrane
PyPSA	Python for Power System Analysis
RE	Renewable energies
SCP	Set covering problem
SME	Small and medium enterprises
SMR	Steam methane reforming
TCO	Total cost of ownership
tkm	Ton kilometers
TRL	Technology readiness level
ttw	Tank-to-wheel
TWkm	Terrawatt kilometers
TYNDP	Ten-Year Network Development Plan
VOM	Variable operating cost

1. Introduction

"The truck is the black sheep of climate protection in the transport sector - and the transport sector as a whole is our black sheep in climate protection." Mrs. Sylvia Kotting-Uhl, the Chairwoman of the Committee on Environment, Nature Conservation and Nuclear Safety in the German Parliament, opened a public hearing of expert witnesses on the topic of European carbon dioxide emissions standards for heavy-duty vehicles (HDV) in February 2019 with this sentence (German Parliament, 2019). Her speech highlights the importance of decarbonizing trucks on multiple levels – from global to national.

1.1 Motivation

There is strong proof that the observed global climate change is being caused by carbon dioxide (CO_2) and other so-called greenhouse gas emissions (GHG) from human activity. In order to limit global warming to 2°C, GHG emissions must be cut by 95 % by 2050 (Intergovernmental Panel on Climate Change, 2013). GHG emissions from global transportation account for 23 % of total global GHG emissions (cf. Figure 1), and about 34 % of these transport-related emissions are due to HDVs – 8 % of total global emissions. According to International Energy Agency (2017a), GHG emissions of the HDV sector are expected to grow, if no major technological changes occur, as most of the fleet runs on fossil fuels and the amount of global truck traffic is expected to increase (e.g. through e-commerce).

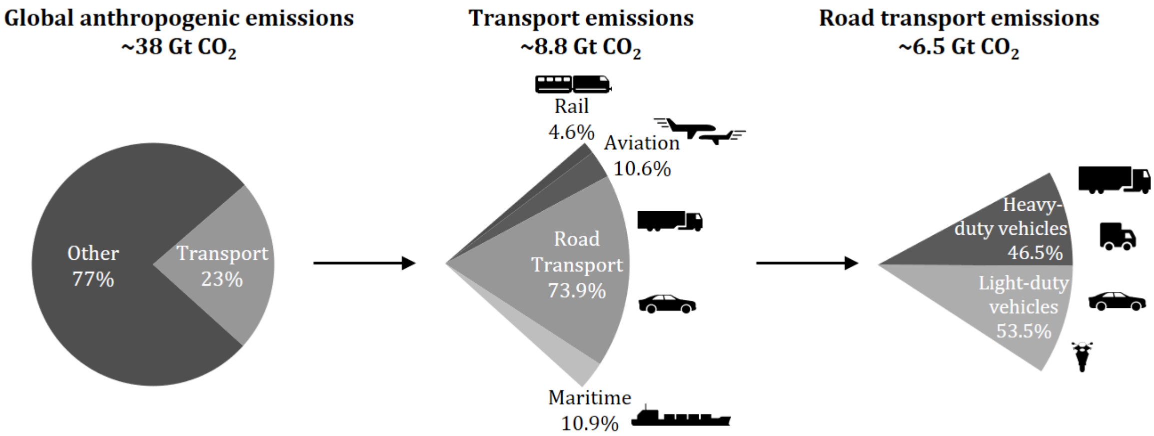

Figure 1: Share of transport sector in global GHG emissions (left), share of road transport within the transport sector (middle) and share of HDVs in road transport (right) in 2011 (own illustration based on Intergovernmental Panel on Climate Change (2013))

Hence, the European transport sector is facing one of the greatest challenges of the coming decades. It is one of three regions with the highest GHG emissions due to HDVs (cf. Figure 2), but significant reductions in GHG emissions are needed to achieve both global and European climate goals (International Energy Agency, 2017b). Long-haul

HDVs above 16t of gross vehicle weight (GVW) account for more than half of the GHG emissions of all truck categories (European Commission, 2019). In 2019, the European Union (EU) introduced regulations on the GHG emissions of HDVs (Eickhout, 2018; Rodriguez, 2019). These regulations aim to cut GHG emissions from newly registered HDVs by 30 % by 2030 compared to 2019 (Eickhout, 2018), and include an incentive mechanism for zero-emission vehicles in the move towards a carbon-neutral Europe by 2050.

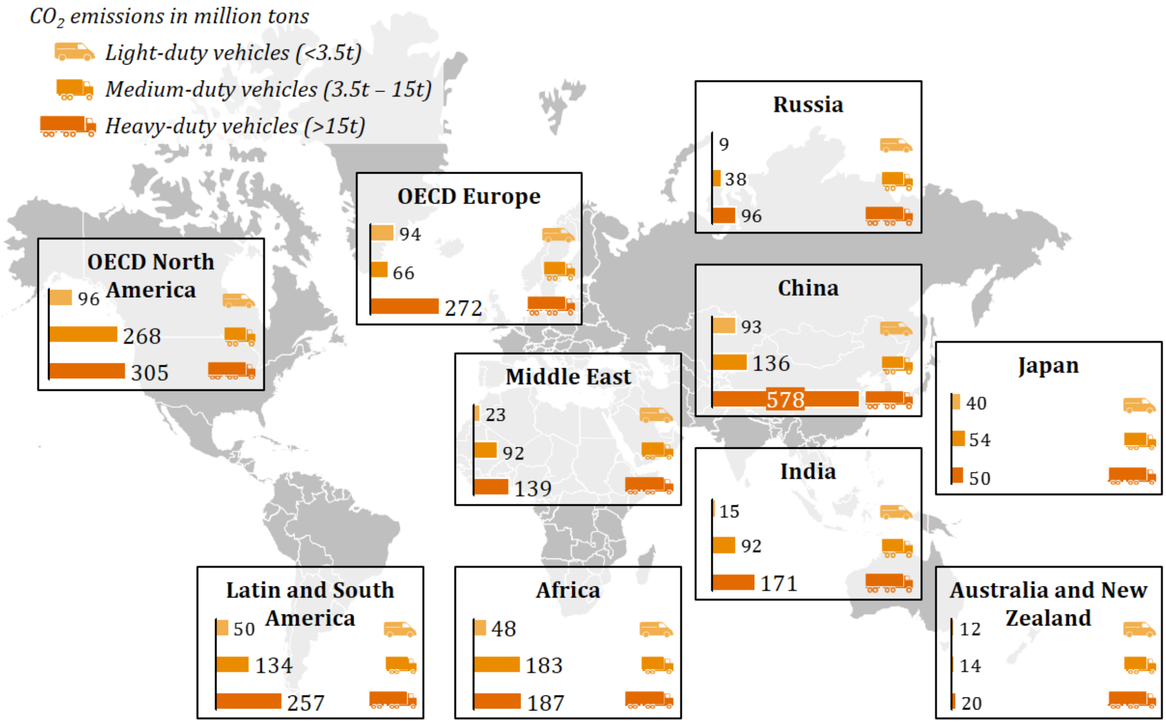

Figure 2: Global well-to-wheel GHG emissions of road freight vehicles in 2015 (own illustration based on International Energy Agency (2017b))

As Europe's largest economy and one of the largest emitters of GHG emissions from HDVs (Plötz et al., 2019), Germany's specific goal for the transport sector is a general 40 % GHG emissions reduction by 2030 (German Federal Environment Agency, 2019a; German Federal Ministry of Transport and Digital Infrastructure, 2019). The 2050 target is adopted from global climate agreements and is not further specified either for the transport sector or for HDVs. Germany has the highest volume of road freight traffic within Europe (315 bn tkm of a total 1,850 bn tkm, equivalent to 17 %), of which more than 300 bn tkm per year are for HDVs above 16t GVW (Eurostat, 2016). In Germany, HDVs represent only 10 % of the total truck fleet. However, they account for about 50 % of the total truck GHG emissions as shown in Figure 3.

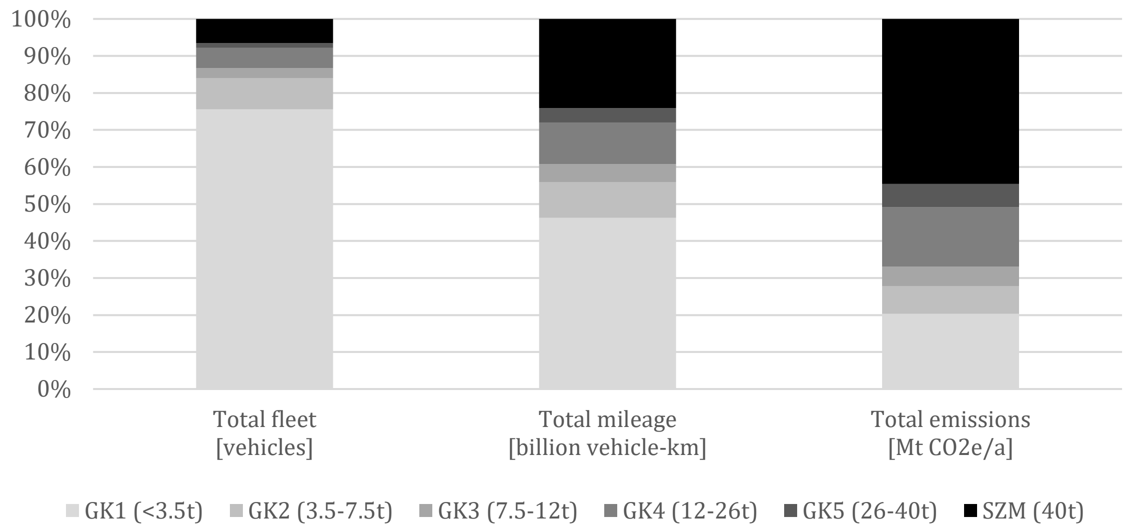

Figure 3: Overview of German truck fleet, mileage and emissions clustered by size categories (Timmerberg et al., 2018)[1]

To sum up, decarbonizing the road freight transport sector and especially HDVs represents a major problem for achieving global climate goals. The transition from the current fossil-fueled to GHG-neutral HDVs poses a major challenge for global HDV markets, such as Germany.

1.2 Problem definition and research gaps

A potential solution for reducing GHG emissions in the transport sector is the use of alternative fuel heavy-duty vehicles (AF-HDV) and an accompanying alternative fuel station (AFS) infrastructure (Capar et al., 2013). In the more progressive climate protection scenarios featured in current research, AF-HDVs dominate the market, indicating their positive influence on GHG emissions reductions (Kluschke et al., 2019a). Within this segment, vehicles using public refueling infrastructure rather than closed fleet systems have the largest potential for AF-HDV (Nesbitt and Sperling, 1998). However, installing a new AFS infrastructure comes with high investments and low utilization at the beginning (Yeh, 2007). In addition, AFS networks bear the risk of being either over-sized (not investment efficient) or under-sized (slows down market diffusion of alternative powertrains), so that those responsible for planning and realizing AFS infrastructures need decision support. In summary, defining and modeling an optimal AFS network before large-scale installation is a valuable yet complex exercise for research, which so far has focused mainly on passenger cars (see for example: Kuby and Lim, 2005; Wang and Wang, 2010; Capar et al., 2013; Jochem et al., 2016; Zhang et al., 2017) and has rarely been carried out for HDVs (Kluschke et al., 2019a).

[1] "GK" refers to the German freight vehicle weight classes (German: "Gewichtsklasse"); "SZM" refers to a tractor and trailer combination (German: "Sattelzugmaschine"). "CO2e" (Carbon dioxide equivalent) describes different GHGs in a common unit. For any quantity and type of greenhouse gas, CO2e signifies the amount of CO_2 which would have the equivalent global warming impact.

One AF-HDV technology with zero tank-to-wheel (ttw) GHG emissions is the fuel cell powertrain. Fuel cell electric vehicles (FCEV) use on-board hydrogen storage to generate electricity within a fuel cell. While multiple AF-HDV technologies are currently competing to replace diesel powertrains (Plötz et al., 2018), fuel cell heavy-duty vehicles (FC-HDVs) show some advantages. Their benefits include a high technological readiness level (TRL), long range due to large energy storage capabilities at low additional weight (e.g. in comparison with battery storage) and short refueling times (Plötz et al., 2018). On the downside, FC-HDVs face increased energy requirements due to high well-to-wheel[2] conversion losses. Currently, several FC-HDVs have been announced or are already in operation as prototypes in various projects (see Table 1).

Table 1: List of current FC-HDV prototype operations including technical details and project partner

OEM	Year announced	H2 tank volume	Weight (max.)	Drive power	Range (max.)	Source
Hyundai	2018	33 kg	34 t	350 kW	400 km	Hyundai Motor Company (2018)
Iveco	2018	50 kg	36 t	400 kW	800 km	FCB 2018)
Kenworth	2018	50 kg	36 t	500 kW	800 km	Field (2018)
Kenworth	2017	20 kg	36 t	415 kW	250 km	Kenworth (2018)
MAN	2016	35 kg	34 t	250 kW	400 km	Barrett (2016)
Nikola Motors	2017	100 kg	36 t	735 kW	1,600 km	Nicola Motors (2018)
Scania	2018	35 kg	27 t	-	500 km	Wassén (2018)
VDL	2018	30 kg	44 t	160 kW	350 km	Wouter van der Laak (2018)

However, it is still unclear whether these prototypes are suitable for most HDV applications as current research has rarely examined HDV user requirements and focused mainly on passenger cars (Graham-Rowe et al., 2012; Axsen et al., 2016; Esch, 2016; Globisch et al., 2018a; Globisch et al., 2018b; Hardman et al., 2018). According to this research, mainstream buyers of passenger cars with alternative powertrains are less engaged with environmental issues, less tech-orientated and value renewable electricity less than pioneer buyers (Axsen et al., 2016). In addition, especially for commercial car pool fleets, the perceived organizational usefulness and perceived ease of use are important factors fostering the acceptance of new powertrain vehicles (Globisch et al., 2018a). This is why FC-HDVs should be comparable to current diesel HDVs with respect to range requirements, refueling time or willingness to make refueling detours. Knowledge about HDV user requirements will help to support a

[2] Well-to-wheel typically defines the assessment of energy losses or environmental impacts across a products total lifespan including production, operation and disposal.

suitable technology layout, which in turn will increase the acceptance and use of FC-HDVs in real applications.

Ceteris paribus, modeling and analyzing an AFS network for fuel cell vehicles has mainly focused on passenger cars when considering the respective user requirements (see for example: Greene et al., 2008; Seydel, 2008; Robinius et al., 2017a; Grüger et al., 2018). This work is not applicable to HDVs due to the different market structures of passenger vehicles and HDVs (higher vehicle utilization of HDVs, almost perfect OEM competition for passenger cars vs. oligopoly for HDVs, etc.) as well as different vehicle and infrastructure technology (power demand, tank sizes, hydrogen demand per refill, no standard for refueling procedure for HDV at 700 bar, etc.).

Further, the implications of a HDV-AFS network for the electricity system seem to be different from passenger car applications. Recent research shows distinctions regarding, e.g. the spatial and absolute required amount of electricity as well as the daytime load distribution (Plötz et al., 2019). The potential to use the infrastructures of the transport sector to enable a more effective integration of renewable energies (RE) has been explored for passenger cars with alternative powertrains (Gnann et al., 2018) but not for FC-HDVs. From an electricity system perspective, no comprehensive analysis exists so far of using dedicated hydrogen production for a HDV-HRS network as a potential flexible option to integrate more RE.

The task of decarbonizing HDVs, especially in HDV-intensive countries such as Germany, combined with the lack of research on AFS network modeling for FC-HDVs poses a promising field for research. Further, research on designing hydrogen refueling stations (HRS) for HDVs as well as modeling a HDV-HRS network for a major market seems necessary, beneficial and relevant in order to determine the future potential of FC-HDVs in the transport sector, to define the relevant legislative measures, and to focus technology development activities.

1.3 Research questions and outline

Based on the three identified research gaps, (i) missing modeling of optimal AFS networks for HDVs, (ii) unclear user requirements for AF-HDVs, (iii) lack of analysis of the interaction of a potential HDV-HRS network and the electricity system, the main research question of this thesis is:

What is the spatial, technological and economic design of an optimal HDV-HRS network for zero-emission FC-HDVs that meets user requirements and the climate targets for Germany in 2050?

This research question has, to the best of the author’s knowledge, not yet been comprehensively analyzed. Since FC-HDVs are a new technology, and data on vehicle prototypes or the HDV-HRS infrastructure are rare, a modeling approach is developed to answer the research question for Germany until 2050. This implies four consecutive questions:

What is a suitable method to model an optimal AFS network for HDVs? Similar to the work on user requirements, previous research on modeling AFS networks has focused strongly on passenger cars (cf. section 1.2). Accordingly, when analyzing FC-HDVs and their HRS infrastructure, modeling approaches have to be investigated and adapted to suit HDV characteristics.

What are the current user requirements for HDVs and what are their implications for FC-HDVs and HDV-HRS? It is important to understand behavioral aspects in order to shape technology (vehicle and infrastructure) to suit end user needs (Axsen and Kurani, 2013). As recent research focuses on passenger car requirements (Hardman et al., 2018), this thesis aims to determine HDV user requirements.

What are the technical and economic parameters of a HDV-HRS network and suitable hydrogen supply options? Once user requirements and modeling needs are clear, the resulting HDV-HRS network needs to be described. Apart from the technical and economic parameters for vehicles and infrastructure, the regional distribution and number of HRS needed to supply German HDVs are determined.

These three sub-questions are also required to analyze a HDV-HRS infrastructure in an electricity system context. This makes it possible to answer a final relevant question that focuses on flexibility options and increased RE integration through HDV-HRS: *What are the effects of a HDV-HRS network on the electricity system and what is the value of flexibility in hydrogen production?*

In this thesis, the focus on Germany makes it possible to determine an optimal HDV-HRS network for a major HDV market in 2050. This optimal network is modeled and analyzed from a macro-economic perspective – i.e. without levies, taxes or other surcharges (e.g. profits) – to support governmental decision-makers in understanding the effects of a national HDV-HRS infrastructure.

The structure of this thesis is as follows: Chapter 2 contains background information on the existing definitions of HDVs and technologies enabling their decarbonization (2.1), a literature review of global AFP-HDV market diffusion (2.2)[3], and a presentation of current AFS infrastructure modeling (2.3). Chapter 3 outlines the method to address the above mentioned research gaps. This method features a new AFS model, namely the traffic flow-based optimization model NC-FRLM (Node-Capacity Flow Refueling Location Model) as well as the derivation of local characteristics, such as traffic demand and user requirements, and a link to the electricity system.[4] Chapter 4 presents the relevant techno-economic parameters to run the NC-FRLM for Germany, such as FC-HDV attributes, HDV-HRS portfolio, and hydrogen production. The results of the optimization are presented in chapter 5, which is divided into three parts: First, a definition of the analyzed scenarios (5.1). Second, the optimal design of a HDV-HRS

[3] This chapter is based on Kluschke et al. (2019a).
[4] This chapter is based on Kluschke et al. (2019b) and Kluschke et al. (2020).

network in Germany in 2050 (5.2). Third, the evaluation of the annual costs[5] of the network (5.3). Chapter 6 analyzes the interplay of the HDV-HRS network and the German electricity system[6]. Finally, the thesis is summarized and conclusions are drawn in chapter 7. Figure 4 summarizes the structure of this thesis.

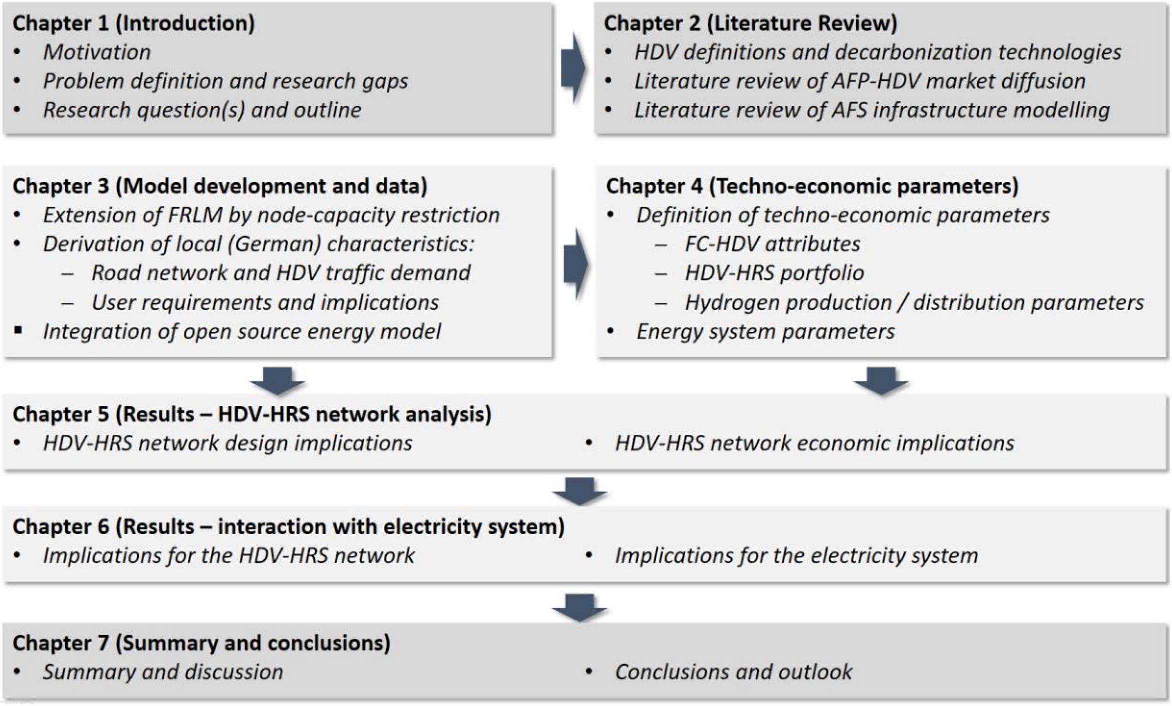

Figure 4: Structure and content of this thesis

[5] Annual costs include operating and capital expenditures for the stations, electrolyzers and electricity. These costs were analyzed from a macro-economic perspective i.e. without levies, taxes or other surcharges.
[6] This chapter is based on Rose and Neumann (2020).

2. Background

This chapter outlines the need for research in the field of HDV decarbonization as well as the related infrastructure and points out what can be learned from earlier work when modeling AFS infrastructure for HDVs. It features three sections: The first section 2.1 defines HDVs according to international standards and presents a brief overview of existing decarbonization options for HDVs. The second section 2.2 presents a literature review of AFP-HDV market diffusion studies to understand the potential market diffusion until 2050. Section 2.3 presents a literature review of infrastructure modeling approaches to gain insights from current modeling approaches.

2.1 Background: Heavy-duty vehicle decarbonization[7]

In order to identify relevant research on AFP market diffusion in HDVs, a comprehensive search was made for publications in online libraries: namely Ebsco, Google Scholar and Science Direct.

2.1.1 Heavy-duty vehicle definitions

Generally, there is no uniform definition of HDVs based on GVW; there are different regional categorizations of HDVs. Some regions, such as the US, define their HDVs as single vehicles ('vehicles' or 'trucks'). Other regions separate HDVs into vehicles and vehicles with trailers ('trailers & semitrailers' or 'tractors'), e.g. the EU and China. Due to these heterogeneous HDV definitions, the definition of HDVs in this section is based on the international truck categories shown in Table 2. The thesis considers the US vehicle category 8, the EU vehicle category N3 and (semi-)trailer category O4, as well as Chinese trucks with a GVW above 16t and a tractor weight above 18t.

[7] The contents of this section have been published in a peer-reviewed paper (Kluschke et al., 2019a).

Table 2: Definition of international truck weight classes and classes considered in the review (International Energy Agency, 2017b)

United States		European Union				China		
Vehicle category	Weight (t)	Vehicle category	Weight (t)	Trailers & semitrailers	Weight (t)	Trucks Weight (t)	Tractors Weight (t)	
		N1	< 3.5	O1	< 0.75			
				O2	0.75 - 3.5			
2b	3.9 - 4.5	N2	3.5 - 12	O3	3.5 - 10	3.5 - 4.5	3.5 - 18	
3	4.5 - 6.4					4.5 - 5.5		
4	6.4 - 7.3					5.5 - 7		
5	7.3 - 8.9					7 - 8.5		
6	8.9 - 11.8					8.5 – 10.5		
7	11.8 – 15.0			O4	> 10	10.5 - 12.5		
8a	15.0 - 27.2					12.5 - 16		
		N3	> 12			16 - 20	18 - 27	Considered
						20 - 25		
8b	> 27.22					25 - 31	27 - 35	
						> 31	35 - 40	
							40 - 43	
							43 - 46	
							46 - 49	
							> 49	

2.1.2 Decarbonization options: alternative fuels and powertrains

Decarbonization options for HDVs can be separated into two categories: alternative fuels and alternative powertrains as illustrated in Figure 5.

Alternative fuels minimize the specific GHG emissions of HDVs with internal combustion engines (ICE) and can be based on fossil fuels or renewables. Liquefied petroleum gas (LPG) contains mainly propane and butane, which are liquefied at comparatively low pressures of around five to ten bar. Liquefied natural gas (LNG) represents a similar state of aggregation, but contains mainly methane and is liquefied by cooling the gas down to -160°C at below four bar. In contrast, compressed natural gas (CNG) is stored in gaseous form in the tank at 200 bar. Renewable fuels include e-methane (eMET, gaseous, 200 bar) and e-synfuels (eSYN, liquid at atmospheric pressure) produced using electricity in power-to-gas and power-to-liquid applications, respectively. Biofuels (BIO) are liquid or gaseous fuels produced from biomass such as plant or animal waste.

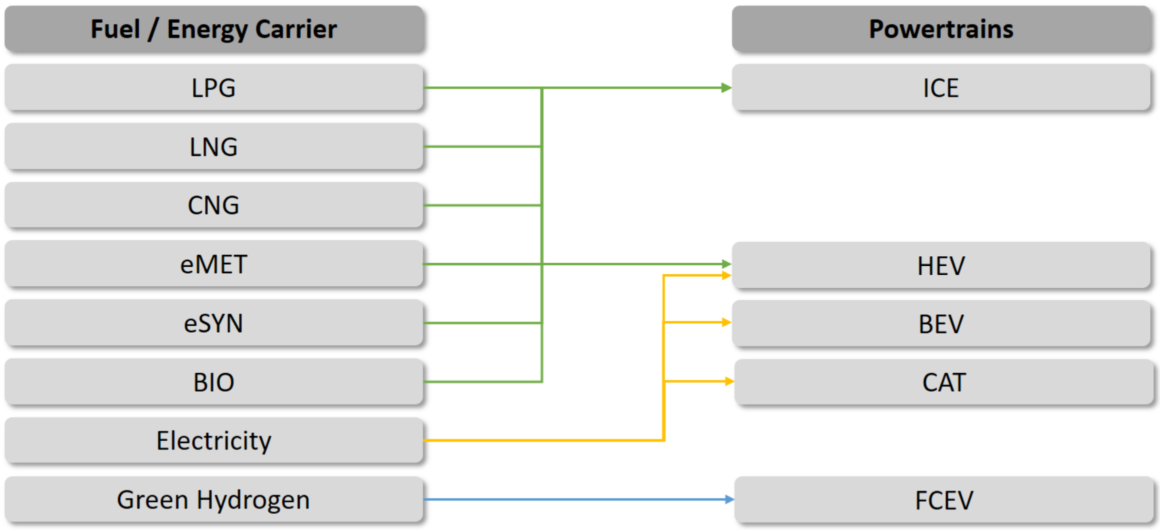

Figure 5: Mind map of different alternative fuels and powertrains (own illustration based on International Energy Agency (2017a, 2017b)) (green = renewable fuels; yellow = electricity; blue = hydrogen)

Electrified powertrains use electric motors for propulsion. Battery-electric vehicles (BEV) store the electric energy in on-board batteries and can be recharged conductively or inductively at charging stations. Catenary electric vehicles (CAT), also called "e-roads", use a similar technology with overhead lines providing continuous power and have a second powertrain (e.g. ICE or larger battery like BEVs) to cope with shorter road sections without overhead lines. Hybrid and plug-in hybrid electric vehicles (HEV) also operate with two powertrains, and are classified as an interim stage between ICE and BEV technology. Fuel cell electric vehicles (FCEV) use on-board hydrogen storages to generate electricity within a fuel cell. The hydrogen is usually stored at 350 or 700 bar.

2.2 Review of market diffusion of alternative fuels and powertrains[8]

In general, the current research on AFP for HDVs comprises two types of studies. The first category focuses on vehicle design (Ridjan et al., 2013; Macauley et al., 2016; Gangloff et al., 2017; Kast et al., 2017) and the economic viability (Zhao et al., 2013; Connolly, 2017; Gnann et al., 2017; Sen et al., 2017; Jordbakke et al., 2018; Mareev et

[8] This section has been published in a peer-reviewed paper (Kluschke et al., 2019a).

al., 2018) of HDVs with AFPs. The second category deals with the diffusion of AFPs in the HDV market and is the focus of this literature review.

As the market diffusion of AFPs in HDVs is a potential lever for large GHG emission reductions, and since the current research does not indicate an unambiguous path towards HDV decarbonization, an overview of the existing findings is beneficial for future research. An overview of AFP market diffusion studies for HDVs is therefore provided and the state of research synthesized. To the best of the author's knowledge, this thesis is the first to summarize the approaches and key findings of research on AFP market diffusion in the HDV sector. This review differs from others with regard to the transport segment (HDV), analysis criteria (design of market diffusion models and their results) and technologies (AFPs) examined.

2.2.1 Presentation of the reviewed studies

Four dimensions are employed to identify relevant studies for this literature review: Definitions of HDVs and AFPs, scientific level, time horizon, search terms and languages. First, the definitions in section 2.1 are used to identify studies focusing on AF-HDVs. Second, the reference is to peer-reviewed journal papers and studies of renowned scientific institutions to ensure research quality standards. Third, the focus is on literature from 2011 onwards to ensure up-to-date research. Fourth, literature is selected using combinations of the following search sets M1 to M3 in both English and German (no results were found using the French and Spanish equivalents):

M1 ("trucks" ∨ "heavy-duty" ∨ "long-haul") ∩

M2 ("alternative fuels" ∨ "alternative powertrains" ∨ "decarbonization" ∨ "electrification" ∨"electric road") ∩

M3 ("market diffusion" ∨ "market penetration")

The resulting literature set contains 46 studies without further filtering. These studies are content crosschecked to identify relevant studies. Three fulfilment criteria are used for the content crosscheck: The studies need to focus on the relevant HDV sizes (cf. chapter 2.1.1), contain market diffusion models, and incorporate quantitative data regarding the market penetration of AFPs. Applying these criteria yielded 19 studies for the review, comprising eight peer-reviewed journal publications, two PhD theses and nine scientific reports (see Table 3). This relatively low number of relevant studies already indicates the early research phase of the topic and the lack of research in some developed countries (e.g. France and Japan) and most developing markets such as Africa, India, Middle East, Latin and South America.

The following sub-sections present the results of the literature review and compare the model designs and results of the analyzed studies.

Table 3: Data collected as input for the literature review

Author	Focus Region	Title	Observation period	Type of publication
Ambel (2017)	EU28	Roadmap to climate-friendly land freight and buses in Europe	2020 to 2050	Study
Askin et al. (2015)	USA	The heavy-duty vehicle future in the US: A parametric analysis of technology and policy trade-offs	2030 to 2050	Peer-reviewed paper
Bahn et al. (2013)	Canada	Electrification of the Canadian road transportation sector: A 2050 outlook with TIMES-Canada	2020 to 2050	Peer-reviewed paper
Bründlinger et al. (2018)	Germany	Pilot Study Integrated Energy Turnaround: Impulses for the design of the energy system until 2050	2030 to 2050	Study
Çabukoglu et al. (2018)	Switzerland	Battery electric propulsion: An option for heavy-duty vehicles? Results from a Swiss case-study	none (only potential)	Peer-reviewed paper
Capros et al. (2016)	EU-28	EU Reference Scenario 2016: Energy, transport and GHG emissions trends to 2050	2030 to 2050	Study
Gambhir et al. (2015)	China	Reducing China's road transport sector CO_2 emissions to 2050: Technologies, costs and decomposition analysis	2050	Peer-reviewed paper
Gerbert et al. (2018)	Germany	Climate paths for Germany	2020 to 2050	Study
Kasten et al. (2016)	Germany	Development of a technical strategy for the energy supply of transport up to the year 2050	2020 to 2050	Study
Liimatainen et al. (2019)	Finland & Switzerland	The potential of electric trucks – An international commodity-level analysis	none (only potential)	Peer-reviewed paper
Mai et al. (2018)	USA	Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States	2020 to 2050	Study
Mulholland et al. (2018)	Global	The long haul towards decarbonizing road freight – A global assessment to 2050	2030 to 2050	Peer-reviewed paper
Naceur et al. (2017)	Global	Energy Technology Perspectives: Catalyzing Energy Technology Transformations	2060	Study
Özdemir (2011)	Germany	The Future Role of Alternative Powertrains and Fuels in the German Transport Sector	2020 to 2030	PhD-Thesis
Plötz et al. (2019)	EU-28	Impact of Electric Trucks on the European Electricity System and CO_2 Emissions	2020 to 2040	Peer-reviewed paper
Repenning et al. (2015)	Germany	Climate protection scenario 2050	2020 to 2050	Study
Seitz (2015)	Germany	Diffusion of innovative drive technologies for CO_2 reduction of commercial vehicles	2020 to 2035	PhD-Thesis
Siegemund et al. (2017)	Germany	The potential of electricity-based fuels for low-emission transport in the EU	2020 to 2050	Study
Talebian et al. (2018)	Canada	Electrification of road freight transport: Policy implications in British Columbia	2040	Peer-reviewed paper

2.2.2 Analysis of alternative fuel and powertrain market diffusion studies

Comparing the studies under review shows that all the authors aim to gain insights into the reduction of future GHG emissions in the HDV sector and thus into the market diffusion of AFP in HDVs. Apart from this shared objective, some authors aim at understanding additional aspects such as cost implications (Gambhir et al., 2015) or the impact on the electricity system (Naceur et al., 2017; Mai et al., 2018; Plötz et al., 2019).

As most of the studies target insights into future emissions, they are in line with the time horizon of global climate targets: The observed time horizon is mainly from 2020 to 2050 (12 studies). Besides this popular time horizon, Özdemir (2011) and Seitz (2015) observe up to 2030, while Plötz et al. (2019) and Talebian et al. (2018) stop at the year 2040. Only Naceur et al. (2017) forecasts until 2060. Çabukoglu et al. (2018) and Liimatainen et al. (2019) decouple HDV decarbonization from a timeline and refer to feasible potentials.

The studies cover different geographical scopes: These range from single countries, such as Canada (Bahn et al., 2013; Talebian et al., 2018), China (Gambhir et al., 2015), Germany (Özdemir, 2011; Repenning et al., 2015; Seitz, 2015; Kasten et al., 2016; Bründlinger et al., 2018; Gerbert et al., 2018), Switzerland (Çabukoglu et al., 2018; Liimatainen et al., 2019) or the US (Askin et al., 2015; Mai et al., 2018) to regions such as the EU28 (Capros et al., 2016; Ambel, 2017; Siegemund et al., 2017) and up to a global perspective (Naceur et al., 2017; Mulholland et al., 2018). The German bias is probably caused by the search languages used, even though other international languages were tried such as French or Spanish.

To sum up, the research questions indicate similar drivers in the reviewed literature: Reduction of GHG emissions in HDVs until 2050. However, the current research still shows black spots on global HDV markets such as Africa, India, Middle East, Latin and South America, which account for about 30 % of today's global HDV stock (International Energy Agency, 2017b).

Designs

Before comparing the results of the literature review, the structure of the applied model of each study is examined. According to Karnowski (2017), the review of literature model designs can be separated into two sub-sections 'model attriutes and 'input parameters'.

When analyzing the modeling attriutes of the existing AFP HDV market diffusion publications, the focus here is on the model type, modeled scenarios, the sectoral scope of modeling, and the economic perspective.

A framework developed by Gnann and Plötz (2015) is applied to classify the model types used in the literature. This framework defines bottom-up models as a combination of individual assumptions to generate an aggregated outcome with a strong focus on technologies. All the models used in the reviewed studies are bottom-up. As shown in Table 29 (see Appendix), seven of the studies apply bottom-up simulation models to reconstruct behavioral processes using either individual agents or systemic rules (system dynamics). The other eleven uses either a bottom-up optimization model, which optimizes supply and demand to reach an economic optimum, or a bottom-up accounting framework to determine sectoral outcomes (e.g. transport and industrial production sector). One of the non-peer-reviewed studies does not provide any information regarding the model used.

All the models construct between one and five scenarios. The majority of models provide a reference scenario as a baseline and add scenarios with increasing GHG emission restrictions. Eleven of the models with at least two scenarios define the reference scenario as an exploratory scenario, while the other scenario(s) are normative. Exploratory scenarios describe potential future developments based on known processes, current trends or causal dynamics and generate a forecast, while normative scenarios are prescriptive, using a future target and backcasting to develop scenarios (McCarthy et al., 2001). The normative scenarios used in the literature mainly set single dimensional target fulfilment (GHG emission target) on different levels, e.g. 80 % or 95 % GHG emissions reduction until 2050. Table 30 (see Appendix) shows the policies considered to reach the normative scenarios. Most authors do not specify the policy lever to reduce GHG emissions; however, some focus on sector-specific policies, e.g. vehicle efficiency standards or fuel taxes. Additionally, two studies considered existing restrictions regarding particulate matter (Askin et al., 2015; Mulholland et al., 2018).

Six studies specifically model the truck sector (Askin et al., 2015; Seitz, 2015; Ambel, 2017; Mulholland et al., 2018; Talebian et al., 2018; Plötz et al., 2019), while all other studies also model passenger transport or even non-road transport sectors such as trains, planes and ships.

Most models refer to a macro-economic perspective, i.e. they determine an overall economic outcome. This perspective looks for a holistic result – e.g. an optimium – for the region analyzed without considering controlling elements such as taxes or subsidies. In contrast, Askin et al. (2015) and Repenning et al. (2015) do not refer to this perspective and consider taxes in their models. Further, Seitz (2015) and Talebian et al. (2018) do not clearly state their model's perspective.

In summary, researchers use different types of bottom-up modeling (simulation, optimization, and accounting framework) to determine the market diffusion of AFP with between three and five scenarios in general.

Subsequently, the input parameters are analyzed. The considered technologies and their GHG emissions are common supply input parameters for modeling the market diffusion of AFP in HDVs. As outlined in chapter 2.1, ten AFP technologies are considered in addition to today's predominant diesel technology: six alternative fuels (LPG, LNG, CNG, eMET, eSYN, BIO) and four electrified powertrains (CAT, BEV, HEV, FCEV). BEV, CNG, FCEV and HEV received the most attention with a citation rate of about 52 % (10/19), 47 % (9/19), 42 % (8/19) and 42 % (8/19), respectively, as shown in Table 31 (see Appendix). Studies published in 2013 or earlier had a stronger focus on alternative fuels as an option to reduce GHG emissions, while literature from 2015 and later focused more on electrified powertrains. Repenning et al. (2015) are the first to mention the CAT powertrain; all other studies dealing with CAT were published in 2017 and later. Apparently, the spotlight while aiming to reduce GHG emissions is now shifting on electrifying HDV powertrains. Besides considering the GHG emissions of technologies, vehicle range is a frequently mentioned attribute to evaluate AFPs. For example, BEV powertrains were excluded from further analysis due to its low range in some cases. Additional potential customer requirements, such as vehicle power or refueling (recharging) time, are not mentioned in most publications. On average, an particular AFP technology is mentioned in only 50 % or less of the studies (cf. Figure 6).

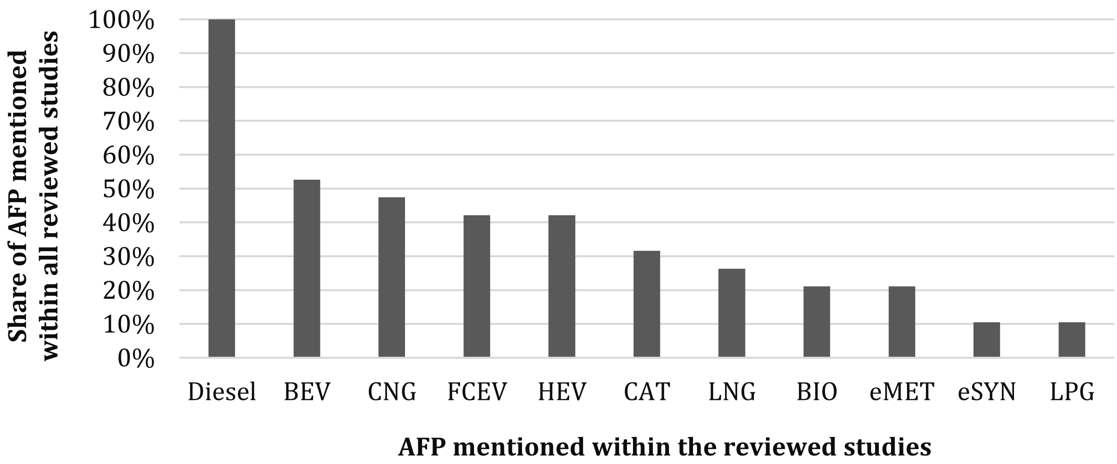

Figure 6: Share of AFP mentioned throughout all reviewed studies (e.g. BEVs were considered in about 50 % of all reviewed studies)

Results

This section reviews a specific output of the analyzed models: the market diffusion of AFPs in HDVs.

The scenario results are categorized into two clusters to compare the studies and their scenarios. All exploratory reference scenarios are categorized within the cluster "reference scenario". The most positive scenarios in terms of AFP are clustered under "climate protection scenario" (these scenarios are mainly normative, only Askin et al. (2015) and Plötz et al. (2019) define a second AFP-optimal exploratory scenario). These two clusters are outlined in Figure 7, which shows the share of AFPs in the HDV stock in percent on the y-axis and the timeline from 2020 to 2060 on the x-axis. Both graphs in Figure 7 contain boxplots only from 2020 to 2050, because there are not enough data points in the studies for 2020 (mainly 0 % market share for AFPs) and 2060 (only one study with data). The exact scenario names, market share figures and most competitive AFPs can be found in Table 32 and Table 33 in the Appendix.

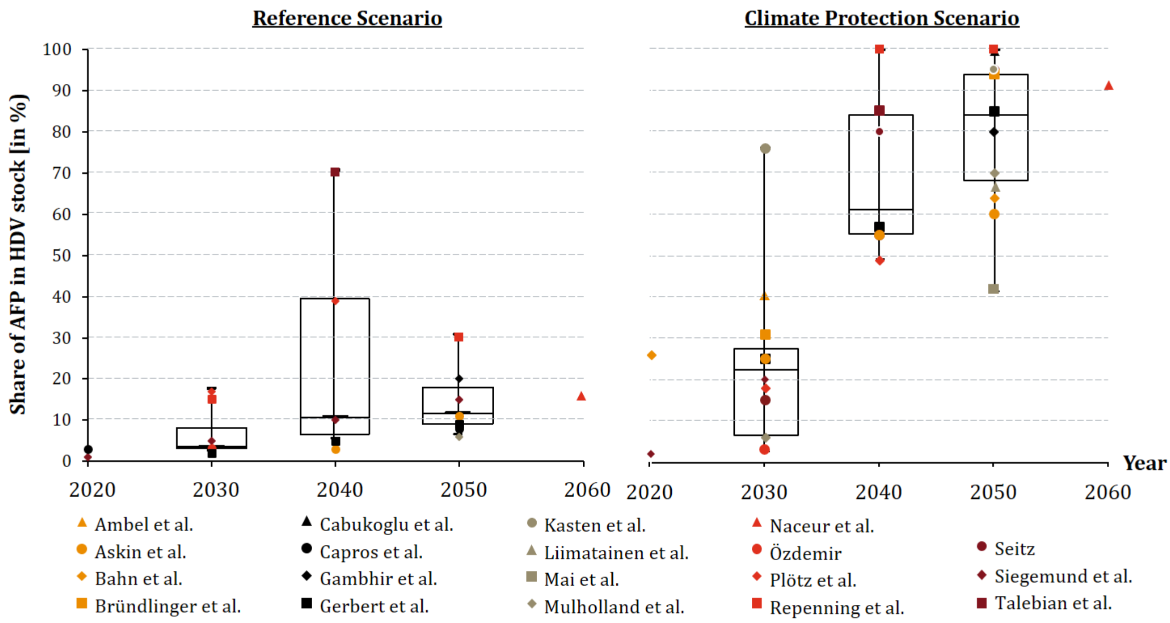

Figure 7: Market diffusion of AFP over time in reference and climate protection scenarios. Boxplots of the studies are shown for the share of AFP vehicles in the stock in different years. The whiskers show the minimum and maximum of all results, while the box contains all values between the quartiles. The solid line represents the median

In the reference scenario cluster (left-hand side in Figure 7) and therefore following an exploratory trajectory, the majority of studies forecast that AFPs will reach a maximum HDV market share of 20 % by 2050. Only Repenning et al. (2015) and Plötz et al. (2019) see a potential market share of 30 % in their exploratory reference scenarios. The median of the reference scenario reaches 3 % in 2030, 10 % in 2040, and 11 % in 2050.

However, in the climate protection scenario cluster, the market shares of AFPs in the HDV stock are projected to reach more than 60 % in 2050. The studies diverge with regard to the most competitive AFP. While alternative fuels dominate diesel in the research conducted before 2016 (Özdemir, 2011; Bahn et al., 2013; Askin et al., 2015; Capros et al., 2016), alternative electrified powertrains are more competitive in more recent publications.

Both the reference and the climate protection scenarios are consistent on a geographic level, i.e. the market penetration range is similar for the single country models such as China, Germany and the US, as well as the multi-regional models such as the EU-28. Further, most studies have a preferred AFP for both the reference and climate protection scenario. Only two studies see different AFP in both scenarios as shown in Table 4.

Table 4: Focus regions and most competitive AFP per scenario (reference and climate protection)

Author	Most competitive AFP (reference scenario)	Most competitive AFP (climate scenario)
Ambel (2017)	[none]	BEV
Askin et al. (2015)	NGV	NGV
Bahn et al. (2013)	BIO	BIO
Bründlinger et al. (2018)	FCEV	FCEV
Çabukoglu et al. (2018)	[none]	BEV
Capros et al. (2016)	LNG	LNG
Gambhir et al. (2015)	HEV	HEV
Gerbert et al. (2018)	HEV	CAT
Kasten et al. (2016)	HEV or CAT	CAT
Liimatainen et al. (2019)	[none]	BEV
Mai et al. (2018)	[none]	BEV
Mulholland et al. (2018)	HEV	CAT
Naceur et al. (2017)	HEV	HEV or CAT
Özdemir (2011)	[none]	CNG
Plötz et al. (2019)	CAT	CAT
Repenning et al. (2015)	BIO	CAT
Seitz (2015)	[none]	HEV
Siegemund et al. (2017)	eMET	FCEV
Talebian et al. (2018)	BEV or FCEV	BEV or FCEV

The model outputs paint a clear picture: Without additional (policy) measures, the underlying market share of AFPs in the HDV stock will be less than 40 % and the GHG emissions targets will not be met. In contrast, with increased efforts to meet the GHG emissions targets, more than 60 % AFPs in the HDV stock seem feasible. However, there is no consensus about which technology prevails.

2.2.3 Discussion of reviewed studies

This section discusses the main findings of the AFP market diffusion literature for HDVs, which can be summarized in five categories. First, all the researchers emphasize diesel ICE dominance: In the exploratory reference scenarios, the diffusion of AFPs in the HDV market is limited to a maximum of 30 % over the next three decades. In other words, diesel-based ICE technology will remain the dominant option for HDVs. Second, even though decoupling energy consumption and driving is projected to increase, the studies state that "decarbonization falls short on agreed targets" with the current policies aiming at greater fuel efficiency of conventional HDVs (Talebian et al., 2018). Alongside improving efficiency and operations, Mulholland et al. (2018) conclude that AFPs are the largest lever in HDV decarbonization. However, simply using alternative fuels will not be sufficient to meet the GHG emissions targets (Askin et al., 2015), and there is an additional need for alternative electrified powertrains with "noteworthy" CO_2 emission reduction potentials (Plötz et al., 2019). Third, optimal and non-optimal niches are mentioned. Kasten et al. (2016) state that FCEV powertrains are more cost-effective for long-haul applications due to comparatively high initial vehicle investments. For urban or short-haul applications, Çabukoglu et al. (2018) and Seitz (2015) find BEV HDVs rather attractive, while Askin et al. (2015) prefer CNG here. Fourth, there are statements regarding economic optima which are derived from normative scenarios using bottom-up optimization models. Accordingly, the direct use of electricity represents the most cost-effective supply of energy (Kasten et al., 2016). Furthermore, raising diesel prices (Capros et al., 2016) while minimizing additional vehicle investments (Askin et al., 2015) is the most effective approach when aiming for fast AFP market diffusion. The fifth main finding concerns the implications for the electricity system. The reviewed studies agree that the (HDV) transport sector will become an additional electricity market participant in the future. However, they gauge the impact of AFP-HDVs on the electric load very differently - from "limited" (Plötz et al., 2019) to "major" (Siegemund et al., 2017).

2.3 Presentation of existing infrastructure location modeling approaches

Subsequent to understanding potential market diffusion of AFP-HDV until 2050, section 2.3 presents a literature review of infrastructure modeling approaches to gain insights from current modeling approaches.

Location planning research can be classified into two groups: finding the right activity at a particular location, and finding the right location for a particular activity (Nickel, 2018). In his dissertation thesis “Theory of soil and land use”, von Thünen (1826) focuses on the first approach by answering which activity (buildings, manufacturing site, service offering, etc.) should be located in a particular place in order to maximize profit. The second group focuses either on the right location for a specific in-house activity on-site (Hundhausen, 1925), e.g. optimizing operations within a facility or production site, or on finding the optimal location among multiple alternatives (Launhardt, 1882; Weber, 1909). This latter approach best describes the task of locating a finite number of infrastructures (activity) in a network (set of locations) and may be solved descriptively or normatively. While a descriptive solution applies a checklist or scores, the normative approach uses objectively verifiable criteria (e.g. models) to make a location decision in particular situations (Nickel, 2018). Given its objective nature, the normative approach has been used extensively in research on AFS infrastructure modeling (see for example: Church and ReVelle, 1974; Hodgson, 1990; Kuby and Lim, 2005; Capar et al., 2013; Jochem et al., 2016).

Moreover, studies of AFS infrastructure modeling have shown that demand-driven location methods outperform strategic location methods on weekly energy transfer (Helmus et al., 2018). Hence, the research field of infrastructure investment modeling focuses primarily on the facility location problem from a demand-driven perspective. Seven research streams can be differentiated for facility location optimization: p-median, set covering problem (SCP), maximal covering location problem (MCLP), flow interception location problem (FILP), flow refueling location problem (FRLP), network sensor problem (NSP) and network interdiction problem (NIP) (Capar et al., 2013). The first three problems can be considered generic facility location problems, and the latter are specifically designed extensions. In particular, these extensions consider paths or flow through a network while also applying parts of the generic problems.

2.3.1 Generic facility location problems

The p-median uses heuristics to minimize the distance traveled from one node to the closest (refueling) facility (Greene et al., 2008). A SCP does not use heuristics and looks for the minimum investment to allocate facilities (or at least one facility) that can cover a set of demand nodes given a determined set of potential facility locations (Daskin, 2011). The MCLP maximizes the number of nodes, including their total population, covered by pre-defined facilities in a pre-defined distance (cf. Batta and Mannur, 1990).

2.3.2 Flow Interception Location Problem

The flow refueling location problem dominates road transportation research, originating with the flow interception location problem (FILP). The FILP is based on the work of Hodgson (1990), who considers traffic as a demand flow, which starts, ends or passes by businesses that want to serve this given demand. Hodgson (1990) suggests using origin-destination (OD) trips to embody the total (refueling) demand flow. These OD trips follow a path along (multiple) nodes, at which candidate AFS facilities are located, e.g. charging or refueling stations. On a highway network, for example, nodes can be referred to as highway entries, exits or intersections.

2.3.3 Flow Refueling Location Problem

Addressing the flow refueling location problem, the flow refueling location model (FRLM) considers the range of the vehicles passing along a path (Kuby and Lim, 2005; Wang and Wang, 2010; Capar et al., 2013). This is especially important for AFV, which may have a shorter range than existing technologies. The FRLM can either maximize the vehicle trips covered when locating a predefined number of stations in a network (maximum covering), or minimize the number of facilities needed to cover a given demand share (set covering) (Jochem et al., 2016).

Although the FRLM has been further developed to some extent, only a few studies consider capacity restrictions on single refueling stations. Capacity limitation on all facilities within a single location (i.e. node) is not considered. In general, these studies follow a maximum coverage approach with a pre-specified number of capacitated facilities, rather than determining the minimum number of capacitated AFS to serve a pre-defined share of the vehicle flow (e.g. 100 %). When the aim is to decarbonize the fleet, it seems more beneficial from a societal and public administrative perspective to determine the minimum number of capacitated AFS. Upchurch et al. (2009) were the first to address the problem of missing station capacity limits in AFS modeling. They presented a greedy heuristic approach to observe station utilization by adding capacity restriction as an additional analysis after a FRLM optimization. Their approach considers only modular units (no fixed facility sizes) and states that "the potential amount of refueling capacity to be built at each node is potentially infinite" (Upchurch et al., 2009). Their model was applied to a small network in Arizona (50-node network) and considered up to 30 capacitated stations per node. More recently, Hosseini and MirHassani (2017) added performance improvements to test larger networks with up to 1,000 nodes. In a second study, they focused on the deviation drivers make from the shortest paths in order to reach capacitated stations (Hosseini et al., 2017). Zhang et al. (2017) turned the capacitated station FRLM from heuristics into an optimization model and applied it to a 300-node network considering 60 AFS. The result suggests up to 70 modules per single node, which already indicates the limited practicability of station capacity limits (versus node-capacity limits). Most recently within the field, Chauhan et al. (2019) applied the station capacitated FRLM to range-constrained drones with no major adjustments to the method.

2.3.4 Network Sensor Problem and Network Interdiction Problem

The fundamental objective of the NSP is to optimally locate sensors to measure flows on a traffic network (Liu and Towsley, 2004). Hence, the approach involves counting or identifying moving objects through the network to cover three levels (Gentili and Mirchandani, 2012): type of sensor to be located on the network (e.g. counting sensors or image sensors), available a-priori information, and flows of interest (e.g. origin-destination flows or route flows). However, the NSP neither takes limited vehicle range nor potential coverage of the entire length of a path into account.

The NIP is less closely related to the FRLM and aims on improving infrastructure security and robustness by identifying the sets of assets (e.g., nodes) that have the greatest impact on a system's ability to perform its intended functions, once these assets were disabled or lost (Cappanera and Scaparra, 2011). Hence, interdiction models focus on providing information about the criticality of some system components, but not about building up an optimal infrastructure across a network (Cappanera and Scaparra, 2011). Similar to the NSP, the NIP does not consider vehicle range limitations.

2.3.5 Infrastructure modeling for heavy-duty vehicles and hydrogen

Despite the growing interest in alternative fuels (AF) as an alternative to diesel as outlined in section 2.2, the literature on HDV AFS infrastructure research is limited. Fan et al. (2017) analyze the potential LNG infrastructure for HDVs in the US and recommend focusing on the highest volume freight routes initially when promoting an AF (Fan et al., 2017). Using a set covering approach, they determine the most profitable HDV-LNG network and discover only a minimal number of stations to be profitable. They conclude that large fleet owners will not be willing to make investments in alternative fuel vehicles unless they are assured of dedicated refueling station availability for their entire travel route. Combining the profitability challenge with station availability to serve a significant amount of HDV traffic demand, infrastructure construction needs to be pre-funded by public authorities or a public private partnership in order to evolve. The study does not give a detailed analysis on the overall investment of the HDV-LNG infrastructure or the individual cost per charge or per km, but points out the high share of energy cost. Wietschel et al. (2017) determine infrastructure build-up and market diffusion for catenary HDVs in Germany. They use a maximum covering approach to define highway corridors with a similar traffic demand to be equipped with overhead power lines. Even though this technology is found to be the most efficient way to decarbonize HDV traffic, Wietschel et al. (2017) also conclude that the large upfront infrastructure investments are a high obstacle to market entry. In sum, they calculate the infrastructure installation investments to be about two to 8-10 billion euros with annual additional maintenance investments of about 40 to 400 million euros. Connolly (2017) also analyzes the catenary technology and determines its investment for the Danish passenger and freight vehicle market. He also follows a maximum coverage approach, assuming a catenary infrastructure network of 2,700 km. Connolly (2017) concludes that catenary infrastructure is cheaper than conductive charging infrastructure for BEV, with four billion euros installation investment and annual investments of 80 to 850 million euros (for installation and maintenance). However, none of the existing studies has determined either the design or the investment of a national FC-HDV infrastructure (cf. Table 5).

Table 5: Overview of HDV infrastructure literature

Author	Covering type	Sector	Tech-nology	Country	Infrastructure amount
Fan et al. (2017)	Set covering	Only HDV	Natural Gas	US	6 - 80 stations (highways)
Wietschel et al. (2017)	Maximum covering	Only HDV	Catenary	GER	1.000 – 8,000 km (highways)
Connolly (2017)	Maximum covering	All passenger and freight vehicles	eRoads	DK	2,700 km

Even though no research has been done on FC-HDV infrastructure, the literature does provide insights for passenger vehicle hydrogen refueling networks. Alazemi and Andrews (2015) review the existing HRS in 2013, which mainly serve passenger cars and light duty vehicles (LDVs) but also buses. Of the 224 HRS that exist globally, 109 stations have on-site hydrogen production and 59 HRS obtain hydrogen from a central production facility via trailer delivery (the production method for 56 stations cannot be identified). Most of the existing HRS are installed in the US (62), Japan (23) and Germany (22). The largest HRS has a daily capacity of 600 kg and is able to dispense up to 30 kg at one time. Seydel (2008) developed a model for developing hydrogen refueling infrastructure for passenger cars at national level. He estimates that about 10 % refuel at highway stations. Apart from analyzing refueling, Seydel (2008) also considers hydrogen production and distribution and the corresponding investments. He projects the HRS network in Germany using a set covering approach and determines infrastructure investments of 21 billion euros for 7.5 million passenger cars and LDVs comprising a network of 10,000 HRS. Other studies obtain similar results for the relative share of HRS per vehicle (Robinius et al., 2017a). For passenger FCEVs, more recent studies already focus on optimal HRS sizing to decrease on-site hydrogen production costs and find that oversizing HRS for future applications does not increase costs significantly (Grüger et al., 2018). On the other hand, they also focus on optimizing the hydrogen production and delivery process and find that hydrogen delivery in a liquid state is not cost-effective or feasible using current technology due to high liquefaction costs and energy losses (Demir and Dincer, 2018). Elgowainy and Reddi (2018) were the first to conduct research explicitly on FC-HDV infrastructure and focused on the design of HDV-HRS. They underline the difference between LDV and HDV hydrogen refueling, develop a refueling model for HDVs, and evaluate the impacts of key parameters on the refueling costs of FC-HDV.

2.3.6 Discussion of reviewed approaches

Table 6 compares the different research streams according to the main differentiation criteria relevant for HDV AFS modeling defined by the author. The FRLM seems to be the most suitable approach, but none of the models considers a potential capacity limit of (fuel) stations.

Table 6: Comparison of existing research streams of facility location problems

Differentiation Criteria	Research Streams						
	P-Median	SCP	MCLP	FILP	FRLP	NSP	NIP
Originator of research stream	Hakimi (1964)	ReVelle and Swain (1970)	Church and ReVelle (1974)	Hodgson (1990)	Kuby and Lim (2005)	Gentili and Mirchandani (2012)	Altner et al. (2010)
Spatial relationship among facilities	-	√	√	√	√	√	√
Considering paths through a network	-	-	-	√	√	√	√
Considering flow passing through a network	-	-	-	√	√	√	√
Considering vehicle range	-	-	-	-	√	-	-
Considering fuel station capacity limit	-	-	-	-	-	-	-

In summary, none of the existing approaches considers station location capacity limits to create an optimal AFS network with realistic station sizes on nodes. Taking this into account means adapting the modeling requirements because there are technical limitations (e.g. amount of provided electricity at a single location) and legal limitations (e.g. quantity of hydrogen stored at a single location; details in section 4) on single nodes, and individual node-capacity will be crucial with an increasing market diffusion of AF-HDVs into global markets.

2.4 Summary of literature findings

Summing up the findings, there are clear takeaways from each of the three sub-sections. First, global definitions of HDVs vary, but most regions consider trucks or trailers above 12 ton weight (40 ton total weight including loading). Second, multiple technologies are available for HDV decarbonization. There is high uncertainty among researchers regarding the dominant technology, with BEV and FCEV mentioned as the top two zero-emission technologies within the reviewed studies. At the same time, only a high share of AF-HDVs can help to achieve climate targets. Third, AFS infrastructure modeling is a well-established research stream. However, the research conducted so far hardly considers AF-HDV infrastructure and the modeling approaches do not consider HDV-specific requirements (especially node-capacity restriction).

FC-HDV is one of the technologies, which is currently being discussed as zero-emission AFP in the literature, and one with the potential to meet HDV range and refueling-time requirements. Further, it seems reasonable to assume that a market share up to 100 % of AF-HDVs is necessary to reach climate targets. Finally, current AFS infrastructure modeling approaches need to be extended to be applicable to HDVs. This thesis therefore develops a modeling approach for HDV AFS and applies it to an AFS infrastructure for FC-HDVs on a national scale.

3. Model development and data

This chapter introduces a new model for developing AFS networks for HDVs, presents the relevant input data for the model, and defines an interface to an existing open-source energy model (see Figure 8). The relevant framework parameters are presented in chapter 4.

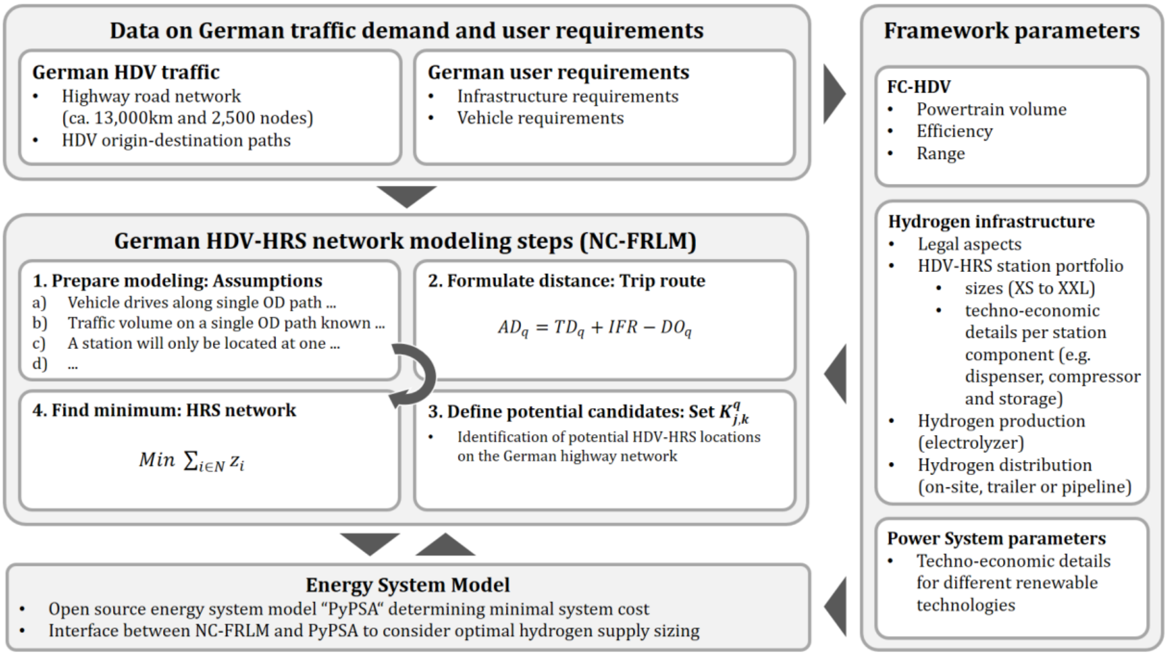

Figure 8: Overview of the method to determine a potential HDV-HRS network for Germany

In the following section 3.1, the Node-Capacitated Flow Refueling Location Model (NC-FRLM) is developed. The relevant input data required to model a HDV-HRS network in Germany is described in section 3.2 (German HDV traffic demand) and section 3.3 (German HDV user requirements). Section 3.4 describes the integration of the NC-FRLM and the open-source electricity system modeling framework PyPSA. Finally, section 3.5 defines the cost equation applied to express economic implications of the network and section 3.6 summarizes the model development and data.

3.1 Development of Node-Capacitated Flow Refueling Location Model[9]

In order to describe the new model, its objectives are defined, following the fundamental FRLM applied, and then the model extensions are outlined.

3.1.1 Model attributes

Location modeling can be described using a number of characteristics such as objective, time, steps, uncertainty, flow direction and capacity restrictions (Nickel,

[9] The content of this section has been published in a peer-reviewed paper (Kluschke et al., 2020).

2018). Figure 9 displays these characteristics and the attributes of the AFS facility location model considered in this thesis.

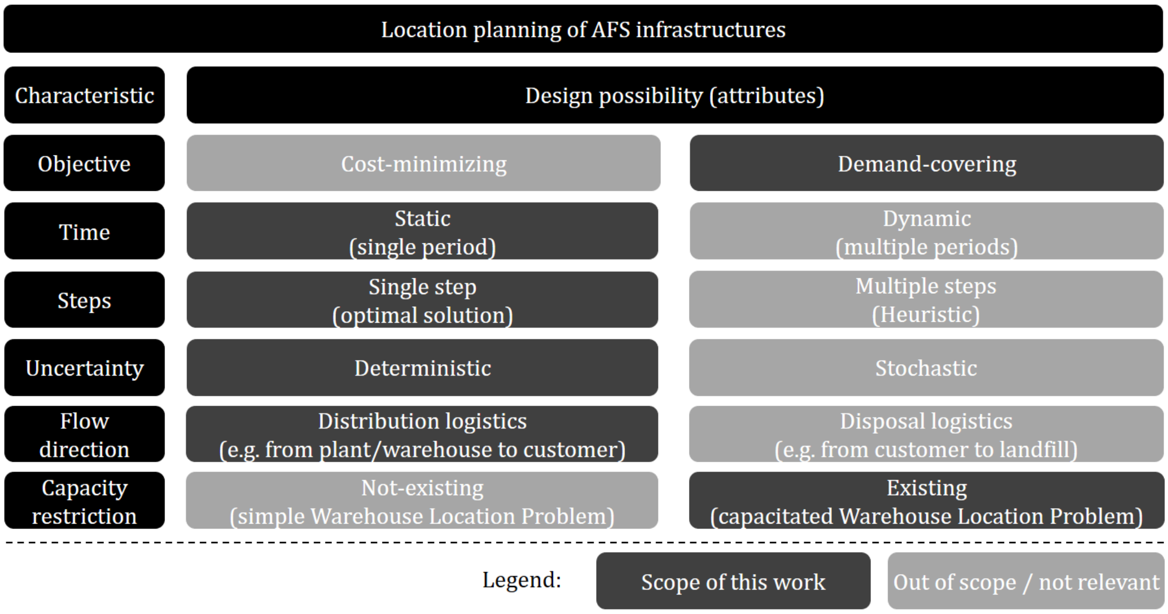

Figure 9: Characteristics of AFS facility location models and the attributes covered in the thesis model (own illustration based on Nickel (2018))

First, a demand-covering approach is chosen due to the focus of this thesis and research questions emphasizing the decarbonization of all German HDV traffic rather than developing strategic, profitable and investment-minimizing AFS networks (cf. section 2.3). Further, the focus is on a single period modeling approach for the year 2050 to create an optimal target picture for AF-HDV infrastructures and subsequently derive a ramp-up from the present to the target by assuming a ramp-up curve based on the climate protection scenario market diffusion of section 2.2 (backcasting).[10] Accordingly, the model runs a single step solution to determine optimal AFS locations rather than defining multiple steps leading to a heuristic outcome. Further, the model relies on precise available input data (such as those from the German Federal Highway Research Institute (2019)) to determine the optimal AFS network instead of using a stochastic approach that considers uncertainties. However, uncertainties will be covered in this thesis by analyzing not only the optimal outcome but also various sensitivities of input data and framework parameters. Given the nature of AFS infrastructure modeling, the flow direction expresses distribution logistics matching alternative fuel production and distribution with multiple customers rather than determining inverted, disposal logistics. Finally, the model integrates the need for a capacity restriction per location (also referred to as the "node" of a network[11]) as

[10] In contrast, modeling an AFS network on an evolutionary basis (forecasting) for each period t would not necessarily lead to an optimal target picture. An optimal AFS network for period t+1 may look different to an optimal solution in period t, however period t+1 needs to include existing – and potentially not suitable – AFS locations of period t.
[11] A node is defined as a potential AFS location, which may be a highway entry or exit here.

explained in section 2.3.3. The attributes mentioned ensure that a model is developed that is able to address the main research question regarding an optimal[12] HDV-HRS network for zero-emission FC-HDV transport for Germany in 2050.

3.1.2 Problem formulation

The formulation of the existing uncapacitated FRLM model is then as follows (cf. Capar et al. (2013)):

$$Min \ \sum_{i \in N} z_i \tag{1}$$

Subject to:

$$\sum_{i \in K_{j,k}^{q}} z_i \ \geq \ y_q, \forall q \ \in Q, a_{j,k} \in \ A_q \tag{2}$$

$$\sum_{q \in Q} [f_q \ \cdot y_q] \ \geq \ S \tag{3}$$

$$y_q, z_i \ \in \ \{0,1\}, \forall q \ \in Q, i \in N \tag{4}$$

Sets and indices

A_q	Set of directional arcs on the shortest path q, sorted from the origin to the destination
$K_{j,k}^{q}$	Set of all potential AFS sites (nodes) that can refuel the directional arc $a_{j,k}$ in A_q
N	Set of all nodes that form the highway network, N = {1,…n}
Q	Set of all OD pairs
i,j,k	Indices of potential facilities at nodes
q	Index of OD pairs
$a_{j,k}$	Index of unidirectional arc from node j to node k

Parameters

f_q	Total vehicle flow per OD trip refueled
S	Objective percentage of refueled traffic flow[13]

Decision variables

y_q	y_q = 1 if the flow on path q is refueled. y_q = 0 if otherwise
z_i	z_i = 1 if an AFS is built at node i. z_i = 0 if otherwise

Equation (1) represents the objective to minimize the number of stations built (z_i) at all nodes *i* in the entire network *N.* Equation (2) is a constraint developed by (Capar et al., 2013) to replace the requirement to calculate initial feasible station combinations

[12] An optimal network is defined here as a network with the least number of stations required to serve a given volume of traffic. See sub-section 3.1.2 for more details.
[13] In this case, S = 100% (all flows will be refueled at least once per trip).

in most FRLM models. Constraint (2) assures that if path q is refueled (y_q), there should be a minimum of one station that is built (z_i) at one of the nodes i that is in a set of potential station sites $K_{j,k}^{q}$. Equation (3) is a constraint, which ensures that the total amount of flow (f_q) in all refueled paths (q) needs to be larger than or equal to the minimum service coverage that wants to be observed. Equation (4) represents the nature of every index and variable, where z_i and y_i are binary variables, q is an element of set Q, and i is an element of set N.

3.1.3 Model extension: Node-capacity restriction

3.1.3.1 Adjusted assumptions

There are seven assumptions that are applied in the original version of this model (Capar et al., 2013). One of these assumptions is adjusted and two are added to fit the case (all shown in *italics*). The following assumptions were made here:

1. A vehicle drives along a single OD path that is determined as the shortest path from the center of the origin area to the center of the destination area.
2. The traffic volume on a single OD path is known in advance.
3. A station will only be located at one of the nodes that is part of the highway network.
4. The distance traveled is proportional to the fuel consumption.
5. *Only trips with a distance greater than 50 km need refueling.*
6. The drivers have full knowledge about the location of AFS along the path and refuel efficiently to complete a single trip.
7. The maximum driving range that can be achieved for each single refueling is similar for each vehicle.
8. *Each vehicle starts and ends its trip with the same fuel level, which is sufficient for a specific range.*
9. *Nodes and AFS are capacitated.*

The first four assumptions are suitable because trucks mostly drive along highway networks from one specific location to another. With regard to the first assumption, the shortest path from the entrance node to the exit node in the highway network is calculated by applying the Dijkstra algorithm (Dijkstra, 1959) to every OD path. This thesis assumes a vehicle completes a single trip instead of shuttle trips because this better suits the focus on trucks, which normally receive a delivery order to another location once they reach their destination (tramp traffic) and thus rely on public refueling stations (Gürsel and Tölke, 2017; Gan et al., 2019). Assumption (2) is inherent to the model approach in order to determine the total demand per AFS location.

Assumptions (3) – (5) are made to increase the effectiveness of AFS deployment. 50km is assumed to be a suitable cap to balance removing travel data from the set as well as incorporating an increasing likelihood of refueling after 30-60 minutes on the road.

The sixth assumption is reasonable since most trucks are now equipped with a decent navigation system technology. AFV-HDV tend to have uniform specifications, especially considering the focus on FC-HDVs, which makes assumption (7) reasonable. The refueling strategy is defined in (8), where no private AFS at the trip's origin or destination are assumed. Due to the previously mentioned tramp traffic nature of trucks, the same fuel levels are assumed at the beginning and end of a trip. Consequently, the total amount refueled equals the total distance of the trip. As subsequent journeys are not considered, applying this assumption also prevents excessive refueling and reflects the energy needed to cover the actual trips made. Assumption (9) describes the capacity limit extension, which will be explained in more detail in sub-section 3.1.3.4. The differences between the extended FRLM and other models are assumption (5) as well as assumptions (8) and (9).

3.1.3.2 New distance formulation

To analyze the effect of node and station capacity restrictions, the model is adjusted to determine the distance of each individual OD path.

The algorithm to determine the set $K_{j,k}^{q}$ uses a slightly different approach at each destination node to ensure that all vehicles at the destination node have the same amount of fuel as they had at their starting point. As can be seen in the algorithm flowchart in Figure 11 in sub-section 3.1.3.3, every time the iteration reaches a destination node, the algorithm adds extra length to the total distance of a trip and determines which (past) potential locations enable the vehicles to reach this new, virtual distance. This approach will not show any differences when applied in the uncapacitated model, but it is an important aspect in the capacitated model. The new distance can be formulated as shown below:

$$AD_q = TD_q + IFR - DO_q \tag{5}$$

Where AD_q is the new, adjusted distance from the starting point, IFR is the initial fuel range, TD_q is the total distance of an OD trip q, and DO_q is the distance from the origin point to the highway entrance.

This new approach is explained using an example to define the potential refueling locations of vehicles to reach the destination. The example is shown in Figure 10, which illustrates a single OD path. Here, the actual distance from node DE1x1 to node DE1x2 is 1,000 km. $a*_{ori,j}$ and $a*_{k,des}$ denote the access (exit) roads from the origin (destination) node to the highway, while $a_{j,k}$ denotes a road within the highway network. Prior to the new approach, the algorithm would determine that refueling at node 3 (and node 4, 5 and 6) is sufficient to reach the destination. Applying the new approach, the total distance is now 1,200 km and nodes 4, 5 and 6 are the only potential refueling locations that can reach the destination. At these nodes, vehicles can safely refuel to a level equal to the remaining distance (200 km) without worrying about the remaining tank level or the fuel level at the destination. Given constraint (2), this OD path will then have at least 2 AFS.

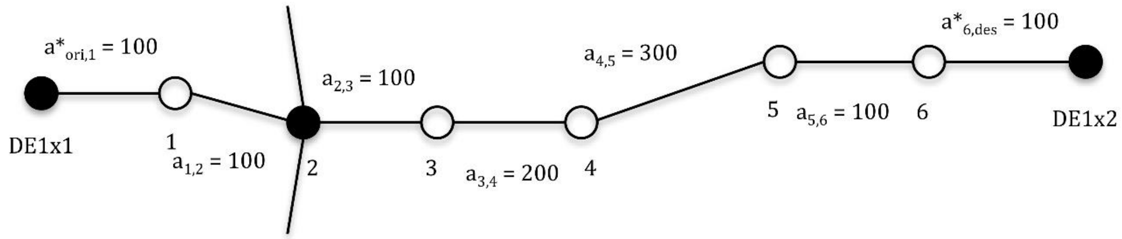

Figure 10: Illustration of an OD path

3.1.3.3 New potential candidate set

The potential candidate set $K_{j,k}^{q}$ is determined prior to the optimization process described in sub-section 3.1.3.4. An algorithm is constructed that uses a similar approach as (Jochem et al., 2016) to define the set $K_{j,k}^{q}$. Figure 11 shows a flowchart for the algorithm. Generally, the algorithm operates with iteration at each node starting from the origin point, and calculates the (cumulative) distances to the next node. If the distance to the next node exceeds the vehicle range, the algorithm will check the (previous) nodes that are potential locations for building a station and store those nodes as a single set of $K_{j,k}^{q}$. The algorithm will repeat the procedure until it reaches the destination.

To provide a better understanding of how to define the set of $K_{j,k}^{q}$, the exemplary trip presented in Figure 10 is used again. Assuming that all vehicles start with enough fuel to cover 400 km and that a single refueling can cover a maximum distance of 800 km, the vehicles within this OD trip should refuel twice to comply with assumptions (4) and (8). The algorithm works by identifying the maximum node within the initial vehicle range, which in this case is node 3. The algorithm then checks the (previous) nodes that enable vehicles to continue their journey to node 4. Here, vehicles can only refuel at node 1 and 3 as node 2 is an intersection.[14] Hence, node 1 and node 3 are stored as a single set of $K_{j,k}^{q}$. For OD trips with a total distance below or equal to the initial vehicle range, the algorithm will then stop and move to the next OD trip. For OD trips longer than the initial range, the algorithm will continue to the next node in the path and repeat the process of determining the set $K_{j,k}^{q}$. In this case, vehicles can refuel at node 1, 3, and 4 to reach node 5, in which nodes are then stored as another set of $K_{j,k}^{q}$. As node 4 is beyond the vehicle's range, a single refueling at node 4 is not an option because of the second constraint in the uncapacitated model.

[14] Nodes that represent intersections were excluded as potential station locations, because an AFS is rarely built at a highway intersection

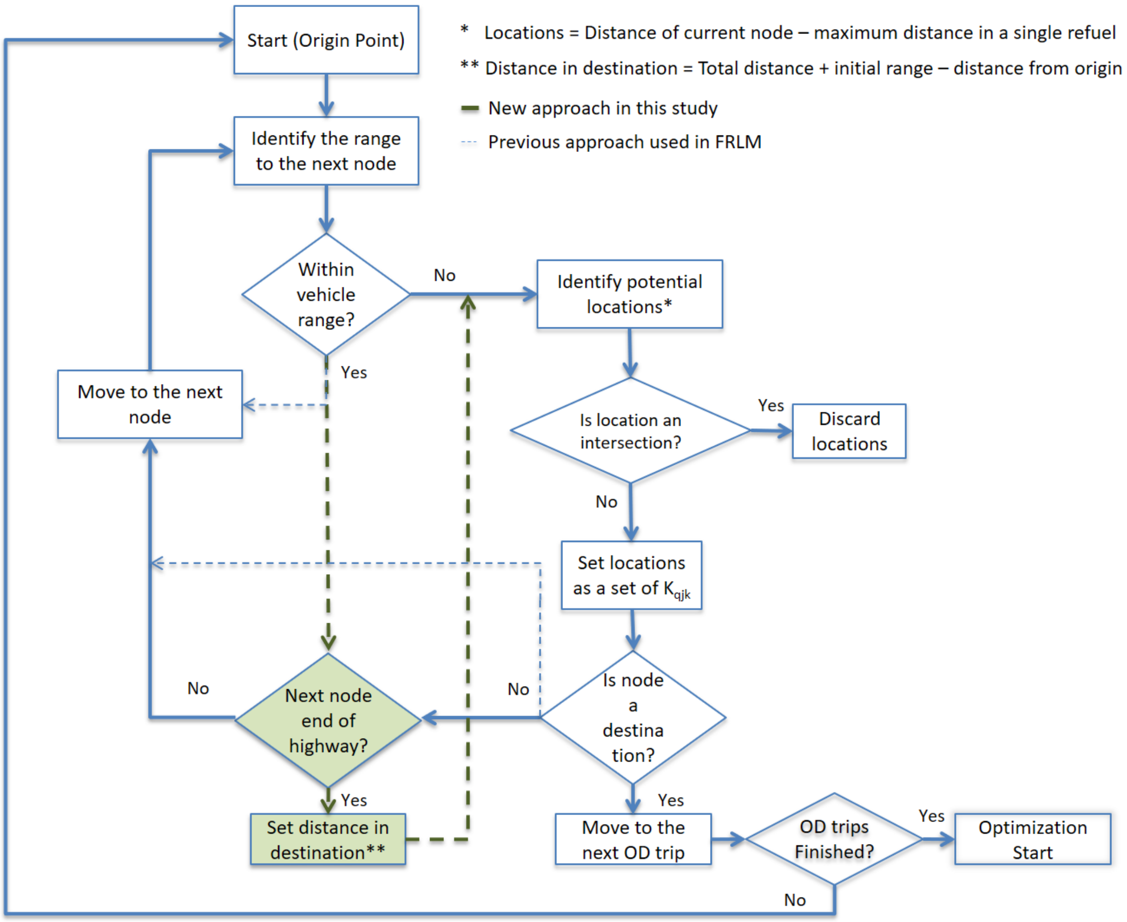

Figure 11: Flowchart to determine $K_{j,k}^{q}$

3.1.3.4 Additional constraints, parameters and variables

In addition to the adjusted assumptions, new distance formulation and new $K_{j,k}^{q}$ set determination, some constraints are added to develop the node-capacitated FRLM (NC-FRLM), which can be seen below:

$$Min\ \sum_{i\in N} z_i \tag{1}$$

Subject to:

$$\sum_{i\in K_{j,k}^{q}} z_i \geq y_q, \forall q \in Q, a_{j,k} \in A_q \tag{2}$$

$$y_q, z_i \in \{0,1\}, \forall q \in Q, i \in N \tag{4}$$

$$\sum_{q\epsilon Q}[f_q \cdot y_q \cdot r_{iq} \cdot p \cdot g_{iq} \cdot x_{iq}] \leq c\, z_i\,, i \in N \tag{6}$$

$$\sum_{i\epsilon K_{jk}^{q}} x_{iq} = y_q, \forall q \in Q, a_{j,k} \in A_q \tag{7}$$

$$\sum_{i\in N} x_{iq} = y_q . l_q \tag{8}$$

$$x_{iq} \leq z_{i,}, i \in N, q \in Q \qquad (9)$$

$$0 \leq x_{iq} \leq 1 \qquad (10)$$

Additional parameters

c	capacity at node i
l_q	refueling occasion on path q
p	fuel efficiency
r_{iq}	amount of refueling to reach maximum tank (difference between current fuel level and maximum fuel level)
g_{iq}	indicator of potential station location

Additional variables

x_{iq}	proportion of vehicles on path q that refuel at node i

Adjustments

y_q	parameter that indicates proportion of vehicles refueled on path q

Constraint (3) is removed.

For the NC-FRLM, constraints (6) to (8) are added to the model to limit the capacity per potential station based on the quantity of consumed energy, e.g. fuel. Constraint (6) says that a station can be built if the total demand served at node i is less than the capacity limit. The total demand that is served at node i on path q is equal to the total flow of trucks (f_q) multiplied by their fuel consumption (p) and the amount of refueling at node i (r_i). g_{iq} is a parameter that functions as an indicator for potential station location. It is equal to 1 if node i is a potential station on path q, and 0 if otherwise. Nonetheless, constraint (6) is a quadratic problem, which is difficult to solve. As the main aim is to observe the minimum number of refueling stations required to meet total demand (100 % demand coverage), this problem is avoided by setting the variable y_q as a parameter that is equal to 1 and removing constraint (3) accordingly. x_{iq} is a variable that determines whether vehicles on path q should refuel at node i so that the sum of vehicles refueling at node i do not exceed the capacity limit. Constraint (7) defines that if path q is refueled, all vehicles on path q can refuel at any open stations along the path. Constraint (8) ensures the refueling occasion of vehicles on path q, which depends on the total distance of the path. Here, l_q is the number of refueling occasions on OD path q, which is calculated by dividing the total distance of OD trip q by the maximum vehicle distance achieved with a single refueling and rounded up. Constraint (9) is that if a vehicle on path q refuels at node i, then a station should be open. The last constraint (10) defines that x_{iq} should be between 0 and 1.

Complying with the assumptions, the refueling amount at node i (r_i) varies depending on the total distance and the distance of the node from the starting point. Vehicles on

OD trips with a total distance that is less than the vehicle range will only refuel once (as $l_q = 1$) with an amount equal to the total distance of path q in all potential locations i. For OD trips longer than the vehicle range, the number of refueling stops on path q depends on the refueling occasion l_q. Defining the set $K_{j,k}^{q}$ ensures that the first refueling takes place at the node with a distance below the initial vehicle range and the next refueling is at the node located at a distance such that the vehicle has the same fuel level at the destination as at its starting point. All vehicles will then refuel to the maximum tank level in their first refueling. Vehicles will refuel to the maximum tank level at nodes where the remaining distance to the destination is larger than the maximum vehicle range. Simultaneously, vehicles will refuel only to the amount they need to reach the destination at nodes where the remaining distance to the destination is below the maximum vehicle range.

3.1.4 Discussion of model development

This approach, which combines adjusted assumptions to a basic FRLM, a new distance formulation, a new set for potential candidate sites as well as new constraints, parameters and variables, can determine the station combination with the minimum number of nodes (AFS locations).

Following Ko et al. (2017), one of the four issues of locating refueling stations is already addressed: objective (= minimize number of AFS while serving 100 % of flow on German highways). The remaining three issues (refueling demand estimation by OD path, vehicle characteristics such as range and refueling time, refueling strategy such as fuel level at the trip origin) are addressed in the next two sections 3.2 (HDV traffic) and 3.3 (user requirements).

3.2 German heavy-duty vehicle traffic

In order to apply the developed model to German HDV traffic, three types of traffic-related input are necessary: highway data to determine the current network system (with nodes and arcs), traffic demand to understand current HDV traffic intensity, and individual HDV vehicle trips to understand traffic flow.

3.2.1 Road network and traffic demand

The German Federal Highway Research Institute (BASt, 2017) regularly provides traffic data pertaining to German highways. This thesis refers to their 2,500 traffic surveillance points (hereafter referred to as "nodes") including distances between adjacent nodes. These nodes and their connecting routes represent the complete German highway network of about 13,000 km and 121 highways as shown in Figure 12. To simplify the computational process, some highways are removed that are separated from the main highway network (e.g. A44 Waldkappel and A94

Winhöring)[15] and each of the highway nodes in the network is represented by a number from 1 to 2,397. Nodes that represent intersections were excluded as potential station locations, because an AFS is rarely built at a highway intersection.

These nodes and routes were enriched with data from the most recent HDV road traffic census (BASt, 2017) and spatial data (geographic coordinates and NUTS3[16] areas). The available HDV data includes trailer and tractor trucks with weight specifications from 26t to 40 tons[17]. For further spatial analyses, the distance between each node is obtained from BASt (2017), assuming a straight line on a globe which can be calculated using the haversine formula. The resulting HDV traffic intensity on all German highways using QGIS software is then illustrated as shown in Figure 13.

Furthermore, information about existing conventional fuel stations in Germany is added to the network as additional nodes (358 highway fuel stations according to Gürsel and Tölke (2017)) in order to be able to compare the new AFS network with the existing conventional station network.

On a side note, passenger car traffic is not considered in this analysis. According to Altmann et al. (2017), passenger cars usually refuel in metropolitan areas and not on highways. Purchasing power and population density are highest in metropolitan areas, so that hydrogen mobility (i.e. passenger cars) is being promoted primarily in urban areas with the greatest interest (cf. Altmann et al. (2017)). The utilization of highway HRS by passenger cars is therefore considered to be rather low and passenger car HRS are currently being developed in metropolitan areas. However, as passenger cars would be also able to refuel at HDV-HRS (as outlined in section 4.2.2), potential interactions between passenger cars and the HDV-HRS network are discussed in Chapter 7.

[15] Removing these highway sections may exclude traffic at particular nodes and lead to higher traffic volumes along the remaining OD paths. This may condense the resulting AFS network to fewer nodes and is discussed in section 7.

[16] Nomenclature of Territorial Units for Statistics (NUTS) is a geocode standard referencing the subdivisions of countries for statistical purposes. For each EU member country, a hierarchy of three NUTS levels is established by Eurostat in agreement with each member state, whereby NUTS3 in Germany consists of 402 districts (counties).

[17] Commonly referred to as tractor-trailer unit (German: Sattelzugmaschine).

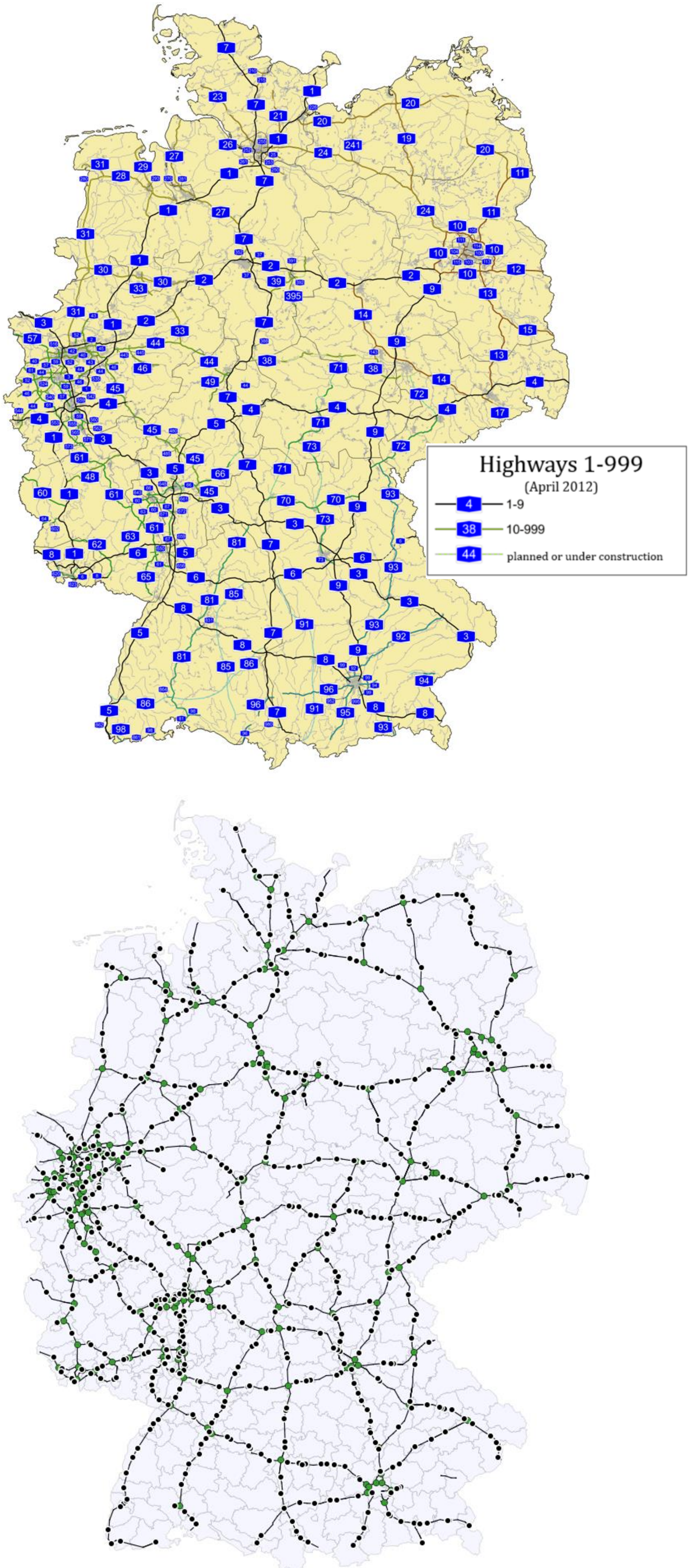

Figure 12: Top: German highway network of 121 highways, about 13,000 km and 2,500 nodes (Weltkarte.com, 2012); bottom: highway network arcs (black lines), nodes (black dots) and junctions (green dots)

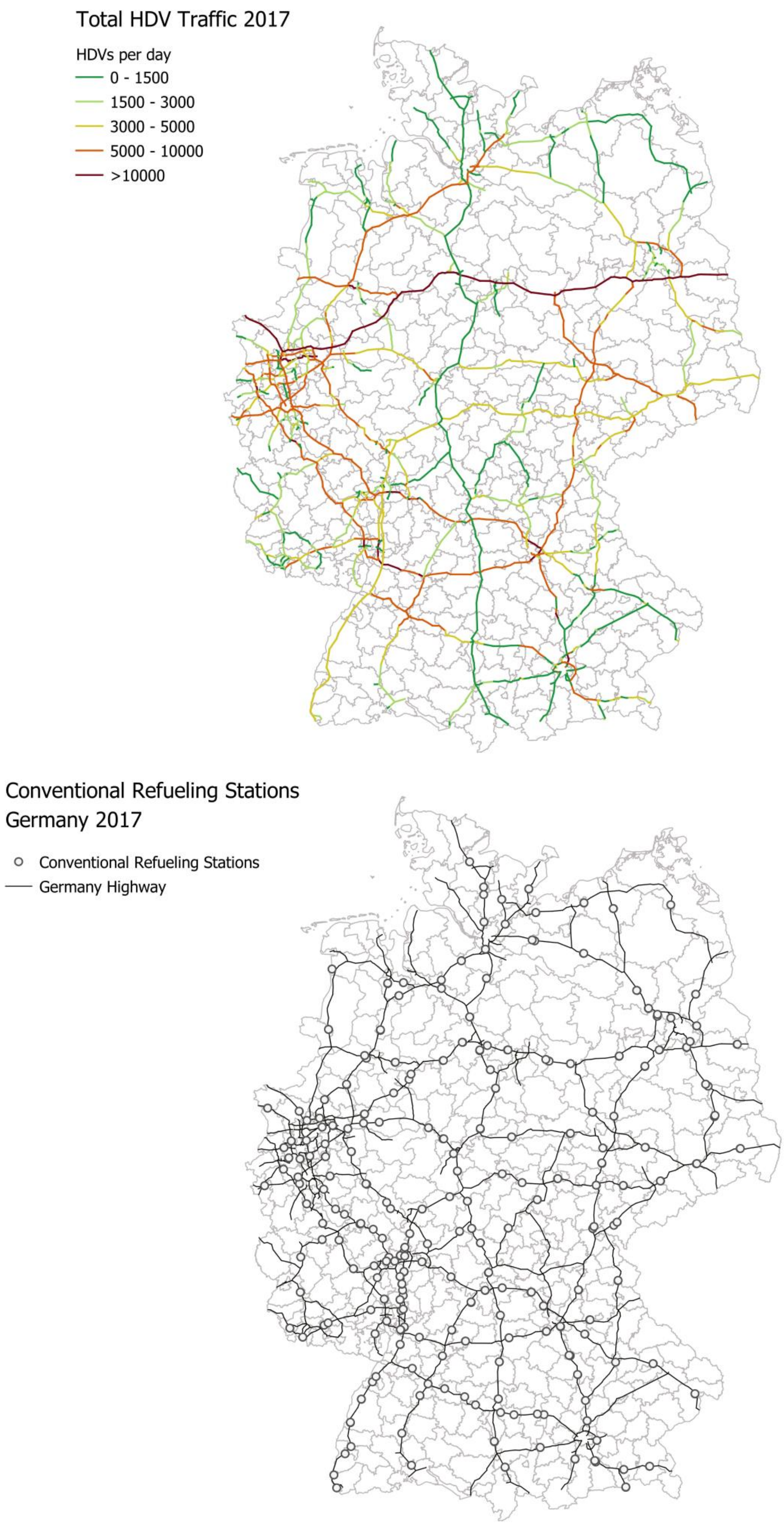

Figure 13: Top: Total HDV traffic on German highways in 2017 (own illustration based on BASt (2017)); bottom: conventional fueling stations along German highways (own illustration based on Gürsel and Tölke (2017))

3.2.2 Heavy-duty vehicle origin-destination paths

Individual vehicle flows are essential information for the developed method addressing the FRLP as outlined in section 3. Data from Wermuth et al. (2012), which is one of the most comprehensive surveys on road traffic in Germany, are used in this thesis. In comparison with other available databases of German traffic from Nederstigt (2012) and Schubert et al. (2014), these data have several advantages for the NC-FRLM, e.g. regarding vehicle types and traffic format. Wermuth et al. (2012) list the HDV segment separately and provide individual HDV OD trips instead of tkm, which better suits the approach of this thesis (cf. Table 7). Wermuth et al. (2012) also limit the scope to national traffic and do not include foreign transit traffic, a point which will be addressed in the course of this thesis.

Table 7: Comparison of different HDV flow data sets covering Germany

Criteria	Wermuth et al. (2012)	Nederstigt, (2012)	Schubert et al. (2014)
Vehicle types			
- Trucks separate	√	√	√
- HDV separate	√	-	-
Traffic format			
- OD trips [#]	√	-	-
- OD matrix [tkm]	-	√	√
Traffic scope			
- National traffic	√	√	√
- Foreign traffic	-	√	√

The data set of Wermuth et al. (2012) covers 44,393 individual vehicle trips of about 35,200 vehicle IDs, which encompass both the origin NUTS3 area and the destination NUTS3 area. 4,104 trips are completed by HDVs (the same trailer and tractor truck weight categories as in BASt (2017)), which form the focus of this thesis. 89 trips have the origin and destination outside Germany and 321 trips have either the origin or the destination outside Germany. These trips were excluded from the data set due to unclear border crossings. An additional 1,039 paths were removed, which have the same origin and destination. This thesis considers the 2,655 HDV domestic trips that commenced and finished in different NUTS3 areas within Germany, of which 1,693 are unique trips (only one vehicle per OD path direction).

Table 8 shows an OD path data example. The description of the example data is as follows: HDVs that travel from the DE235 NUTS3 area to DE238 NUTS3 area enter the highway at node 70 and leave it at node 1817. The shortest path from node 70 to node 1817 is via node 1476. The distances between the nodes (or in other words, the length of the arcs) taken from the raw data are 10.5 km from node 70 to 1476, and 3.5 km from node 1476 to 1817. Adding the distance from DE235 centroid to node 70 and from node 1817 to the centroid of DE238, the total distance of this OD path is about 52.40 km.

Table 8: Example of OD path data

NUTS3 origin	NUTS3 destination	Nodes on the shortest path	Distances between nodes	Distance from origin [km]	Distance to destination [km]	Total distance [km]
DE235	DE238	(70, 1476, 1817)	(10.5, 3.5)	36.26	2.14	52.40

Four dimensions were considered when integrating this data into the highway network. First, nodes identified as highway junctions were excluded, as these are not available for HDVs to enter the network or for the construction of potential HDV-HRS. Second, short trips of less than 50 km were excluded to reduce computation time, as such trips might not require public refueling infrastructure (= 198 OD paths).[18] This resulted in a remaining set of 1,495 HDV OD trips, which represent about 90 % of the unique HDV OD paths as shown in Figure 14. Third, the growth in traffic volume between 2017 and 2050 is addressed by assuming an annual growth rate of 0.6 % based on Hacker et al. (2014).

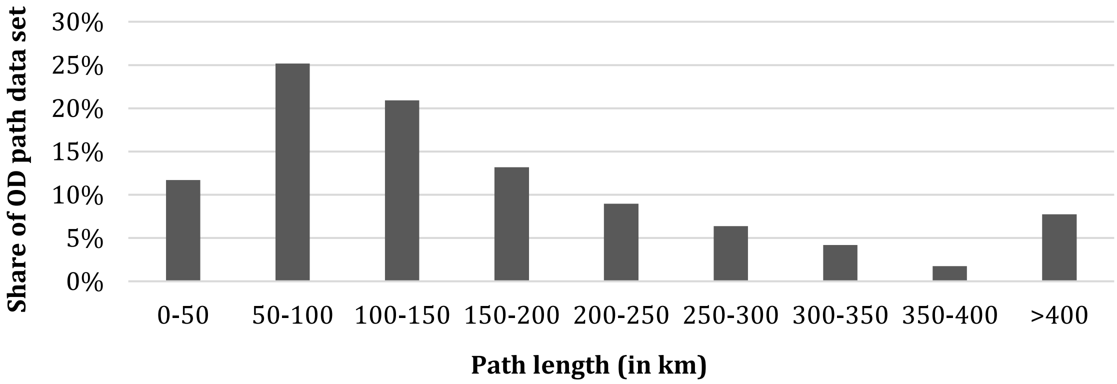

Figure 14: Share of 1,693 OD paths by path length

The fourth dimension supplemented the existing OD trips of Wermuth et al. (2012) in order to represent the total HDV road traffic census by BASt (2017). The following traffic subsets were defined to describe HDV traffic on German highways:

$$HDV_{Total\_Traffic} = HDV_{Inner\text{-}German\_Traffic} \cup HDV_{Transit\_Traffic} \quad (11)$$

$$HDV_{Inner\text{-}German\_Traffic} = HDV_{Domestic\_Traffic} \cup HDV_{Border\_Traffic} \quad (12)$$

[18] The exclusion of these 198 OD paths may exclude traffic on particular nodes and additionally lead to higher traffic on the remaining OD paths. Hence, it may concentrate the resulting AFS network to fewer nodes.

Nomenclature

Sets

$HDV_{Total\_Traffic}$ Set of total HDV traffic on German highways represented by the data set of BASt (2017), defined here as 100 % or about 72 million daily kilometers driven in 2050

$HDV_{Inner-German\_Traffic}$ Set of HDVs that start or end on German highways, defined as 80 % based on German highway toll data (Logistik Heute, 2018) or about 58 million daily kilometers driven

$HDV_{Transit\_Traffic}$ Set of HDVs that start and end outside Germany but drive along German highways, representing the HDV transit traffic, deduced as 20 % or about 14 million daily kilometers driven

$HDV_{Domestic\_Traffic}$ Set of HDVs with origin and destination in Germany represented by the data set of Wermuth et al. (2012), defined as 75 % of the German HDVs on German highways based on Wietschel et al. (2017) and deduced as 60 % of the total HDV traffic or about 42 million daily kilometers driven

$HDV_{Border\_Traffic}$ Set of HDVs with either origin or destination outside Germany, deduced as 25 % of domestic HDV traffic or 20 % of the total HDV traffic or about 16 million daily kilometers driven

As a result, $HDV_{Domestic\_Traffic}$ OD trip data (Wermuth et al., 2012) only include about 60 % of the total HDV traffic on German highways. These OD paths were subsequently subtracted from the $HDV_{Total\_Traffic}$ (BASt, 2017) to synthesize the subsets of $HDV_{Transit\_Traffic}$ and $HDV_{Border\_Traffic}$ from the remaining data. Accordingly, three OD paths were synthesized for $HDV_{Transit\_Traffic}$ and five OD paths for $HDV_{Border\_Traffic}$.

The final OD path subsets and their vehicle intensity are displayed in Figure 15 for both domestic traffic and synthezied traffic. The longest OD trip in the data set is from DE138 (Konstanz) to DEF01 (Flensburg), a total distance of around 900 km, which only needs a maximum of two refueling stops.

Applying the developed algorithm from section 3 to these nodes and OD trips, $K_{j,k}^{q}$s results in 10,374 sets from all 1,503 OD trips. These sets are utilized in the new optimization model.[19]

[19] Additional traffic data, such as congestion, was not considered.

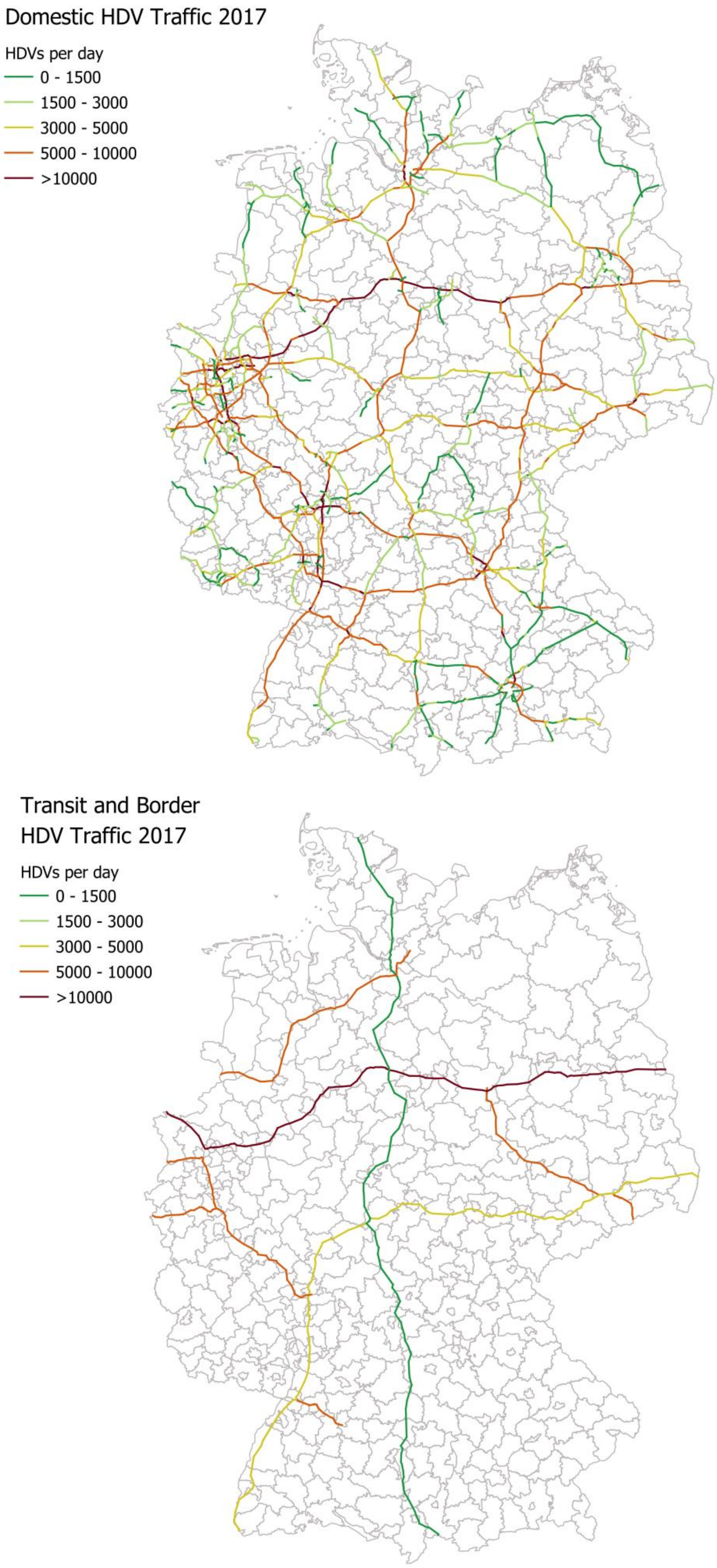

Figure 15: Traffic of OD trips used in this thesis including domestic HDV traffic (top, based on Wermuth et al. (2012) as well as synthesized transit and border HDV traffic (bottom)

3.2.3 Origin-destination data quality

The vehicle intensity per OD path is then determined by an optimization to maximize the coefficient of determination R^2. Figure 16 shows the regression diagram of vehicles per individual node for the OD paths and traffic census (BASt, 2017) used in this thesis, with a resulting R^2 of above 50 %.

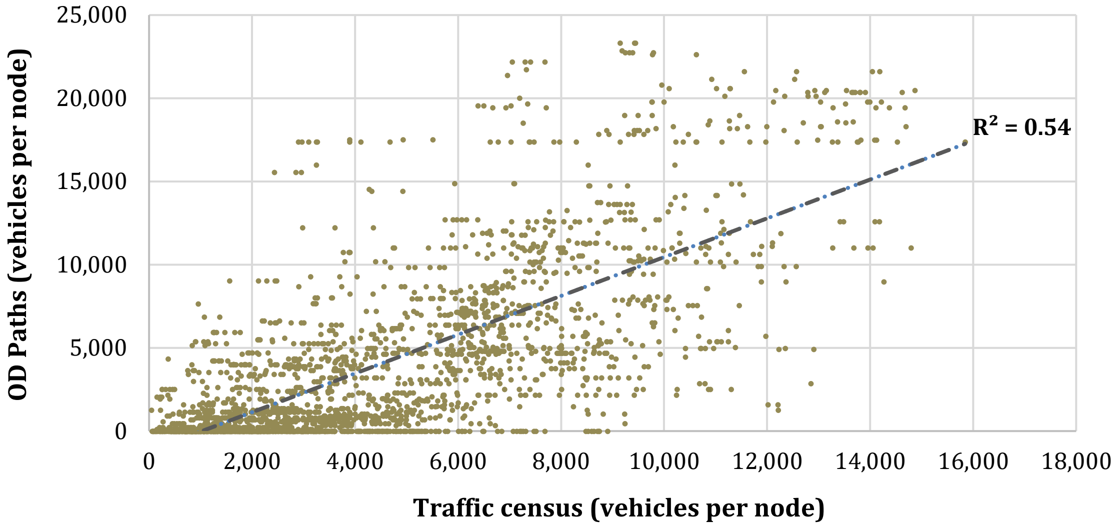

Figure 16: Regression diagram displaying vehicles per individual node (dots) for both OD path and traffic census

The difference to a coefficient of determination of 100 % can be explained by missing data. On the one hand, the OD data set of Wermuth et al. (2012) does not depict a full matrix of all existing origin to destination connections but only a sample. Further, OD paths of less than 50 km (198 OD paths) were removed, because they were expected to generally not use the highway, but they may in reality partly access highways and thus contribute to lowering the R^2. Finally, the synthesized OD paths – transit and border traffic – contain the average HDV traffic per path, but in reality traffic levels vary along these paths.

3.3 German heavy-duty vehicle user requirements[20]

In addition to the German HDV traffic data, user requirements are needed as the second input to the NC-FRLM, as these shape the general model assumptions regarding vehicle layout and infrastructure requirements. This section aims to identify HDV user requirements based on primary data from expert interviews and an online survey.

[20] The content of this section has been published in a working paper (Kluschke et al., 2019b).

3.3.1 Data collection

The methodological background to collecting user requirement data is outlined before describing the data collected for this thesis.

Qualitative and quantitative research methods are described and classified according to the methodological approach of Tausendpfund (2018) as shown in Table 9. These two types of method differ in aspects such as the research objective, the research process itself and the evaluation methods. Often, these two approaches are combined by examining the research topic qualitatively to start with and then conducting quantitative surveys (Tausendpfund, 2018). In this thesis, due to the lack of information on the user requirements for HDVs and their infrastructure, primary research is conducted using both approaches. Qualitative studies have proven useful to set up an initial hypothesis and gain a first, basic understanding of unknown fields of research (e.g. user preferences and requirements). Qualitative methods are applied typically on a small input scale, e.g. via guided expert interviews. Quantitative research methods are applied after qualitative studies to explain these initial findings in a field of research and to verify them with numbers (Tausendpfund, 2018). Hence, quantitative studies often follow qualitative studies with larger scale surveys using a structured questionnaire.

Table 9: Comparison of qualitative and quantitative methods (Tausendpfund, 2018)

Dimension	Qualitative methods	Quantitative methods
Research objective	understand	explain
Research process	circular	linear
Case number	few	many
Research data	words	numbers
Hypothesis	generating	probing
Research logic	inductive	deductive
Evaluation	open	statistical methods
Generalization	low	high

In this thesis, qualitative expert interviews are conducted first and serve as a basis to identify HDV user requirements. A quantitative online survey is then conducted in order to prioritize and quantify the identified requirements.

For the expert interviews, the aim is to interview owners of HDVs, mainly found in transportation, logistics and haulage companies. In Germany, most HDVs are owned by small and medium enterprises (SME). The targeted experts within these SMEs can be roughly clustered into three categories: managing board, fleet management and drivers. 15 interviewees were gained through logistics associations. In detail, in addition to six managing directors and managing partners, eight executive employees could be recruited, six of whom are active in fleet management. A driver was also interviewed to obtain information about the attitude of direct users. Guided face-to-face interviews[21] in German were held with these experts between September 2018 and January 2019, which lasted between 30 and 60 minutes.

An online questionnaire was prepared for the subsequent quantitative survey (see Figure 47 in the Appendix). Similar to the expert interviews, participants were recruited through the member newsletters of logistics associations between April and Juli 2019. 115 potential participants followed the hyperlink to the questionnaire. 99 of these started the questionnaire and 70 completed it. Seven participants who completed the questionnaire were not part of the target group.[22] Consequently, the analysis is based on a sample of 63 participants from Germany. The majority of these participants are managing directors. Truck drivers, tour planners and fleet managers also took part in the survey. Figure 17 gives an overview of the distribution of the participants based on their job description for both user studies.

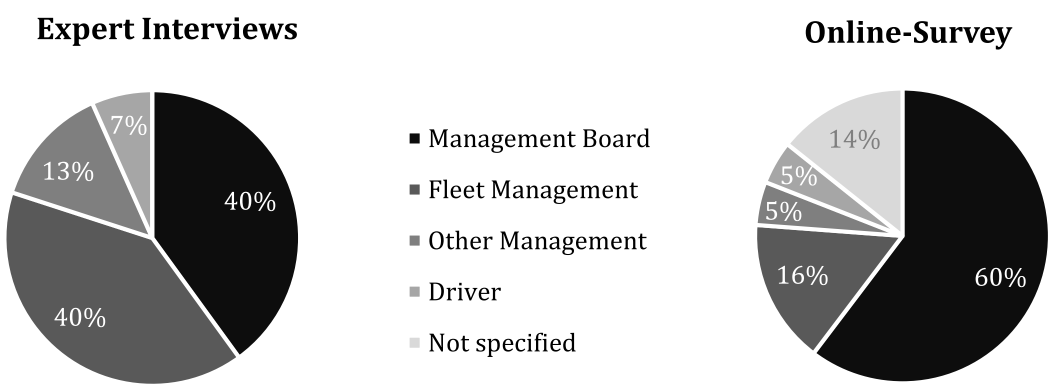

Figure 17: Share of interviewee positions within logistics companies in the qualitative expert interviews (left, n = 15) and the quantitative online survey (right, n = 63)

3.3.2 Descriptive analysis

The data of both studies are subsequently described based on the following two aspects: company and fleet characteristics as well as vehicle and infrastructure requirements.

Company and fleet characteristics are only queried by the online survey, as the expert interviews focused on user requirements. The survey data sample is examined based on various company characteristics such as company and fleet size, type of HDV financing, type of goods transported, and transport tasks performed. In terms of company size, the distribution shows the SME character of the logistics and freight sector: 50 % between 10 and 100, a quarter of the participating companies have

[21] The interview guideline can be found in the Appendix in Figure 46.

[22] Those candidates and / or their companies do not own HDVs.

between 100 and 200 employees and a further 25 % have 101 to 200 employees. Larger companies with 201 to 3,000 employees account for around 17 %, while only a small proportion have fewer than 10 employees and the smallest share are companies with more than 3,000 employees. The HDV fleet sizes show a similar distribution to the employee numbers, with a large majority of the companies owning 10 to 200 HDVs. Overall, there is a strong preference of the surveyed companies to buy (about 63 %) rather than lease HDVs (about 32 %). When buying HDVs, many organizations either finance the transaction or pay cash. More than half of the companies primarily transport palletized goods. Unpacked bulk goods are also frequently indicated. Tramp transport is the most frequent sole transport task of a company, but is also often mentioned as part of a mixed form. More than 75 % of the companies cover national transport, the remaining 25 % are equally divided between regional and international transport. Figure 18 summarizes these statistics. Further details can be found in Table 34 in the Appendix.

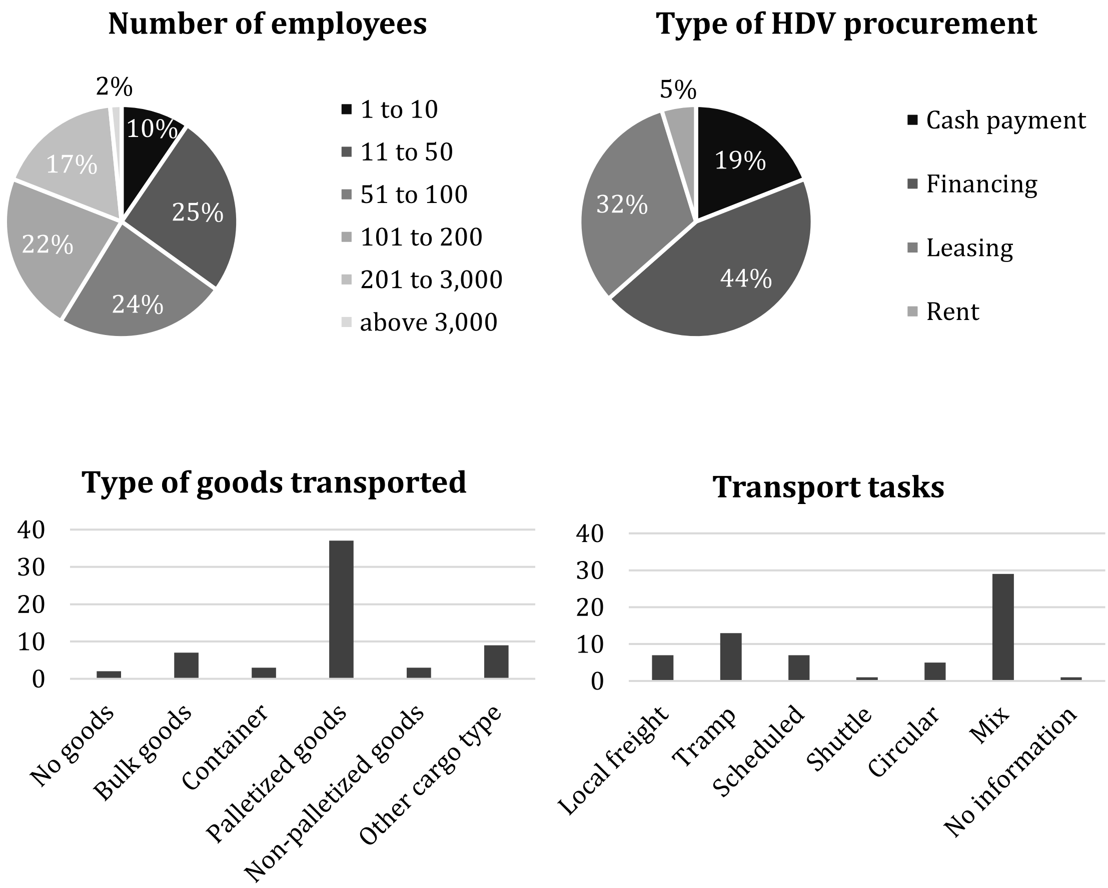

Figure 18: Number of employees (top left), type of HDV procurement (top right), type of goods transported (bottom left) and transport task (bottom right) of survey participants, based on quantitative analysis

Vehicle and infrastructure requirements are identified first through the expert interviews and subsequently quantified using the online-survey. To gather the experts' requirements – not influenced by the interviewer – all interviewees were asked: "What requirements do you have as a user of a HDV?" This records the interviewees' initial thoughts on the topic of user requirements. Figure 19 summarizes the user requirements mentioned and adds a quantitative mean value of relevance per requirement drawn from the online survey (1 = very relevant, 4 = very irrelevant). Relevance in this context describes the importance of a particular requirement on an absolute scale. The 16 stated requirements can be clustered along three categories: economic, technological and ecological. Overall, the mean relevance of the economic category is 1.4, the technical requirements have a mean value of 1.9 and the ecological requirements 2.1. In detail, the lowest mean value – which equals high importance – can be found in the Total Cost of Ownership (TCO). The three other economic requirements of consumption, reliability and investment also have average values of less than two. Standard deviations for the four economic requirements are lower than the other two categories. This indicates that the test persons agree on the significance of economic requirements. A more differentiated picture emerges when looking at the technical requirements. Range, infrastructure and loading capacity have the highest importance, while refueling duration and motor power have mean values above two (i.e. medium importance). The higher standard deviations here also indicate a differentiated opinions with regard to technical requirements. However, the lowest importance overall can be found in the ecological category. The individual mean values per requirement indicate the relatively high importance of toll classification, environmental protection and avoidance of driving bans. Image and pressure from clients have the highest average values of all requirements, i.e. they appear quite unimportant. A potential explanation for these widely differing opinions in the ecological category may be the direct connection between some ecological and economic effects (e.g. low-emission HDVs are currently exempt from tolls, driving bans would have a negative impact on orders).

As the technology requirements are very important criteria for AFS modeling and design, more detailed information is quantified through the online survey regarding vehicle range, maximum refueling time and acceptable detour for refueling. In addition, these quantitative results are supplemented by statements from the expert interviews. The median range required for HDVs is about 800 km. Most respondents in the expert interviews give their daily mileage as between 400 and 800 km. The minimum vehicle range mentioned is 350 km and the maximum range mentioned is 1,600 km. The median refueling duration is approx. 15 minutes in the random sample. The maximum specified duration is 60 minutes (mentioned by one person) and five persons would accept 45 minutes. 50 % of the responses are between 10 and 30 minutes. The median of detour acceptance is about 20 km (50 % of the respondents indicated a value between 10 and 30 km), which is less than 2.5 % of the required median vehicle range. Extreme values are at 50 km, and some respondents also have 0 km detour acceptance. These statistics are summarized in Figure 20.

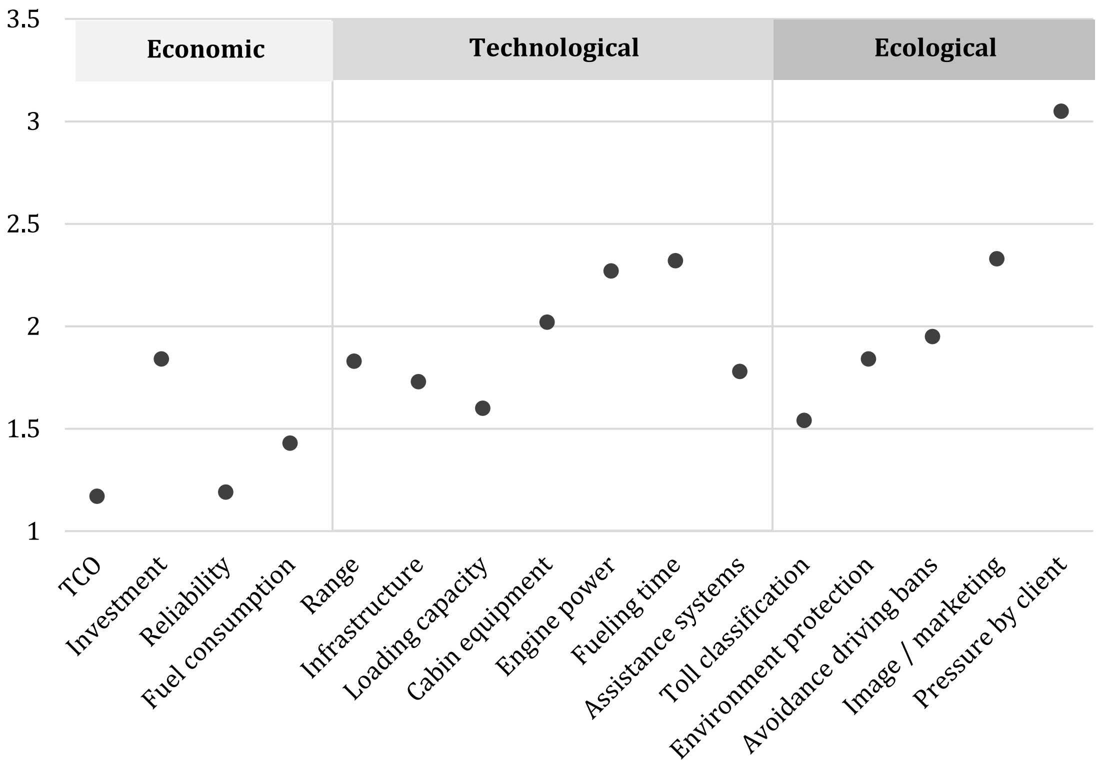

Figure 19: User requirements for HDVs and their infrastructure (shown is the mean value of relevance with 1 = very relevant and 4 = not relevant), based on survey results

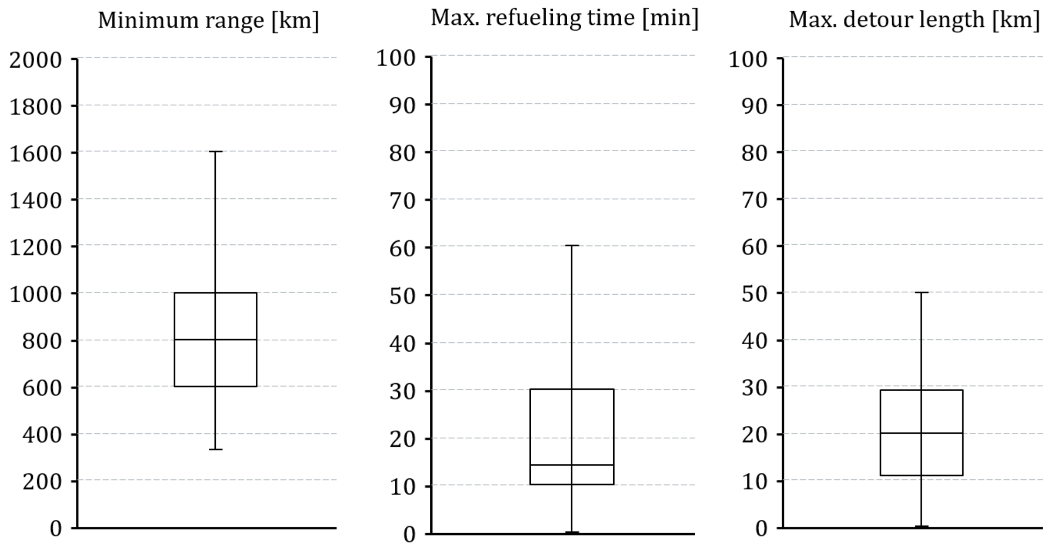

Figure 20: Requirements of survey participants: vehicle range (left), maximum refueling duration (middle) and acceptable detour to refuel (right)

3.3.3 Data quality

As there is no complete list of HDV owners in Germany, it was not possible to randomly select participants for the online survey. This means the sample may not be representative. In addition, the online distribution may lead to distortions by addressing predominantly those who are open to online media and questionnaires. The sample is therefore compared with the population as a whole in order to classify the quantitative evaluations mentioned above. The two characteristics company size and fleet size in the survey are compared with the total population to determine whether these characteristics correspond to the basic population of HDV owners in Germany, which is based on commercial road freight traffic from the German Federal Office for Goods Transport (BAG, 2015)

Comparing the sample and the population in terms of company size, it can be seen that larger companies are slightly overrepresented and smaller companies are slightly underrepresented in the sample. Comparing the sample and the population by fleet size, the same trend is more pronounced. While considerably more companies with a fleet of one to three HDVs are represented in the overall basic population, companies with between 11 and 50 HDVs are strongly overrepresented in the sample. As a result, larger companies and/or larger fleets are overrepresented as shown in Figure 21.

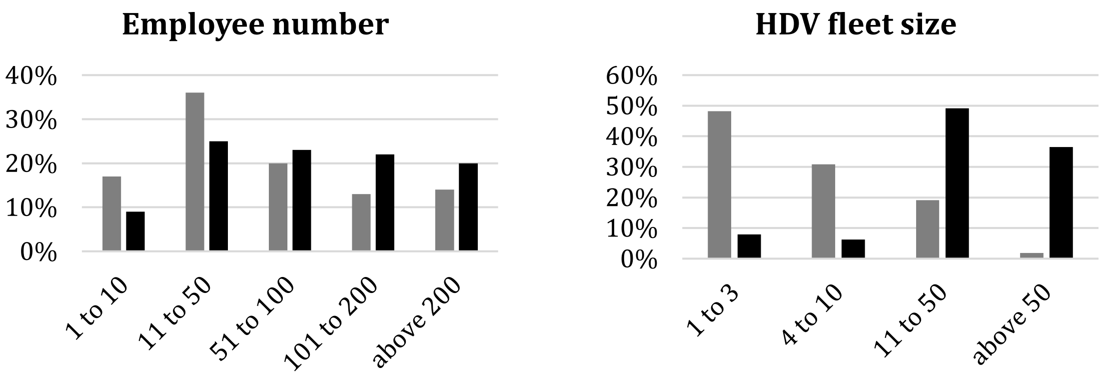

Figure 21: Comparison of sample (black) and basic population in Germany (grey) regarding both company employee numbers (left) and HDV fleet sizes (right) (own illustration based on own survey data sample and BAG (2015))

Even though the target group is difficult to recruit as participants, the size of the sample is sufficient for the purposes of this thesis. However, for further statistical investigations (e.g. correlations between different criteria), more comprehensive and representative samples would be advantageous.

3.4 Integration of open-source energy model[23]

Having assured the availability of the relevant input data required for the NC-FRLM approach, the next focus is on modeling the interaction of a potential HDV-HRS network in Germany with the electricity system.

The electricity system modeling framework PyPSA[24] is applied to analyze the integration of a HDV-HRS network in an electricity system (Brown et al., 2018; Hörsch et al., 2018). PyPSA is an open-source software seeking to bridge the gap between electricity system analysis software and general energy system modeling tools. It combines a multi-period optimal power flow problem with linearized load flow equations and the capacity expansion of generators, energy storage units, and the transmission network infrastructure in a single investment planning problem.

The objective of PyPSA is to find the electricity system with the least investments in the long term, comprising the annuitized infrastructure investments (CAPEX) plus the short-term costs (OPEX) over one year, subject to the following set of linear constraints:

1. The energy demand must be met at each location and each point in time.
2. The generator dispatch of renewable generators (such as wind, solar and run-of-river plants) is constrained by temporally and spatially fluctuating availability time series.
3. The dispatch of storage units (such as battery, pumped-hydro, and hydrogen storage) is constrained by their nominal power rating as well as their charging level.
4. The capacity limits of transmission lines must be complied with.
5. The linearized DC power flow equations implementing Kirchhoff's second law must be observed.
6. The installed capacities of generators and storage units may not exceed their geographical potentials.
7. Specified carbon dioxide emission reduction targets must be met.

PyPSA has models for mixed alternating and direct current networks, HVDC links, dispatchable generators as well as generators with time-varying power availability. Moreover, it allows conversion between different energy carriers (e.g. from power to hydrogen) and accounts for efficiency losses as well as inflow and spillage for hydroelectric power plants. As a result, it is not only capable of pure electricity system analysis but also a more comprehensive energy system analysis. In such a cross-sectoral setting, the simultaneous co-optimization of generation, storage and transmission infrastructure is pivotal when accounting for the multitude of trade-offs between the varieties of energy technologies. The resulting linear optimization

[23] The content related to the interaction of the NC-FRLM and PyPSA has been published in a peer-reviewed paper (Rose and Neumann, 2020).
[24] PyPSA stands for "Python for Power System Analysis".

problem forms the input to the commercial solver Gurobi, which yields the total annual system investments. In addition to the optimal values of the primal variables, evaluating the dual variables or shadow prices of primal constraints also delivers valuable information such as nodal prices and an endogenous price for carbon dioxide. Full details on the software package PyPSA and the complete problem definition are presented in Hörsch et al. (2018).

General data on Germany's electricity system assets are taken from PyPSA-Eur, which is an open model dataset of the European electricity system at the transmission network level (Hörsch et al., 2018).[25] This includes:

- the transmission infrastructure for the ENTSO-E area using the tool GridKit,
- an open database of conventional power plants obtained with the power plant matching tool, which merges multiple publicly available power plant databases,
- spatially and temporally resolved time series for electrical demand derived from a top-down heuristic based on population and gross domestic product,
- spatially and temporally resolved time series for variable renewable generation availability based on weather data for the year 2013 and underlying technical wind turbine and PV module characteristics, and
- geographic potentials for the expansion of renewable generation based on land eligibility, nature conservation areas and assumptions on allowable densities.[26]

Since a network of hydrogen refueling stations is limited to Germany in this analysis, the author only uses an extract of the European model. This results in a network with 333 nodes, in which electricity imports or exports to adjacent countries are disregarded and thereby an energy balance within Germany is enforced (contrary to the current net surplus). The temporal resolution is reduced to two hours for one year yielding 4,380 snapshots. This is a compromise between computational tractability on the one hand and considering a large range of operating conditions that are vital to investment planning on the other.

When linking PyPSA with the HDV-HRS network, the potential station locations and their individual hydrogen demand are integrated into PyPSA as additional power demand. The objective of this link is to determine the optimal electrolyzer sizes per station depending on the temporal and spatial marginal cost of electricity, ultimately

[25] Transmission-level voltages are usually considered to be 110 kV to 765 kV AC, varying by the transmission system and by the country. Following Hörsch et al. (2018), the transmission network level appears to be right for the connection with electrolyzers sizes of 1 MW and above (cf. section 4.2.3).
[26] Full details on the routines and data sources of PyPSA-Eur are found in Hörsch et al. (2018).

aiming to minimize the total electricity system costs in 2050. Further, this analysis aims to determine the levelized cost of hydrogen (LCOH)[27] per station.

3.5 Determination of network cost

As this thesis aims at analyzing and comparing also the economic results of the model (cf. section 5.3), a consistent determination of the network cost is required. Hence, the equation used to determine the total annual station network costs is defined and presented in this section:

$$TI = \sum_{i\in N}\sum_{s\in S}[([FI]_s + [EL]_s + [OM]_s) * z_{is} + l_{is}] \quad (13)$$

Equation (13) defines *TI* as the total annual costs (in €/a) of building a station network. These annual costs consist of capital expenditures (CAPEX) and operational expenditures (OPEX) subject to z_{is} (size *s* station built at node *i*). The CAPEX consist of FI_s (fixed annuitized investment for size *s* station in €/a) as well as El_s (on-site electrolyzer annuitized investment that complies with size *s* station in €/a).[28] The OPEX consist of variable operating and maintenance costs (OM_s in €/a, which are 4 % of CAPEX). Finally, the electricity costs (l_{is} in €/a) to produce hydrogen that meets demand at node *i* in size *s* station are added to the equation. Accordingly, the total annual network costs cover the cumulative CAPEX (annuitized station investment including all network components, e.g. low-pressure hydrogen storages or compressor, electrolyzer) and OPEX (operating and maintenance cost) as well as electricity costs throughout the year. The detailed parameters will be defined in section 4.

Besides on-site hydrogen production, this thesis also covers a centralized hydrogen production scenario. For the centralized production scenario including pipelines to transport hydrogen from the production site to the stations, the previous cost formula (13) is adjusted as shown:

$$\begin{aligned} TI_p = &\sum_{p\in N}\big((FI_p + El_p + OM_p\big) * P_p + \\ &\sum_{p\in N}\sum_{i\in N}\big(FI_{pi} + OM_{pi}\big) + \\ &\sum_{i\in N}\sum_{s\in S}((FI_s + OM_s) * z_{is} + l_{is}) \end{aligned} \quad (14)$$

Equation (14) determines TI_P (total annual costs for the pipeline scenario in €/a) from the total annual costs for hydrogen production facilities, a hydrogen pipeline system as well as the total annual station costs. The hydrogen production facilities cover FI_p (fixed annuitized investment to build centralized hydrogen production site size p in €/a), OM_p (variable operating and maintenance costs of centralized hydrogen production site *p* in €/a), El_p (electrolyzer annuitized investments that comply with

[27] Conceptionally, the LCOH is very similar to the levelized cost of electricity (LCOE). The LCOH determines the full life-cycle costs of hydrogen production and expresses them as costs per unit of hydrogen produced.

[28] For the CAPEX within this analysis, the annuity factor concept has been applied to the asset investments to represent the costs per year of owning an asset over its entire lifespan (Wöhe and Döring (2010). For all technologies, a universal discount rate of 7 % is assumed.

centralized hydrogen production site p and total demand at s in €/a) and P_p (centralized hydrogen production site p). The total annual costs for a hydrogen pipeline system include FI_{pi} (fixed annuitized investment of pipeline from production site p to station site I in €/a) and OM_{pi} (variable operating and maintenance cost of pipeline from production p to station site I in €/a). Finally, the total annual station costs cover FI_s (fixed annuitized investment of building station with size s in €/a), OM_s (variable operating and maintenance cost of s in €/a), z_{is} (size s station built at node i)) and the total annual electricity costs l_{is} (electricity costs to produce hydrogen that meets demand at node i in size s station in €/a).

When linking the NC-FRLM with PyPSA, both the cost of the station network as well as the cost of the electricity system will be determined (cf. chapter 6). This allows splitting the electricity cost into its various components (production assets, grid, storage, operation and maintenance costs), unlike the previous two equations defining electricity cost as a direct input. As a result, the cost-minimal electricity system layout to serve the station network (= minimal electricity cost) can be observed (cf. scenario A in section 6.3). Moreover, chapter 6 will analyze how to size hydrogen production capacities in order to leverage an even less costly electricity system layout and thus reduce electricity costs (cf. scenario B in section 6.3).

3.6 Summary of model development and data

The aim of this chapter was to construct a model (NC-FRLM) capable of developing a potential HDV-HRS network for Germany, to provide fundamental data to run the model and to define an electricity system model, in which the NC-FRLM results can be integrated. Following Ko et al. (2017), the four issues of locating refueling stations are addressed in this chapter:

- **Objective**: Minimize the number of AFS while serving 100 % of the HDV traffic flow on German highways as outlined in section 3.1.
- **Refueling demand estimation**: using origin-destination (OD) paths as outlined in section 3.2.
- **Vehicle characteristics**: 800 km range and maximum of 30 min refueling time as outlined in section 3.3.
- **Refueling strategy**: Stations need to be at (or very close to) the nodes of the highway network, and the beginning and remaining fuel level must be sufficient for 400 km range as outlined in section 3.3.

In summary, developing the NC-FRLM, providing the relevant data on HDV traffic and user requirements as well as the interface with an open-source energy model serve as the foundation to address the research questions stated in section 1.3. The next section defines the techno-economic parameters needed to apply the developed method and answer the research questions.

4. Techno-economic framework parameters

This chapter defines the three techno-economic framework parameters required in order to apply the previously defined method (chapter 3) and retrieve analysis results (chapter 5 and chapter 6). These required parameters cover the vehicle (a FC-HDV in section 4.1), the hydrogen infrastructure (section 4.2) – including legal aspects, a HDV-HRS portfolio definition as well as hydrogen production and distribution – and the electricity system (section 4.3).

4.1 Fuel cell heavy-duty vehicles

This section defines a FC-HDV design complying with the previously collected user needs (cf. section 3.3) to derive required inputs for the NC-FRLM such as range and refueling amount. As mentioned in Section 1.2, currently there are no FC-HDVs in commercial operation (TRL 9), only prototypes (TRL 7) are available with limited available technological data.[29] Therefore, a FC-HDV design is developed based on the regulatory framework in the EU and Germany and on the technological feasibility of the subcomponents. Thus, this section focuses on the vehicle dimensions, efficiency and energy consumption of the specific standard FC-HDV considered in this thesis.

The German road traffic regulations (StVO) stipulate the maximum dimensions, weight and speed of HDVs. According to §32 StVO, HDVs may be 2.55m wide, 4.00m high and 18.75m long. §34 StVO limits the weight to 10t per axle for a maximum of four axles (40t). The speed of HDVs is limited to 80km/h on highways (§18 StVO). The EU directive 2015/719 allows HDVs with alternative powertrains an additional 50cm in length as well as up to 2t of additional permitted weight. A computer aided design (CAD) model of a conventional diesel HDV tractor that complies with German road traffic regulations can be seen below in Figure 22.

[29] Three Fuel Cell passenger vehicles are already commercially available (TRL 9): Honda Clarity, Hyundai Nexo and Toyota Mirai (fueleconomy.gov, 2019).

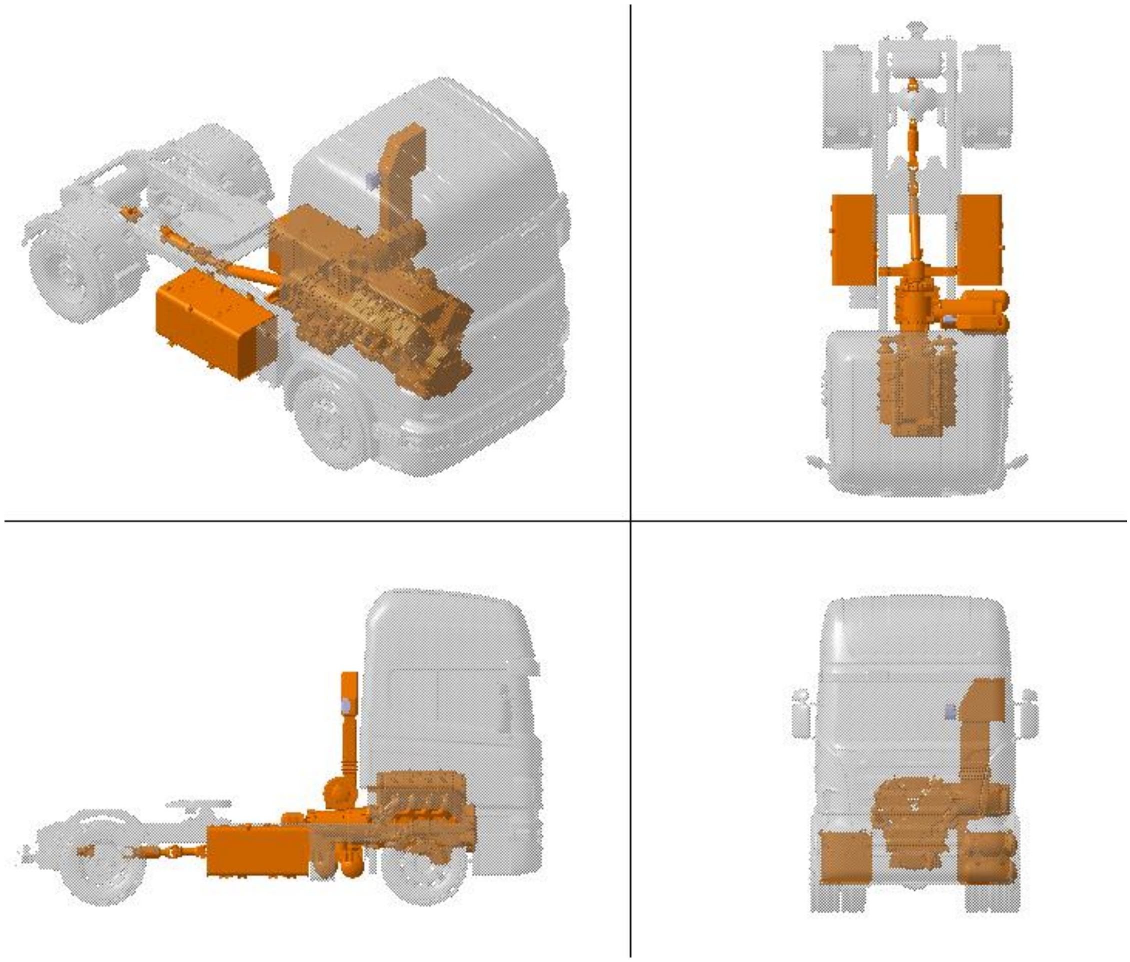

Figure 22: CAD model of current conventional HDV tractor that complies with German road traffic regulations (Jadim, 2018)

Subsequently, parameters are defined for a FC-HDV including components that comply with the given regulatory framework with special attention to volume, length and weight. Neglecting the fuel storage components, the volume of a FC powertrain is almost the same as a conventional diesel HDV. The hydrogen storage capability is determined by the available space on the HDV tractor. Under the EU directive 2015/719, an average HDV tractor would provide about 4.3 m^3 behind the driver cabin[30]. An additional 1 m^3 stemming from the previous conventional fuel tank[31] will be used for battery system components (cf. Table 10). For on board hydrogen storage, the necessary conversion of square tanks to cylindrical ones as well as storing the hydrogen in type 4 tanks (Töpler and Lehmann, 2017) imply a 50 % loss of space. As a result, circa 2.15 m^3 could be available in HDVs for onboard hydrogen storage. The two most common hydrogen pressure levels in automotive applications – 350 bar and 700 bar – mean that a volume of 2.65 m^3 is equivalent to either 34 kg (at 350 bar considering a gravimetric energy density of 16 kg/m^3) or 50 kg (700 bar, 23 kg/m^3) (Töpler and Lehmann, 2017). This translates into a driving range of about 550 km

[30] Space assessment behind driver cabin: x-axis (600 mm), y-axis (2,400 mm), z-axis (3,000 mm).
[31] The size of diesel fuel tank is estimated at about 500 liter (1,400 mm x 600 mm x 600 mm) with two tanks per HDV.

(350 bar) or 810 km (700 bar), assuming a tank-to-wheel (ttw) powertrain efficiency of about 51 %[32] and energy consumption of a fully loaded HDV (2.10 kWh/km). Given the German HDV user requirements derived in section 3.3, with a required average HDV range of 800 km, only the 700 bar option seems suitable for a FC-HDV powertrain. Figure 23 shows the CAD layout of the FC-HDV including dimensioning.

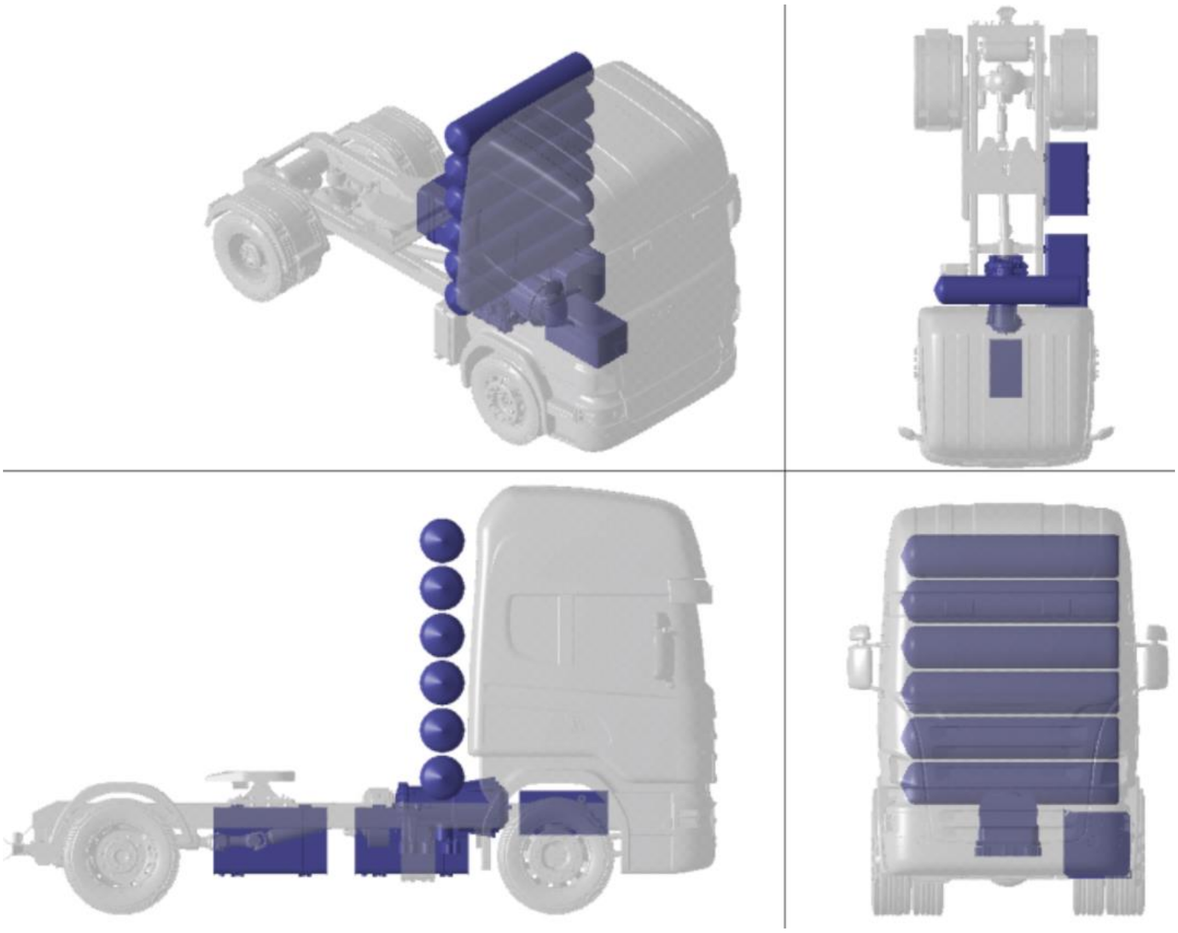

Figure 23: CAD model of potential FC-HDV tractor after replacing the diesel engine with a fuel cell powertrain, which meets user and legal requirements

On a side note, no significant constraints for FC-HDVs in terms of weight are identified. The overall weight of diesel HDV powertrains is around 2.4 tons, with 1 tons for the filled fuel tank, 1.3 tons for the engine and gears and 0.1 tons for the exhaust system (Mercedes Benz, 2019). In contrast, the FC-HDV powertrain is considered to be 2.2 tons as shown in Table 10. As a result, the additional range would be limited by current HDV length restrictions rather than weight restrictions, as the designed FC-HDV makes full use of the available tank space but is slightly lighter than its diesel equivalent.

[32] This efficiency is based on a component level (cf. Table 10) and corresponds to most of the prototypes listed in section 1.2.

Table 10: Techno-economic parameters: power, volume, efficiency and weight for FC-HDV in 2050 (own assumptions based on mentioned sources)

Component	Energy / Power	Volume	Efficiency	Weight	Source
Motor	350 kW	0.5 m^3	92 %	200 kg	Dünnebeil et al. (2015)
Battery system	30 kWh	0.08 m^3	95 %	150 kg	Thielmann et al. (2017)
Stack	300 kW	0.5 m^3	60 %	450 kg	U.S. Department of Energy (2018)
Tank [33]	1,665 kWh[34]	2.65 m^3	98 %	1,400 kg	Gangloff et al. (2017)
Total	-	3.73 m^3	51 %	2,200 kg	

In addition to the previously defined powertrain component parameters, vehicle energy consumption is an important input for the analysis. In this thesis, the energy consumption for FC-HDV in 2050 is based on the on-wheel energy consumption (Gueterverkehr Fachzeitschrift, 2012), efficiency improvements over time through non-powertrain improvements (Hacker et al., 2014) as well as HDV fuel cell powertrain efficiency (Table 10). The result is a ttw-efficiency of 2.10 kWh/km for a fully loaded (25 tons load weight) FC-HDV and 1.16 kWh/km for an empty FC-HDV (0t load weight) in 2050. As the data from (Wermuth et al., 2012) in section 3.2 shows, about 30 % of the HDVs operate with full load and about 30 % with zero load. Therefore, an average load of 12.5 tons and an energy consumption of 1.63 kWh/km (equaling 4.89 kg hydrogen per 100 km) are assumed for each HDV in the entire fleet in this analysis.

4.2 Hydrogen infrastructure

Having defined the relevant FC-HDV parameters to apply the NC-FRLM, this section outlines the parameters for modeling a HDV-HRS infrastructure. First, the German legal framework for stationary hydrogen applications is summarized to ensure modeling takes place within the legislative boundary conditions. Second, a HDV-HRS station portfolio is designed as a basis for the HDV-HRS network modeling. Third, the framework parameters for hydrogen production considered in this thesis are outlined. Finally, different hydrogen distribution options are compared to identify suitable hydrogen delivery options for FC-HDV refueling.

4.2.1 Germany's legal framework for hydrogen applications

It is important to identify and consider the relevant German legal framework and regulations for hydrogen applications – in particular hydrogen storage and production – due to the implications for HDV infrastructure modeling constraints (cf. chapter 3)

[33] at 700 bar
[34] 1,665 kWh equals 50 kg hydrogen

and for the design of technology packages to deploy an infrastructure for FC-HDVs (section 4.2.2).

Generally, three legal texts need to be considered when operating a hydrogen storage and/or production facility in Germany, which focus on the environment, employee safety and land use. First, a major part of German environmental law is the Federal Immission Control Act (German: "Bundesimmissionsschutzverordnung", short "BImSchV"), which protects the environment against harmful effects of air pollution, noise, vibrations and similar processes. More specifically, BImSchV Version 4 "Ordinance on Installations Requiring a Permit" (German: "Verordnung über genehmigungsbedürftige Anlagen") covers permits for industrial installations of all kinds that may have significant environmental impacts. Second, and focusing on employee health, the "Ordinance for Industrial Safety and Health" (German: "Betriebssicherheitsverordnung"; short "BetrSichV") regulates the use of work equipment by employees at work and the operation of equipment requiring monitoring in terms of occupational health and safety. Third, and focusing on land use, the "Federal Land Utilisation Ordinance" (German: "Baunutzungsverordnung"; short: "BauNVO") regulates the type and extent of the structural use of a plot of land, the construction method and what can be built on it.

Stationary Hydrogen Storage

Depending on the amount of stored hydrogen, the legal specifications with regard to the environment (BImSchV) define three classes for storing hydrogen, each with different requirements. Below 3 tons of stored hydrogen, no approval is needed for storage construction and operation. Between 3 and 30 tons, the BImSchV defines a simplified permit procedure with a lead time of about 6 months. Storing more than 30 tons of hydrogen requires the strictest permit procedure including public participation and at least 12 months lead time.

The approval hurdles concerning employee health (BetrSichV) are in line with other common industrial applications, while land use regulations (BauNVO) only allow hydrogen storage facilities to be built on industrial and commercial areas, not in residential areas.

Hydrogen Production

Currently, the legal environmental specifications (BImSchV) for hydrogen production define any size as "industrial scale" without a lower limit, which implies the strictest permit procedure including public participation and a long lead time for all hydrogen production facilities. However, the BImSchV defines exemptions for conventional fuels (gasoline, diesel) and methanol, which facilitates their permit procedure. As hydrogen potentially serves as a fuel the future, Pokojski et al. (2019) suggest creating a derogation analogous to other fuels. This thesis takes up this suggestion and assumes that the environmental regulations for hydrogen production are linked to a station's hydrogen storage. Hence, the subsequent analyses assume a 30 tons legal limit for HDV-HRS deployment.

The next section takes these legal limitations into account as well as the previously defined FC-HDV layout to construct a suitable, discrete HDV-HRS portfolio for the analyses in this thesis.

4.2.2 Heavy-duty vehicle hydrogen refueling station portfolio

Techno-economic details on the available station portfolio are crucial when modeling AFS networks. Currently, 700 bar HDV-HRS do not exist. Therefore, this section defines a HDV-HRS station portfolio for the modeling approach.

Globally, there are 343 active HRS (DoE H2 Tools, 2019)[35], operating at mainly two pressure levels: 700 bar and / or 350 bar. Of these stations, the majority operates at exclusively 700 bar (217 stations) or both 700 bar and 350 bar (37 stations). Only a few exclusively use 350 bar (32 stations) and there is no information available for the pressure levels at the remaining 57 stations. About 60 % of these active stations are located in three countries: Japan, Germany and USA. Most stations have a similar setup featuring the five main components shown within the dotted line in Figure 24. They also include a power supply, which is necessary to provide electricity for an electrolyzer to split water into oxygen and hydrogen. Details on the production of hydrogen are outlined in section 4.2.3. The hydrogen is then stored in a low pressure (LP) tank (below 250 bar) on-site at the HRS. To prepare for a vehicle refill, a compressor increases the pressure of the hydrogen by reducing its volume (to 800 to 1,000 bar) to store it in a smaller (high-pressure, HP) storage before it is filled into vehicles via dispensers.

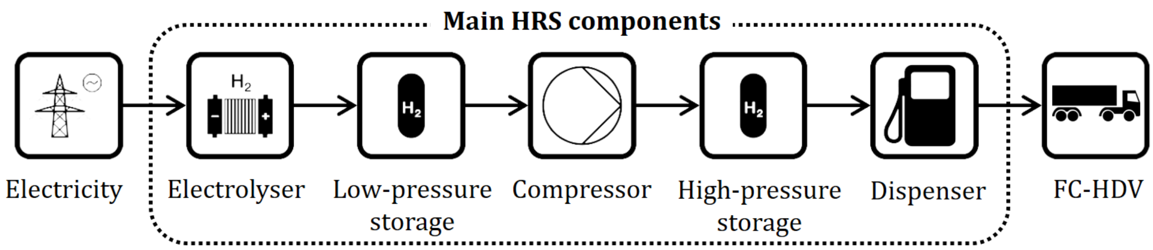

Figure 24: Schematic structure of a HRS and its main components (power supply, electrolyzer, LP-storage, compressor, HP-storage, dispenser and end-user) (Grüger, 2017)[36]

In Germany, HRS are mainly planned and located around metropolitan areas based on analyses that identified the highest purchasing power and population density here.

[35] Compared with the reviewed paper of Alazemi and Andrews (2015) in section 2.3.5, this indicates an installation of about 120 new HRS (ca. 11 % p.a.) globally between 2015 and 2019.
[36] A LP storage is required to store hydrogen in larger amounts at the station (LP storages are less costly than HP storages) and a HP storage is required to enable the vehicle refilling process.

This is why hydrogen mobility in passenger cars is promoted in urban areas with the greatest interest in the technology (Altmann et al., 2017). All currently active HRS in Germany are displayed in Figure 25, which are about 75 stations.

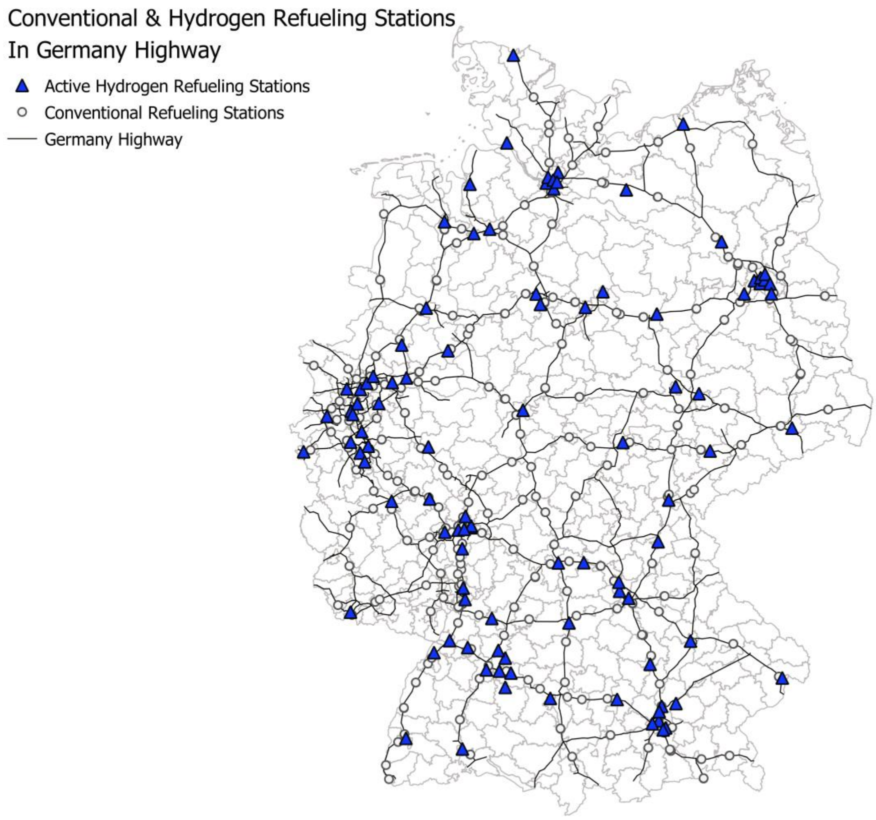

Figure 25: Active HRS (blue) and conventional highway fuel stations (white) in Germany (Gürsel and Tölke, 2017; H2-Mobility, 2019))

HRS deployed in Germany follow a discrete HRS portfolio approach. H2-Mobility, a joint venture of German automotive OEMs, gas and oil companies founded in 2015, aims at developing a nationwide hydrogen infrastructure to supply passenger cars equipped with fuel cell powertrains in Germany (H2-Mobility, 2019). In order to fulfill this task most efficiently, the joint venture defined a structured HRS station portfolio of discrete station sizes. They argue that discrete HRS sizes are economically more advantageous for the market ramp-up, since it is possible to adjust them flexibly in line with local demand (Altmann et al., 2017).[37] These station sizes range from XS to XL and are differentiated mainly by the number of cars served each day. Table 11 shows the maximum number of vehicles per day, the resulting hydrogen demand, the number of dispensers, the investment as well as the operating and maintenance costs per station size. All of the existing and planned stations have a daily hydrogen demand between 56 and 2,200 kg (DoE H2 Tools, 2019), which theoretically would be enough hydrogen to refuel between one (smallest station) and 44 FC-HDVs (largest station) per day.

[37] Altmann et al. (2017) state that conversion cost only play a subordinate role.

Table 11: Overview of passenger car HRS portfolio (XS, S, M, L and XL) based on (Altmann et al., 2017)

Parameter	Unit	XS	S	M	L	XL
Vehicles	[cars/d]	14	42	84	175	550
Hydrogen demand	[kg/d]	56	168	336	700	2,200
Dispenser	[#]	1	1	2	4	8
Investment	[million €]	0.5-0.9	0.8-1.1	1.1-1.9	1.9-3.3	5.1-8.8
O&M	[k€/a]	100-124	146-176	205-264	367-475	977-1264
Vehicles	[HDV/d]	1	3	7	14	44

However, the existing HRS are hardly suitable for FC-HDVs as neither a refueling standard nor a guideline exists for FC-HDV refueling at 700 bar. The existing global refueling standard SAE J2601 was developed for passenger car hydrogen refueling up to 10 kg per refuel at both 350 and 700 bar. Consequently, active public HRS are capable of dispensing a maximum of 10 kg hydrogen per refuel, before the HRS needs to refill its internal HP storage for the next refuel process. The existing HRS are therefore not suitable to refuel a FC-HDV with 50 kg at 700 bar (cf. section 4.1) within a limited timeframe (cf. section 3.3). In contrast, the guideline SAE J2601/2 is intended for buses and freight vehicles, but focuses exclusively on 350 bar, which does not comply with the vehicle space requirements for a FC-HDV on-board hydrogen storage running at 700 bar (cf. section 4.1). Therefore, U.S. American start-up Nikola Motors, which plans to build FC-HDVs and the related refueling infrastructure by 2021 in the U.S., is currently developing a guideline for FC-HDV to enable hydrogen refueling at 700 bar for HDVs on a global standard (Schneider, 2019).

As HDV-HRS do not exist at present, this thesis defines a station portfolio in line with the user requirements (cf. section 3.3) and the legal restrictions in Germany (cf. section 4.2.1). The collected user requirements towards refueling infrastructure mainly focus on the refueling time, stating 30 min or less. Accordingly, all stations are designed for an average hydrogen refueling rate of 40 g/s.[38] The German BImSchV defines the strictest permit procedure and long construction lead times for facilities with more than 30 tons hydrogen storage. Hence, 30 tons is considered the maximum (LP) storage capacity for the new HDV-HRS portfolio.[39] 30 tons hydrogen storage at a station translates into a capacity to refuel about 600 HDV daily with 50 kg each. The upper limit of the HDV-HRS portfolio should therefore be a station with a daily capacity of 600 HDVs, which is defined in this thesis as an “XXL” station. The number of HDVs per day for the remaining HRS sizes are allocated exponentially with an XS

[38] Refueling 50 kg hydrogen within 30 min equals 28 g/s. As current passenger cars HRS protocols are capable of a hydrogen refueling rate at 40 g/s (Schneider, 2013), this benchmark is also applied to the HDV-HRS (which translates into a total FC-HDV refueling time of 20 min).
[39] Nikola Motors also mentions 30 tons as the maximum limit for their HDV-HRS (Schneider, 2019).

station accounting for a similar number of vehicles as the passenger car XS station, but with a much higher daily hydrogen demand. Subsequently, the new HDV-HRS station portfolio is specified in more detail using the Heavy-Duty Refueling Station Analysis Model (HDRSAM) by Elgowainy and Reddi (2017). Table 12 shows an overview of the new HDV-HRS portfolio. For example, a size "M" HDV-HRS station could serve about 75 vehicles per day, would have two dispensers, a LP storage hydrogen capacity of 3,750 tons, a compressor rate of up to 455 kg hydrogen per hour, a HP storage capacity of 455 kg hydrogen, a footprint of 1,190 m^2; and a total investment of about 7.2 million or 358,000 euros per year. These HDV-HRS would also be suitable for fuel cell passenger car refueling.

Table 12: Techno-economic parameters for the HDV-HRS portfolio (XS to XXL) in 2050 (own assumptions based on HDRSAM model by Elgowainy and Reddi (2017))

Parameter	Unit	XS	S	M	L	XL	XXL
Vehicles	[HDV/d]	19	31	75	150	300	600
Hydrogen demand	[kg_H2]	938	1,875	3,750	7,500	15,000	30,000
Dispenser	[#]	1	2	2	4	8	16
LP-Storage size	[kg_H2]	938	1,875	3,750	7,500	15,000	30,000
HP-Storage size[40]	[kg_H2]	114	228	455	900	1,821	3,642
Compressor rate	[kg_H2/h]	114	228	455	900	1,821	3,642
Footprint	[m^2]	290	565	1,190	2,725	6,330	13,470
Dispenser	[k€]	107	214	214	428	856	1,712
LP-Storage size	[k€]	189	377	755	1,509	3,019	6,037
HP-Storage size	[k€]	130	260	521	1,042	2,083	4,166
Compressor	[k€]	1,578	2,761	5,522	10,649	20,692	40,989
Cooling unit	[k€]	14	14	28	560	1,120	2,240
Safety features	[k€]	115	115	115	115	115	120
Total investment	[k€]	2,133	3,742	7,154	14,303	27,885	55,265
Lifetime	[a]	20	20	20	20	20	20
Annuitized investment	[k€/a]	201	353	675	1,350	2,632	5,216

Before using this new HDV-HRS portfolio in the thesis method outlined in section 3, the average waiting time of a HDV at the new stations will be checked. Long waiting times of more than 15 minutes[41] decrease the likelihood of the technology being

[40] The HP storage size is determined by the peak hour hydrogen demand on an average day. Data of the German Federal Highway Research Institute (2019) shows that peak demand is about three times the average daily demand (equaling ca. 60 HDVs/h or 3,000 kg hydrogen).
[41] Section 3.3 revealed a maximum detour of 20 kilometers, which translates into 15 min assuming the official highway speed of 80km/h in Germany.

adopted by potential users. Waiting times and queue lengths at the stations can be predicted using queueing models. To check the station portfolio regarding acceptable waiting times, the M/M/c queueing model[42] is applied following Bhat (2015). The term "M/M/c" denotes the distribution of the inter-arrival time of HDVs ("M" stands for Markov and is commonly used for an exponential distribution), the service time at the station ("M" also stands for an exponential distribution) and the number of dispensers ("c" stands for the number of identical servers in parallel at a single-channel queue) (Bhat, 2015).

Table 13 shows an overview of the input and output parameters. The input parameters are based on the station layout (e.g. number of dispensers) and the daily peak arrival rate of HDVs based on the data from BASt (2017) (e.g. number of HDVs arriving per hour). The analysis results indicate average waiting times of less than 20 minutes for all station sizes. These times are comparable to conventional fuel stations and in line with current user requirements.[43]

Table 13: Input and output of M/M/c queueing model applied to HDV-HRS portfolio

				HRS Portfolio					
		Parameter	Unit	XS	S	M	L	XL	XXL
Input	c	Dispenser	[#]	1.0	2.0	2.0	4.0	8.0	16.0
	λ	HDVs per hour	[#]	1.0	2.1	4.1	8.3	16.5	32.9
	μ	Refuels per hour	[#]	2.8	2.8	2.8	2.8	2.8	2.8
	L_s	Average HDVs in system	[#]	0.58	0.85	3.21	4.31	6.82	12.30
Output	L_q	Average HDVs in queue	[#]	0.12	1.74	1.36	0.93	0.51	0.12
	W	Average time spent	[h]	0.57	0.41	0.78	0.52	0.41	0.37
	W_q	Average waiting time	[h]	0.21	0.06	0.32	0.17	0.06	0.02
	W_q	Average waiting time	[min]	12.47	3.35	19.28	9.91	3.38	0.92
	p	Dispenser utilization[44]	[%]	41	37	81	76	74	73

[42] Generally, an M/M/C queue is shorthand notation for Markovian arrival rate, Markovian Service Rate, and C the number of resources (Bhat, 2015).

[43] For other technologies with slower energy refueling rate (e.g. battery-electric HDVs), a queuing analysis may result in longer waiting times and may be therefore not only a verification but an integral part of the infrastructure modeling.

[44] The M/M/c analysis focuses exclusively on the station utilization at the dispensers to evaluate the sufficient availability of dispensers to reduce waiting times at peak hours. In contrast, the subsequent analysis with the NC-FRLM focuses on the station utilization based on the daily storage capacity in order to match traffic energy demand and station sizing and location.

4.2.3 Hydrogen production

While the previous sections focused on defining the techno-economic parameters for both a FC-HDV and a discrete HDV-HRS station portfolio, this section defines the hydrogen production parameters required for the analyses, such as production technologies, capacities, efficiencies and investment.

Currently, about 160 hydrogen production plants exist in Europe, 30 of them in Germany, producing about 1,000 tons of hydrogen as a daily average – mainly for the chemical industry (DoE H2 Tools, 2019).[45]

Hydrogen can be produced in different ways. Most of the previously mentioned global hydrogen production is realized using fossil energy carriers, e.g. steam methane reforming (SMR), resulting in so-called "grey" hydrogen. However, in order to reduce carbon emissions, future hydrogen applications should be based on renewable energies instead. A promising way to produce carbon-neutral hydrogen – also known as "green" hydrogen – is using (renewable) electricity to split water through electrolysis. Further, such electrolyzers not only have the potential to produce hydrogen with zero GHG emissions, but also to increase the integration of fluctuating renewable energies by acting as flexible loads addressing the last research question of this thesis.[46]

The existing electrolyzer technologies can be classified into three types: alkaline, polymer electrolyte (PEM) and high-temperature electrolysis (cf. Töpler and Lehmann (2017) and Xing et al. (2018)). Alkaline electrolysis is the most widely used, well-tried and tested technology and has been applied globally for almost 50 years. Its technological characteristics allow large-scale applications with high space requirements (alkaline low current densities lead to a high space requirement) and continuous electricity supply as in the case of hydropower.[47] However, slow dynamic response and hence low flexibility have a negative effect on integrating fluctuating renewable energies. Compared to alkaline electrolysis, PEM electrolysis enables a larger dynamic response, which is particularly advantageous for coupling with fluctuating renewable energies. In addition, PEM are more compact than alkaline and potentially more advantageous for on-site applications at HRS with limited space requirements compared with large industrial applications such as dams. Research and development has focused on PEMs over the last 25 years and they represent the majority of most recently announced large electrolysis projects (cf. Figure 26). Of all electrolysis technologies, high-temperature electrolysis has the lowest Technology Readiness Level (TRL), but promises the highest efficiency rates if sufficient thermal heat is available. This technology is well suited to operate at industrial sites with a

[45] As of 20 November 2015.

[46] *"What are the effects of a HDV-HRS network on the electricity system and what is the value of flexibility in hydrogen production?"*

[47] The list of countries that already produce hydrogen from hydropower is fairly long: Canada, Chile, Egypt, Iceland, India, Norway, Peru and Zimbabwe (Holbrook and Leighty, 2009).

large amount of waste heat. The PEM electrolyzer seems to be the most suitable for HDV-HRS applications due to its fast dynamic response, low space requirements and no need for (industrial) waste heat.

Currently, multiple small to large-scale PEM projects have been announced, as shown in Figure 26. For example, the North American company “Hydrogenics” recently started offering a new standard PEM electrolyzer with 500 kW power and an average daily hydrogen production of about 200 kg. Further, “Nikola Motors” plans to open their first (small) HDV-HRS in the United States with a daily hydrogen production of one ton at a capacity of 2.2 MW. Later, it is planned that a larger HDV-HRS will produce about 30 tons daily corresponding to 66 MW. In Germany, large PEM projects include “Refhyine” (10 MW, 3.5 tons hydrogen daily) to support a refinery site with renewable hydrogen and the “Hybridge” project (100 MW, 34 tons hydrogen daily), initiated by a grid operator to support the energy transition using hydrogen to store renewable energy.

Even though the optimal electrolyzer dimensions will be determined within the electricity system analysis in section 5, assuming a linear trend line between these projects already indicates the potential electrolyzer dimensions for the HDV-HRS portfolio. Based on the daily demand per station, as defined in section 4.2.2, the electrolyzers would range from 2.5 MW for a XS station, over 5.0 MW (S), 11 MW (M), 22 MW (L), 45 MW (size XL), to 90 MW for an XXL station (cf. Figure 26).[48]

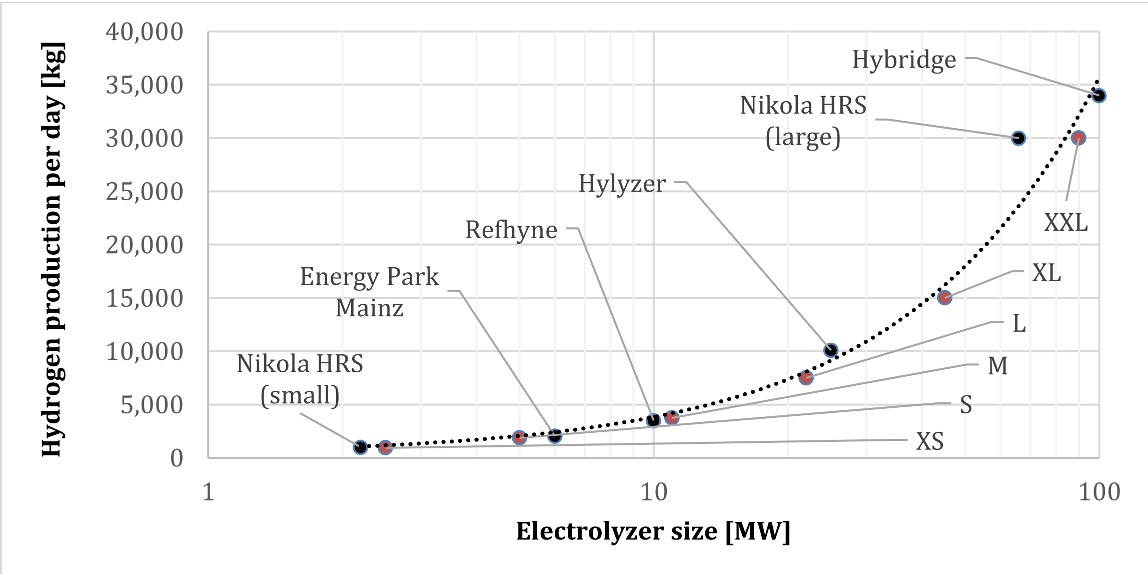

Figure 26: Examples of PEM electrolysis projects announced by capacity (in MW) and daily hydrogen production (in kilogram hydrogen per day) and the potential electrolyzer sizes for HDV-HRS portfolio.[49]

[48] The ratio of electrolysis-capacity (input) and hydrogen (output) indicates an average utilization of 90% following the assumptions in Table 14.
[49] Details on the projects can be found in the Appendix in Table 36.

To determine both the total network cost as well as the optimal electrolyzer dimensions when integrating the HDV-HRS infrastructure network with the electricity system using the PyPSA tool (cf. section 3.4), techno-economic input parameters are required, such as efficiencies, investment, operating and maintenance cost, production rate, lifetime, grid connection and transformer investment. The techno-economic parameters for electrolyzers in this thesis are summarized in Table 14.

Table 14: Techno-economic parameters for electrolyzers in 2050

Parameter	Unit	Value	Source
Electrolyzer efficiency	[%]	68	Smolinka et al. (2018)
Electrolyzer investment	[€/kW]	510	Glenk and Reichelstein (2019)
Electrolyzer operating & maintenance cost	[%/a]	4	Michaelis (2017)
Electrolyzer production rate	[Nm^3/h/MW]	200	Smolinka et al. (2018)
Electrolyzer lifetime	[a]	20	Smolinka et al. (2018)
Connection investment	[EUR/MW/m]	11	Gamborg et al. (2017)
Transformer investment	[EUR/MW]	27,000	Gamborg et al. (2017)

4.2.4 Hydrogen distribution

Having defined a HDV-HRS portfolio as well as a suitable hydrogen production technology, the final category required is the hydrogen supply from the production site to the station. Hence, this section focuses on the hydrogen distribution considered in this thesis.

At the HDV-HRS, hydrogen can be provided on-site at the station (using a local electrolyzer) or delivered from a central electrolyzer at a place with low electricity costs. On-site hydrogen production needs almost no additional distribution effort.[50] On the other hand, hydrogen delivery to the station involves additional expenditures to cover the costs of either using trucks or a dedicated pipeline network (Emonts et al., 2019).

There are three options for truck delivery of hydrogen: gaseous hydrogen (GH), liquefied hydrogen (LH) or liquid hydrogen using liquid organic hydrogen carriers (LOHC). Truck trailers transporting gaseous hydrogen have payload capacities of up to 640 kg hydrogen (cf. Elgowainy et al. (2014)), which equals about 13 FC-HDV refueling processes. Based on the HDV-HRS portfolio in section 4.2.2, the smallest station ("XS") would require 1.5 truck deliveries per day on average and the largest "XXL" station would need almost 50 daily deliveries. These routines seem unpractical for real-world infrastructures and are accordingly ruled out by leading hydrogen

[50] 104 of today's 343 active HRS have on-site hydrogen production. At 239 HRS, the source of hydrogen is "unknown" (cf. DoE H2 Tools (2019)).

delivery companies (Edwards, 2018) and in this thesis as well. Liquid hydrogen delivery has the advantage of being able to store more than five times as much hydrogen per trailer (up to 3.5 tons per trailer, cf. Air Liquide Hydrogen Energy (2019)) and would avoid the challenge of multiple deliveries per day even for small stations. Unfortunately, "liquefying hydrogen requires far more energy than compressing into a tube trailer" (Bauer et al., 2019)[51] and additionally suffers from boil-off effects of about 1.5 % per day (Töpler and Lehmann, 2017). These factors have a substantial negative effect on energy efficiency so that liquid hydrogen trailer deliveries are also excluded in this thesis. The third hydrogen delivery option is to use LOHC. LOHC carries hydrogen within a liquid molecule structure (i.e. hydrogen is bound to the LOHC) during transport and is unloaded after distribution. Hydrogen carried with LOHC acts like conventional fuels under standard conditions, e.g. no additional pressure tanks or cooling are necessary in contrast to gaseous or liquid hydrogen, respectively. However, similar to liquefying hydrogen, loading LOHC with hydrogen requires large amounts of energy, i.e. of 100 % input energy, about 70 % remains within the stored hydrogen and 30 % is used to load the LOHC with hydrogen (Jörissen, 2019).[52] In addition, the LOHC represents about 90 % of the total weight (and hydrogen only 10 %), which makes it "especially advantageous for long-term storage [or] long distance transport applications" (Niermann et al., 2019b), such as maritime, neither of which is the case for HDV-HRS. To sum up, none of the truck delivery options seems suitable for a HDV-HRS network in Germany and all are excluded from further analysis.

Hydrogen pipelines are well established throughout the world with about 4,500 km of installed assets, of which 390 km are in Germany. Hydrogen pipelines are currently most commonly used in the chemical industry (DoE H2 Tools, 2019). Accordingly, pipelines seem a good option for transporting large amounts of hydrogen overland without large energy losses, especially to supply a larger HRS network, e.g. on a national scale (Seydel, 2008; Robinius, 2015). Moreover, German highways are inalienable federal property, therefore, theoretically, there is the chance of a shorter installation time for pipelines here (Wulfhorst, 2017).[53] In contrast, a pipeline network alongside existing natural gas pipelines may imply property right challenges and usually does not run near German highways (cf. Seydel (2008) and Krieg (2014)). Thus, besides on-site hydrogen production, a hydrogen pipeline network seems another feasible option to distribute hydrogen from a central electrolyzer to a national HDV-HRS network. The advantages and disadvantages of each delivery technology are summarized in Table 15.

[51] Converting hydrogen into a liquid accounts for an energy loss of about 30% to 40% (based on the lower heating value of hydrogen) (cf. Chisholm and Cronin (2016); Niermann et al. (2019a)).
[52] Furthermore, once hydrogen is unloaded from the LOHC (e.g. at the HRS), the LOHC needs to be transported back to the loading location (e.g. the electrolyzer).
[53] Compared with most other German street types that are state or private property, which would have to be bought or expropriated in order to install pipelines.

Table 15: Advantages and disadvantages of hydrogen delivery technologies and their suitability for HDV applications

Delivery option	Advantage	Disadvantage	HDV suitability
On-site production	• very low delivery cost • established technology • reduce grid extension • local flexible load potential	• local RE may be more expensive than RE from other regions	High
GH trailer	• established technology	• only small volume of hydrogen per trailer	Low[54]
LH trailer	• more hydrogen per trailer than GH	• high energy losses for liquefaction	Low
LOHC trailer	• more hydrogen per trailer than GH	• high energy losses for loading LOHC	Low
Pipeline	• low energy losses • established technology	• high investment makes it unattractive for low hydrogen demand • lengthy construction time	High

To determine whether a pipeline network is competitive with on-site production, techno-economic parameters are defined for the hydrogen pipeline. First, the pipeline diameter depends on the specific hydrogen mass flow rate and vice versa:

$$D = \sqrt{\frac{4*\dot{m}}{v*\rho*\pi}} \tag{15}$$

with

D	diameter	[m]
$\dot{m}$	(hydrogen) flow rate	[kg_h2/s]
v	speed	[m/s]
ρ	density (at standard conditions)	[kg/m^3]

Equation (13) determines the required pipeline diameter based on the given mass flow between a specific HDV-HRS location (i.e. its daily hydrogen consumption) and the central electrolyzer. In the case of parallel pipelines, e.g. due to two HRS relatively close to each other, the diameters of each station are added to result in a single pipeline. Krieg (2014) defines 100 mm as the minimum and 600 mm as the maximum diameter for hydrogen pipelines. In this thesis – similar to the discrete HRS sizes – discrete pipelines diameters are applied in steps of 100 mm (i.e. 100 mm, 200 mm, 300 mm, 400 mm, 500 mm and 600 mm). Based on the required hydrogen diameter, the specific pipeline investment per diameter dependent on hydrogen mass flow rates

[54] GH trailer delivery may be interesting for the initial market diffusion of FC-HDV and infrastructure.

is determined as shown in Table 16, ranging from 360 to 1,570 €/m (Krieg, 2014). The lifetime of a hydrogen pipeline network is assumed at 40 years (Krieg, 2014).

Table 16: Pipeline diameter and resulting hydrogen flow rate (in tons per day) as well as investment (in € per meter) based on (Krieg, 2014)

Diameter [mm]	Hydrogen flow [t/d]	Investment [€/m]
600	2,185	1,570
500	1,517	1,210
400	971	960
300	546	720
200	243	490
100	61	360

For on-site hydrogen production, in addition to the HDV-HRS and the electrolyzer asset investment, no additional distribution investments are taken into account.

4.3 Electricity system parameters

In addition to defining the techno-economic parameters for both the FC-HDV and the hydrogen infrastructure, the electricity system parameters should also be specified.

As outlined in section 3.4, the open-source tool PyPSA determines the long-term cost-optimal electricity system, considering operating (OPEX) and capital expenditures (CAPEX).[55] This section aims at defining the techno-economic parameters for the cost-minimal scenario for 2050 covering both the electricity system and the total HRS network. Thus, asset parameters are defined that address CAPEX as well as time series parameters that address OPEX.

As the outlook to 2050 exceeds the lifetime of most existing components, a greenfield planning approach is applied, which is based on present electricity demand.[56] This approach largely ignores the current electricity system layout and disregards the pathway from present power capacity installations (assets) to the optimal system layout. An exception to this is the AC power transmission infrastructure, for which current electrical characteristics are employed. Further, the only fossil-fueled generators considered are open-cycle (OCGT) and combined-cycle gas turbines (CCGT). At the same time, it is assumed that nuclear, lignite and hard coal power plants are phased out under regulatory law by 2050. The renewable generators considered

[55] In this thesis, capital expenditures are defined as annuitized investments.

[56] The present electricity demand in Germany is about 509 TWh_{el}, of which 229 TWh_{el} occur by industry, 152 TWh_{el} by trade, commerce and services, 118 TWh_{el} by households and 10 TWh by transportation (Muehlenpfordt, 2019).

include solar photovoltaic, run-of-river power plants, and onshore as well as offshore wind farms connected to the mainland by either high-voltage alternating (HV-AC) or direct (HV-DC) current lines. In terms of energy storage, hydrogen storage with electrolysis and reconversion in fuel cells and generic batteries are permitted at every node without capacity restrictions. The pumped-hydro power plants currently in operation are also considered.

Transmission lines can be reinforced up to double their current capacity. HVDC link route options are taken from the Ten-Year Network Development Plan (TYNDP) provided by ENTSO-E (ENTSO-E, 2019) and, independently of currently planned capacities, are allowed to expand up to 10 GW of net transfer capacity. Table 17 outlines the techno-economical parameters used for electricity system assets.

Table 17: Asset investment assumptions of the electricity system model including fixed and variable operating and maintenance cost (FOM and VOM, respectively)

Asset	FOM [%/a]	VOM [€/MWh$_{el}$]	Efficiency [%]	Fuel [€/MWh$_{th}$]	Lifetime [a]	Investment	Unit
HVAC overhead	2				40	400	[€/MW/km]
HVDC inverter	2				40	150,000	[€/MW]
HVDC overhead	2				40	400	[€/MW/km]
HVDC submarine	2				40	2,000	[€/MW/km]
CCGT	2.5	4	50	21.6	30	800	[€/kW$_{el}$]
OCGT	3.75	3	39	21.6	30	400	[€/kW$_{el}$]
Run of river	2		90		80	3,000	[€/kW$_{el}$]
Solar PV	4.17	0.01			25	600	[€/kW$_{el}$]
Biomass	4.53		46.8	7	30	2,209	[€/kW$_{el}$]
Onshore wind	2.45	2.3			30	1,110	[€/kW$_{el}$]
Offshore wind	2.30	2.7			30	1,640	[€/kW$_{el}$]
Pumped hydro storage	1		75		80	2,000	[€/kW$_{el}$]
Battery inverter	3		81		20	323	[€/kW$_{el}$]
Battery storage					15	154	[€/kWh]
Electrolysis	4		68		20	510	[€/kW$_{el}$]
Fuel cell	3		58		20	339	[€/kW$_{el}$]
Hydrogen storage					20	19	[€/kW$_{el}$]

Spatially and temporally resolved time series for electrical demand as well as variable renewable generation are already included in PyPSA (cf. section 3.4). However, the demand time series of hydrogen at individual stations need to be defined to determine minimal system cost. In this thesis, the hydrogen demand series by HDV are determined by the product of their local annual demand and a normalized time series representing the share of annual demand consumed in each snapshot (see Figure 27). The latter is obtained by projecting the hourly driving patterns of heavy-duty trucks in Germany in a typical week to a full year taking seasonal variations into account (German Federal Highway Research Institute, 2019). Note that, due to the lack of more appropriate data, this method assumes perfect correlation between refueling patterns and driving patterns and neglects regional variations; i.e. the normalized demand time series is the same for every location.

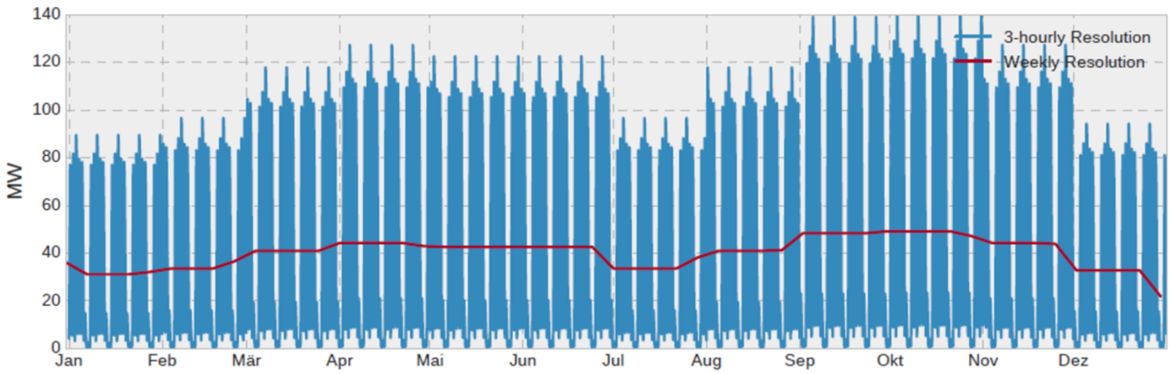

Figure 27: HDV demand time series for hydrogen at HRS stations [in MW] over a yearly period (based on German Federal Highway Research Institute (2019))

4.4 Summary of techno-economic parameters

The aim of this chapter was to define the three techno-economic framework parameters required in order to apply the model developed in chapter 3 to the research questions. Thus, parameters were defined on three dimensions: FC-HDV, hydrogen infrastructure (covering hydrogen regulations, HDV-HRS, hydrogen production and hydrogen distribution) and the electricity system.

A FC-HDV is defined as having sufficient space for about 50 kg on-board hydrogen storage, matching range user requirements at 700 bar technology. Further, Germany has strong legal regulations on storing and producing hydrogen and accordingly, HDV-HRS are limited to 30 tons (LP) storage in this thesis to make use of the simplified approval procedure when installing a station.[57] In addition, the defined HDV-HRS portfolio uses the established passenger car categorization (XS to XXL), but with larger component sizing to match vehicle requirements (per-refill capacity) and traffic requirements (daily hydrogen capacities). Further, potential electrolyzer capacities

[57] In chapter 5, implications of potential legal adjustments towards higher storage limitations are also analyzed.

from 2.5 MW for XS to 80 MW for XXL seem feasible for the HDV-HRS portfolio. The techno-economic parameters for PEM are defined to determine the optimal PEM sizes of the HRS network within the electricity system analysis in order to integrate as much fluctuating renewable energy as possible. To distribute hydrogen, either on-site production or supply via dedicated hydrogen pipelines seem the most promising options and will therefore be considered in the further analysis. Finally, asset parameters for the electricity system analysis have been defined as well as the FC-HDV demand time series.

5. Analysis of heavy-duty vehicle hydrogen refueling station network

This chapter presents the analyses performed with the newly developed NC-FRLM model to answer the main research question "*What is the spatial, technological and economic design of an optimal HDV-HRS network for zero-emission FC-HDVs that meets user requirements and the climate targets for Germany in 2050?*" from a spatial and technical design as well as an economic perspective. Hence, section 5.1 defines the analyzed scenarios, whose outcomes are outlined and compared regarding network design (section 5.2) and economics (section 5.3). Section 5.4 summarizes the results of the analysis.

5.1 Scenario definition

This subsection defines scenarios for the future development of a HDV-HRS network for Germany in 2050. Generally, scenarios make it possible to evaluate outcomes based on different developments, but do not give prognoses or probabilities for their realization. At the same time, defining consistent scenarios shows the range of potential results (Gnann, 2015).

The design, economics and electricity system impact of a HDV-HRS network are strongly influenced by four dimensions: the station capacity limit (cf. section 3.1), the volume of traffic served (cf. section 3.2), the FC-HDV range (cf. section 3.3 and section 4.1) and the type of hydrogen distribution (cf. section 4.2).[58] A reference scenario is described based on the defined techno-economic parameters and data. Four additional scenarios analyze variations in the mentioned dimensions to gain a more comprehensive understanding of a potential HDV-HRS network in Germany in 2050. Table 18 shows an overview of the scenarios analyzed in this thesis and their differences, which are explained in the following sub-sections.

Table 18: Overview of the five scenarios

Scenarios	Reference	S-1	S-2	S-3	S-4
Station capacity limit[59]	30 t	No limit to 7.5 t limit	30 t	30 t	30 t
Traffic demand	Total	Total	Domestic vs. total	Total	Total
Vehicle range	800 km	800 km	800 km	400 km to 1,000 km	800 km
Hydrogen distribution	On-site	On-site	On-site	On-site	Pipeline

[58] The latter dimension will not influence the spatial design of the HDV-HRS network, but the hydrogen production and distribution for the network and thus its cost.
[59] The station capacity limit defines the permitted low pressure hydrogen storage size at the station, which is equal to the permitted daily hydrogen demand.

5.1.1 Reference scenario

The reference scenario is characterized by default assumptions of the techno-economic parameters and data for a potential HDV-HRS network in Germany in 2050.

For this scenario, a default is set for each of the four dimensions: station capacity limit, traffic demand, vehicle range and hydrogen distribution. With regards to the station capacity limit, the reference scenario considers the legal (hydrogen storage) capacity limit of 30 tons per station presented in section 4.2.1 when modeling the optimal HDV-HRS network. Further, the reference scenario takes the total HDV traffic on German highways into account, i.e. assuming a 100 % market diffusion of FC-HDVs on German highways. Thus, this scenario considers all GHG emissions by HDVs on German highways for decarbonization through FC-HDVs. The vehicle range considered in the reference scenario is based on the user requirements identified in section 3.3 and is therefore in line with the corresponding FC-HDV layout in section 4.1, resulting in 800 km. Finally, hydrogen is produced via on-site electrolysis in the reference scenario and thus no hydrogen distribution is required. The size of on-site electrolyzers at the stations corresponds to section 4.2.3 and is in line with recently announced projects.

This reference scenario serves as a basis for comparison with the following scenario variants.

5.1.2 Scenario 1: Station capacity limit variation

The first scenario variation analyzes the effect of various HRS capacity limits on the network design and cost as the limitation of capacities is a core part of the new NC-FRLM approach developed in section 3.1. Both higher and lower hydrogen LP-storage limits per station will be compared in this scenario. At first, no station capacity limit is considered to understand the general impact of the node-capacity restriction on the network as this is a main part of the method outlined in section 3.1. Subsequently, other variants with capacity limits above and below the legal capacity limit of 30 tons per station will be examined. The capacity limit reduction will be in line with the HDV-HRS portfolio along the HRS sizes. Three separately adjusted limits will be analyzed: XL (15 t), L (7.5 t) and S (3.75 t).

5.1.3 Scenario 2: Traffic demand variation

The second scenario varies the volume of traffic to analyze the effect of varying traffic demand on the network design and cost. First, the impact of domestic-only HDV traffic versus total HDV traffic (cf. section 3.2) on German highways is analyzed to understand the difference in network design and cost between a network for domestic traffic compared to total traffic. Next, different market penetrations of FC-HDVs are compared: 40 %, 60 %, 80 % and 100 % market diffusion of FC-HDVs within total HDV traffic. These different penetrations will help to identify potential key thresholds of traffic demand regarding network design and cost. The traffic gradations are implemented by varying the traffic flow on the OD paths. This implicitly assumes an equal distribution of new FC-HDVs across the highway network. The assumption is made due to missing data on potential spatial hotspots for FC-HDV diffusion.[60]

5.1.4 Scenario 3: Vehicle range variation

This scenario analyzes different vehicle ranges and their impact on the HDV-HRS network design and cost. The user requirement analysis in section 3.3 unveiled a FC-HDV range requirement of 800 km and the techno-economic parameters for the FC-HDV design in this thesis were defined accordingly in section 4.1. This third scenario considers both alternatives: longer and shorter ranges. First, a longer vehicle range is analyzed with an additional 25 % of range (= 1,000 km). A longer range may be achievable through technology advantages, e.g. better efficiencies of the HDV powertrain (less hydrogen per kilometer, same amount of hydrogen on board the vehicle), hydrogen storage advantages (more hydrogen on board in the same tanks, same powertrain efficiency) or another vehicle layout (more hydrogen on board in additional tanks, same powertrain efficiency). Second, shorter vehicle ranges, which may result from external factors (such as congestion or extreme temperatures), will be analyzed, reducing the initial range by 25 % (= 600 km range) and 50 % (= 400 km range), respectively.

5.1.5 Scenario 4: Hydrogen distribution variation

The fourth scenario compares local on-site hydrogen production and central hydrogen production including a pipeline to understand the implications of hydrogen distribution on the network. As mentioned in section 5.1, this does not affect the spatial HDV-HRS network design, but does influence the network economics. Hence, this scenario aims to identify the most economical way of supplying hydrogen to the HDV-HRS network.

Existing studies assume that central electrolyzers in Germany will produce hydrogen in the north close to the coastline (Robinius, 2015; Pfluger et al., 2017). Additionally, these studies assume more off-shore wind potentials from the North Sea than from the Baltic Sea and therefore greater dispersion in the west.[61] Accordingly, this scenario assumes four equally sized central electrolyzers with a capacity dispersion of 75 % on the west coast (three electrolyzers) and 25 % on the east coast (one electrolyzer).

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[60] The implications of this assumption will be discussed in chapter 7.

[61] Robinius (2015) assumes 13 hydrogen production locations with 75% capacities distributed at the North Sea and 25% at the Baltic sea in his long-term scenarios, while Pfluger et al. (2017) assume five locations with a 90% (west) / 10% (east) capacity split.

5.2 Design implications: Spatial distribution and station sizes

This section presents the model-based HDV-HRS network design for the reference scenario and the other four scenarios.[62] The author aims at understanding the station network and the effects of different assumptions on the network design. The economic implications are presented in the next section 5.3.

5.2.1 Reference scenario

Considering a switch of the total HDV traffic on German highways to FC-HDVs in the reference scenario would result in a fuel demand of about 3,600 tons of hydrogen per day (1.3 million tons per year). Considering the electrolyzer parameters mentioned in section 4.2.3, this hydrogen demand translates into an annual electricity demand of about 65 TWh_{el}.

Based on the assumptions in the reference scenario, the model-based analysis results in the HDV-HRS network shown in Figure 28 for Germany in 2050. In sum, 137 stations are required to serve all vehicles in all OD trips. Of these 137 stations, 96 stations reach the maximum capacity of 30 tons, and the average capacity of all stations is around 28 tons. The lowest station capacity is less than 3.5 tons; this is located in the east on highway A4 near Görlitz close to the Polish border. In terms of HRS portfolio sizes, 122 stations are XXL (30 t), eleven are XL (15 t), two are L (7.5 t) and two are M (3.75 t). Around 75 % of the stations are located in western and southern Germany, which is a result of the high traffic flow and number of OD trips starting and finishing here. The average hydrogen storage utilization per station is 96 % and the total electrolyzer capacity of the HDV-HRS network amounts to 12.6 GW. The exact location, size, utilization and electrolyzer capacity of each station can be found in the Appendix in Table 38.

When comparing this HDV-HRS network with the existing 360 conventional fuel stations on German highways, it appears smaller at about a third of the size of the existing fuel station network. Further, the existing conventional fuel stations are more concentrated in some areas, such as the metropolitan areas around Frankfurt and in Bavaria (Munich and Nuremberg), and cover more of the North and East of Germany than the HDV-HRS network does. However, the existing fuel station network serves additional types of vehicles that are not considered in the HDV-HRS modeling approach (e.g. passenger cars and light-duty vehicles).

[62] The author used Pyomo (Hart et al., 2017; Hart et al., 2011) for the optimization platform with Gurobi as the solver (Rothberg et al., 2019) and successfully reached global optimality. The model is run with 2.6 GHz Intel Core i5 with 2600 MHz DDR3 memory and took a minimum of 300 seconds to solve.

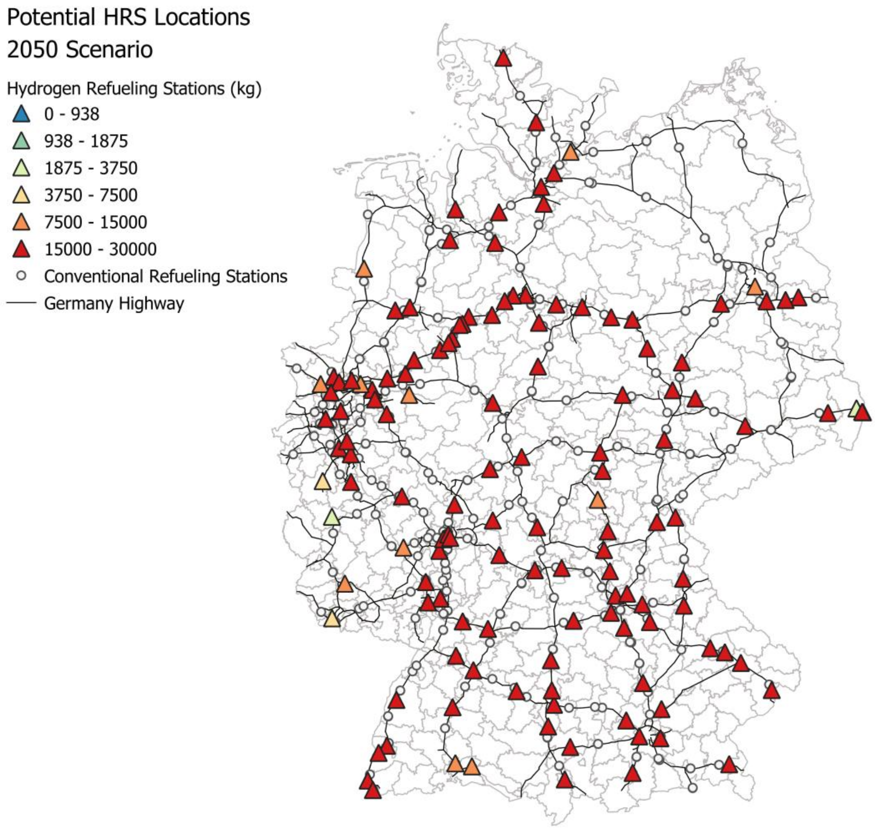


Figure 28: Potential HDV-HRS locations (triangles) in the reference scenario

In addition to the optimal HDV-HRS network in 2050, the author derived a potential network ramp-up from the present (2020) to 2050. Basis for the network ramp-up is the optimal network in the future (2050), i.e. the optimal locations for the stations are known in advance. Hence, the temporal HDV-HRS network installation is based on a perfect foresight approach and derives a potential ramp-up using backcasting from 2050 to the present. In contrast, a step-by-step network determination from the present to 2050 (myopic approach) would lead to higher costs (Heinrichs, 2013) and is therefore not considered. Perfect foresight results can be regarded as a lower limit for the costs and should be interpreted as such. Based on this perfect foresight approach, the temporal development of HDV-HRS from 2020 to 2050 is shown in Figure 29, which defines the chronological ramp-up curve of the various filling station sizes. The figure shows the clear dominance of smaller stations (XS, S and M) in the early ramp-up phase (between 2020 and 2030), followed by a period dominated by large stations. By around 2040, very large stations (XL and XXL) start to be built and eventually dominate the HDV-HRS network (cf. Figure 29). Further, the average storage utilization rate increases continually over time from 5 % in 2020 to 96 % in 2050, with similar patterns for the station size development, but with time delays.

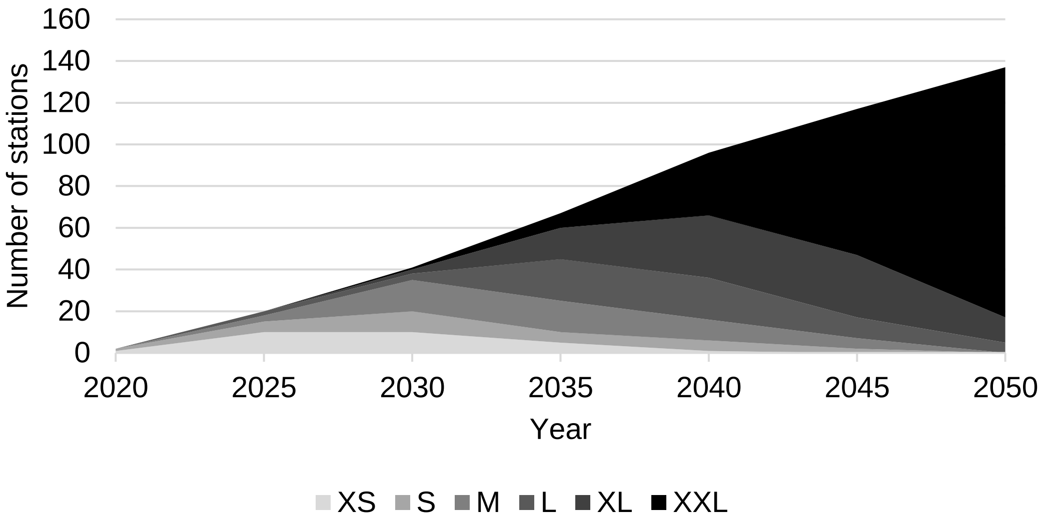


Figure 29: Ramp-up of HDV-HRS network in Germany from 2020 to 2050

5.2.2 Station capacity limit variation scenario

This first scenario analyzes the effects of varying the HRS capacity limit on the HDV-HRS network design. Compared to the reference scenario with 30 tons capacity restriction per node and thus per HRS, either removing the capacity limit or raising it to 60 tons reduces the number of stations in the HDV-HRS network by about 40 stations (from 137 to 100) as shown in Table 19. Of those 100 stations, 63 stations have a very large capacity of above 30 tons. The share of very large stations is thus smaller than in the scenario with a 30 tons capacity limit, where about 90 % of the stations have the largest possible station size. Further, the heterogeneity of stations increases when raising the capacity limit, with nearly all station sizes represented in the 100 station network. 100 stations in a network with no capacity limit and in a network with a 60t capacity limit indicate the lower bound of stations required in the network to serve the HDV traffic. This lower bound will be observed in the next scenario as well.

On the other hand, a lower capacity limit increases the number of stations in the network. Implementing a 15 tons limit (size "XL") results in a network of 276 HRS, and a 7.5 tons (size "L") limit results in 552 HRS. This seems plausible, since a lower capacity limit means the same hydrogen demand needs to be served by smaller stations and thus a larger number of them. A capacity limit of 3.75 tons (size "M") could not be solved, most likely due to not meeting the constraints (cf. section 3.1.3). Theoretically, following the pattern of the previous capacity limit variants, a 3.75 tons limit would require a network of about 1,100 HRS. Considering the 2,500 nodes on the German highway network (cf. section 3.2.1), this would translate into a station at almost every second node.

Table 19: The effect of varying capacity limits on HDV-HRS portfolio composition

Capacity limit	Number of HRS [individual HRS capacity in tons]							∑ HRS
	XS [0.94]	S [1.88]	M [3.75]	L [7.5]	XL [15]	XXL [30]	[none] [>30]	
without limit	-	1	1	3	12	20	63	100
60 t limit	-	1	1	3	12	20	63	100
30 t limit	-	-	2	2	11	122	-	137
15 t limit	-		-	-	276	-	-	276
7.5 t limit	-	--	-	552	-	-	-	552

Overall, the capacity limit has a negative correlation with the number of stations in the network. Moreover, the HRS portfolio within the HDV-HRS network becomes less heterogeneous with a lower capacity limit: While a 30 tons capacity limit makes use of five different HRS sizes (S to XXL), a 15 tons limit only considers two sizes (L and XL). Hence, the capacity limit appears to have a positive correlation with the heterogeneity of the HRS portfolio: a lower limit means less variety in station size. A potential explanation is the operation mode of the optimization solver (Gurobi), which focuses on building the largest stations first and builds the remaining stations afterwards.

Further, a lower capacity limit has a positive effect on the average station LP-storage utilization, i.e. a larger number of smaller stations seem to address the spatial hydrogen demand better than a network consisting of fewer larger stations (cf. Figure 30).

The effect of varying capacity limits on the regional distribution of the HDV-HRS network can be observed in Figure 31. In the case of a higher capacity limit (i.e. 60 t) and thus fewer stations, the network would be geographically more balanced compared to the 30 tons capacity limit in Figure 28. Most stations above 30 tons capacity can be found in western and southern Germany – similar to the key areas in the reference scenario and correlating with the HDV traffic intensity. In contrast, lowering the capacity limit reinforces the regional imbalance of stations. With a limit of 15 tons, the state of Bavaria already has about 25 % of all HRS in the network and local hubs with many stations can be found in Essen, Frankfurt and Nuremberg. On the one hand, this trend emphasizes the regional HDV traffic flow. On the other hand, it may also be caused by the large number of OD trips in that region.

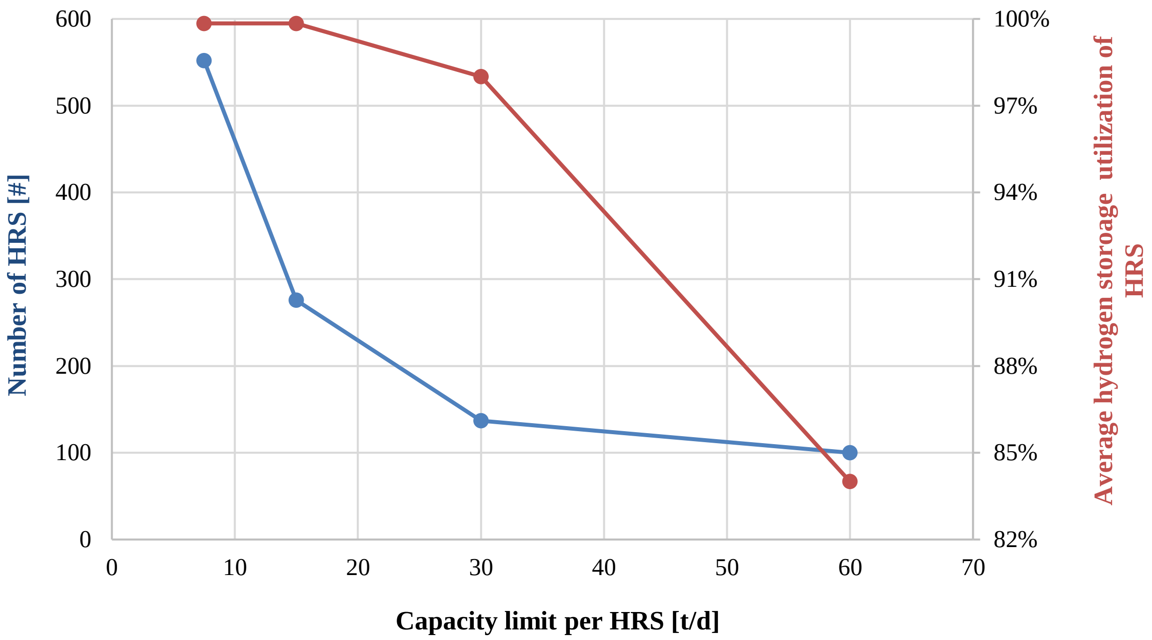
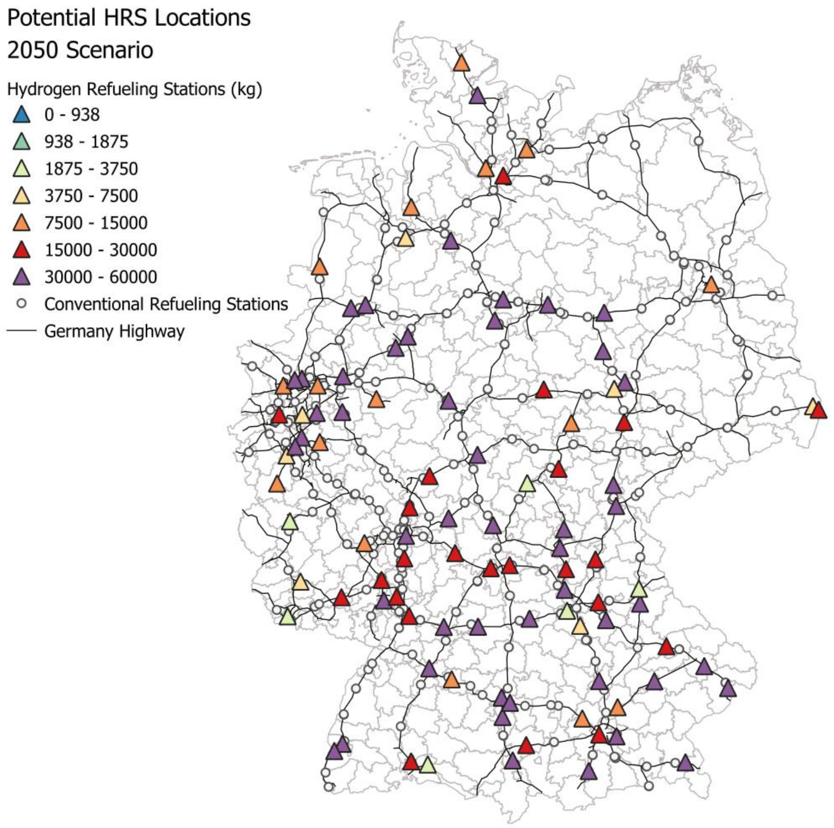


Figure 30: Optimal number of HDV-HRS depending on the capacity limit per station [blue line and left y-axis legend]; expected average LP-storage utilization of all HRS in the network [orange line and right y-axis legend][63]

To conclude, a 30 tons limitation on daily hydrogen demand at a station would lead to a potential HDV-HRS network that is only a third above the theoretical minimum number of stations needed to serve all FC-HDV traffic (137 HRS with 30 tons limit vs. 100 HRS without capacity limit). Additionally, this 30 tons HRS network is significantly smaller than the existing conventional fuel station network on German highways (137 HRS vs. 360 conventional fuel stations). However, considering that the fuel stored at conventional fuel stations lasts for a week or longer, a 30 tons hydrogen limit per HRS would translate into about three to four tons of hydrogen per day, assuming seven to ten days of constant demand.[64] Such a daily demand equals HRS size "M" (3.75 tons) of the portfolio defined in section 4.2.2 and – to serve the total HDV traffic – would require a network of about 1,100 HRS (cf. Table 19). Such a network would be three times larger than the existing conventional station network, but was not solvable using the NC-FRLM approach. This suggests that a network able to cover all the HDV traffic on German highways with stations that last for a week is likely to be infeasible given the current legal hydrogen storage limitations. In general, direct and indirect capacity limitation variations have a large impact on the HRS network design and could lead to both a smaller or larger HDV-HRS network compared with the existing conventional fuel station network on German highways.

[63] Note that this analysis focuses on the station utilization based on the daily LP-storage capacity and not on the utilization at the dispensers as mentioned in section 4.2.2.
[64] Such a fuel retention period poses an indirect capacity limit per station, as the daily demand multiplied by the retention period reflects the total station capacity.



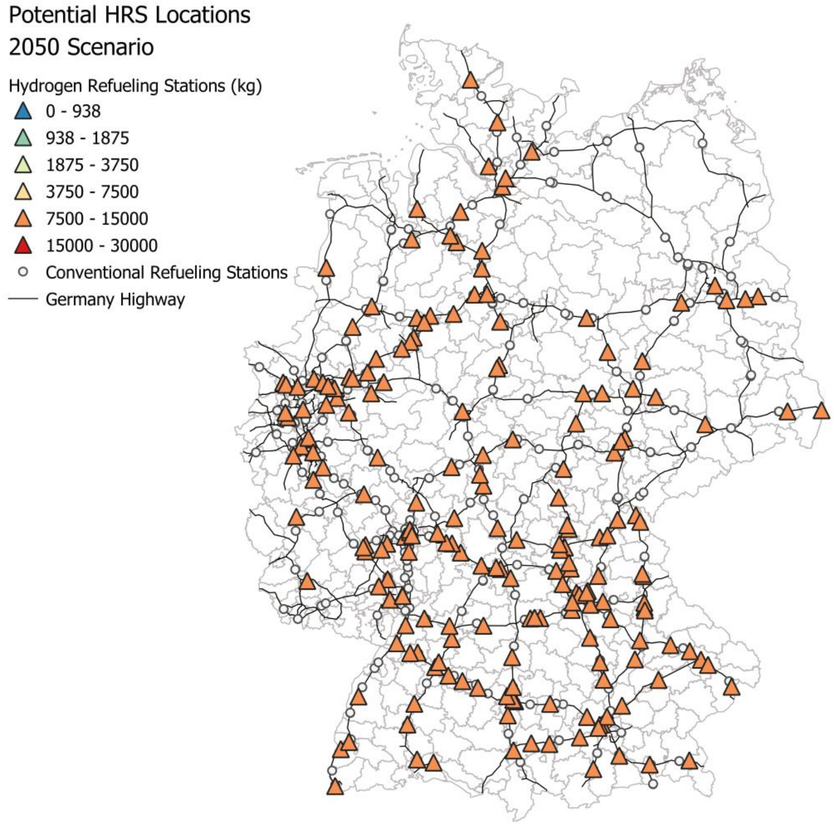


Figure 31: Regional distribution of 100 potential HRS locations (triangles) based on the capacitated FRLM with 60t limit (top); and 276 potential HRS locations (triangles) based on capacitated FRLM with 15 tons limit (bottom), both including the 360 existing conventional fuel stations (white points)

5.2.3 Traffic demand variation scenario

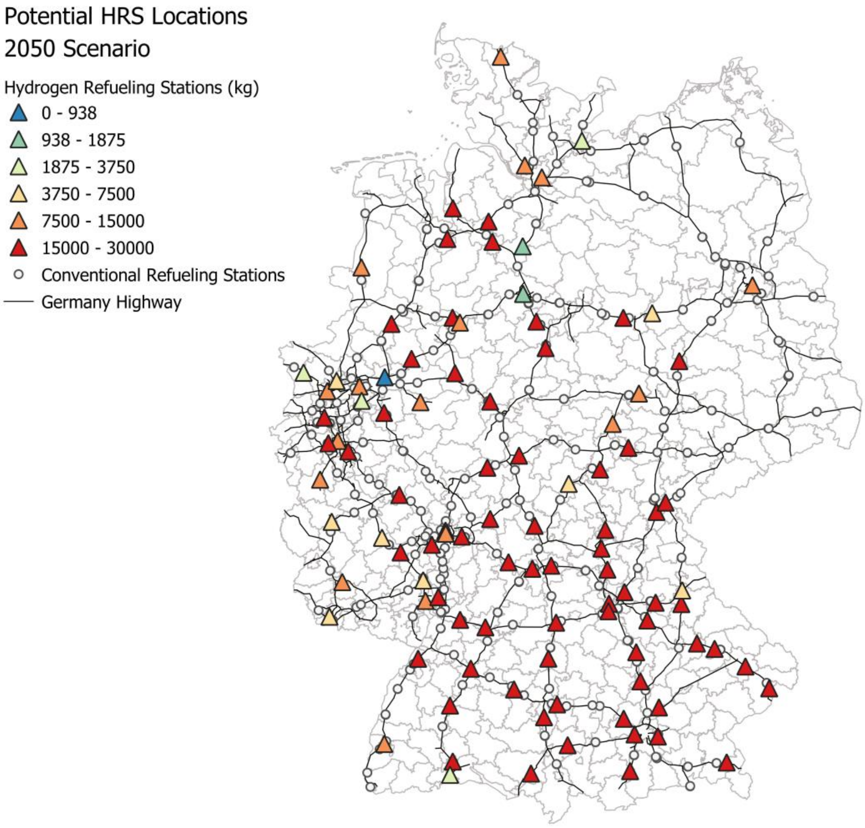
The second scenario analyzes the effect of varying traffic volumes on the network design in two ways. First, the total HDV traffic is compared to domestic HDV traffic[65] to understand the effects on the network design of excluding transit HDV traffic. Second, the total HDV traffic is gradually minimized from 100 % to 40 % to understand the effect of different market diffusion rates of FC-HDV on the HRS network.

The domestic HDV traffic represents about 60 % of the total HDV traffic on German highways, which was applied in the reference scenario. The domestic HDV traffic, which considers domestic OD paths only, translates into 42 million km per day and would require about 2,000 t of hydrogen per day.

The resulting HDV-HRS network that considers a full market diffusion of FC-HDV only in domestic HDV traffic consists of 100 stations: 68 XXL stations, 17 XL, eight L, four M and three S. This HRS network consisting of 100 stations implies that the minimum number of HRS to serve all traffic routes is reached. Hence, a network of fewer stations to serve all HDV routes is not possible, which is a similar outcome to section 5.2.2.

The spatial distribution shown in Figure 32 reveals fewer stations along large transit routes compared with the reference scenario, e.g. A2, A4 and A5. In sum, the stations have an annual total demand of 38 TWh_{el}, which is consistent with the 40 % traffic reduction compared to the total HDV traffic scenario (cf. 5.2.1). However, the storage utilization per station drops from 98 % (network for total HDV traffic) to 83 % (network for domestic HDV traffic).[66] A lower utilization rate indicates that – on average – stations and electrolyzers have oversized capacity. Indeed, the installed electrolyzer capacity for the domestic HDV traffic network is 7.8 GW and thus 0.4 GW larger than at a higher utilization rate.[67]

[65] Set of HDVs that start or end in Germany (cf. section 3.2).
[66] The detailed utilization rates per station size: XXL (89%), XL (72%), L (74%), M (67%), S (60%).
[67] At a similar utilization rate as the reference scenario (96%), an electrolyzer capacity of 7.4 GW would be required in the domestic traffic scenario.



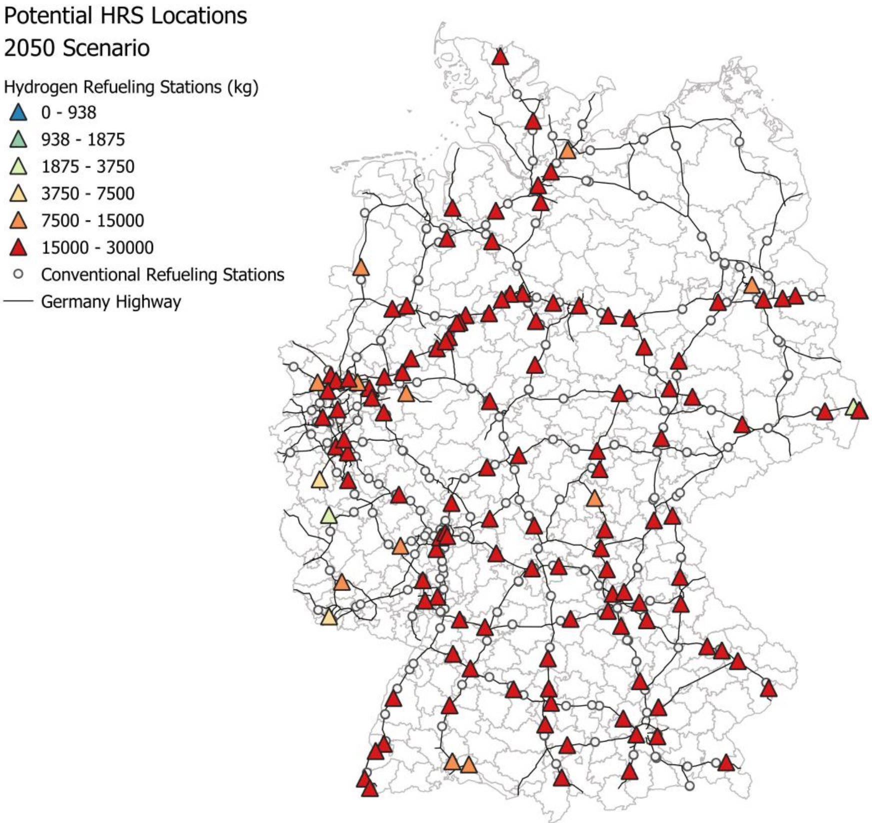


Figure 32: Potential HDV-HRS locations (triangles) in domestic (top) and total HDV traffic (bottom, reference)

Next, the results of different FC-HDV diffusion rates are compared (100 %, 80 %, 60 % and 40 %). These were modeled by varying the volume of traffic per OD path considering all OD paths (domestic, border and transit traffic). At 100 % diffusion on German highways, Figure 32 shows the resulting HDV-HRS network with 137 stations (similar to the reference scenario). With a lower market diffusion of FC-HDV and hence lower hydrogen demand from HDV traffic, the potential HRS network would decrease from 137 stations (at 100 % traffic flow) to 100 stations (at 40 % traffic flow) as shown in Table 20. The station network already reaches its lower bound of 100 HRS (already described in section 5.2.2) with 60 % HDV traffic. In other words, the optimal HDV-HRS network should consist of at least 100 stations to comply with the NC-FRLM assumptions and constraints at a total market diffusion of 60 % FC-HDV or less in 2050.

Table 20: Varying total HDV traffic from 100 % to 40 % and the resulting potential HDV-HRS network compositions

Dimension	Unit	Traffic flow variance			
		100 %	80 %	60 %	40 %
HDV traffic	[million km/d]	72	57.6	43.2	28.8
H2 demand	[t/d]	3,600	2,080	1,560	1,440
XXL	[#]	121	116	68	55
XL	[#]	11	3	17	22
L	[#]	2	2	8	11
M	[#]	3	-	4	6
S	[#]	-	-	3	4
XS	[#]	-	-	-	2
Utilization	[%]	96	91	82	61
Total HRS	[#]	*137*	*121*	*100*	*100*

Further, the heterogeneity of the HRS network increases with lower traffic demand, e.g. XS stations become part of the optimal network. Hence, lower traffic and a higher capacity limit (cf. section 5.2.2) both lead to a higher heterogeneity of stations in the network and vice versa. An additional table analyzing the effect of traffic flow variances and capacity limitation variances on the potential network station sizes can be found in the Appendix in Table 38.

Similar to the domestic HDV network, the average station utilization decreases significantly between 100 % and 40 % traffic – by more than 30 % (from 96 % to 61 %, respectively). Hence, once the network reaches its lower bound of 100 stations – e.g. through high capacity limits or less traffic – station utilization rates decrease noticeably. This effect can be explained by the set covering approach of the

NC-FRLM, which aims at the least number of stations to serve a given traffic amount to ensure (hydrogen) supply to the vehicles, and therefore accepts lower utilization rates at the stations.

In result, all traffic variations show that reducing HDV traffic by either focusing on domestic HDV traffic only or by reducing overall HDV traffic has similar implications for the HDV-HRS network: fewer stations, higher station heterogeneity and a decreased utilization rate. Additionally, focusing on domestic HDV traffic only or reducing overall traffic results in a different spatial distribution of stations. Domestic traffic results in fewer stations along transit routes, e.g. A2, A4, A5, while the reduction of overall traffic leads to proportionally fewer stations across the network until the lower bound is reached.

5.2.4 Vehicle range variation scenario

The vehicle range scenario analyzes varying FC-HDV ranges – both longer and shorter – and their implications for the HDV-HRS network in Germany. Range variations may occur due to advances or delays in vehicle technology such as powertrain efficiency and on-board hydrogen storage until 2050.

Compared with the reference scenario (800 km range), a longer vehicle range of 1,000 km does not have any impact on the station network, resulting in the same number and sizes of stations shown in Table 21. This result is due to the OD trip data. The longest OD path in Germany is only slightly above 800 km (cf. section 3.2.2) and thus nearly all trips will refuel before driving more than 800 km.

On the other hand, a lower range – e.g. 600 km or 400 km – results in slightly more stations in the network as shown in Table 21. This trend is enhanced when combining a lower range with a higher station capacity limit or less traffic demand as shown in the Appendix in Table 40.

Table 21: Vehicle ranges and their impact on the HRS network station portfolio

	Vehicle range			
Stations	400km	600km	800km	1,000km
XXL	121	121	121	121
XL	11	11	12	12
L	1	2	2	2
M	3	2	2	2
S	3	1	-	-
XS	-	-	-	-
∑ HRS	139	138	137	137

5.2.5 Hydrogen distribution variation scenario

As described in section 5.1.5, the hydrogen distribution variation scenario analyzes the effect of on-site vs. centralized production of hydrogen. Generally, the type of hydrogen distribution has no impact on the station network design in this analysis as the design is based on hydrogen (energy) demand and not on hydrogen (energy) supply. As a result, varying the type of hydrogen distribution – on-site or centralized production via pipeline supply – has no influence on the spatial station distribution or the station portfolio composition, but serves as a baseline to determine the economic implications of supplying hydrogen per pipeline to the stations.

Hence, this section describes the additional pipeline network required to distribute hydrogen from centralized production sites to the HRS stations. A hydrogen pipeline system along highways is modeled to reach each HRS of the network.[68] As mentioned in section 5.1.5, four main central electrolyzers are assumed; three at the North Sea coast (near Bremerhaven, Cuxhaven and Wilhelmshaven) and one at the Baltic Sea (near Rostock). The pipeline system follows a Dijkstra algorithm (Dijkstra, 1959) to determine the shortest path for the pipeline system under the given centralized electrolyzer capacities as an additional constraint.[69] The resulting pipeline is shown in Figure 33, has a total length of 5,381 km with an average diameter of 0.23 m and the pipelines with the largest diameters have a North-South orientation. Pipelines become narrower towards the south and the decentralized station locations. For comparison, this supply pipeline system for a HDV-HRS network is significantly shorter than a hypothetical pipeline system to supply a passenger car HRS network in Germany: According to Robinius (2015), a full HRS network for passenger cars requires a pipeline network of about 42.000 km (12.000 km transmission and 30.000 km distribution pipelines) to supply about 10.000 stations with about three million tons hydrogen per year.[70]

[68] As the German highway network is federal property, it is assumed that installing a new hydrogen pipeline here is much easier than installing one on private property. Other authors assumed new hydrogen pipeline installations close to existing gas pipelines (cf. Robinius (2015); Seydel (2008)), which will be discussed in chapter 7.

[69] The Dijkstra algorithm was applied in analogy to the highway network setup described in section 3.2.1.

[70] For comparison, the HDV-HRS network determined in the reference scenario of this thesis has 137 stations and requires 1.3 million tons hydrogen annually.

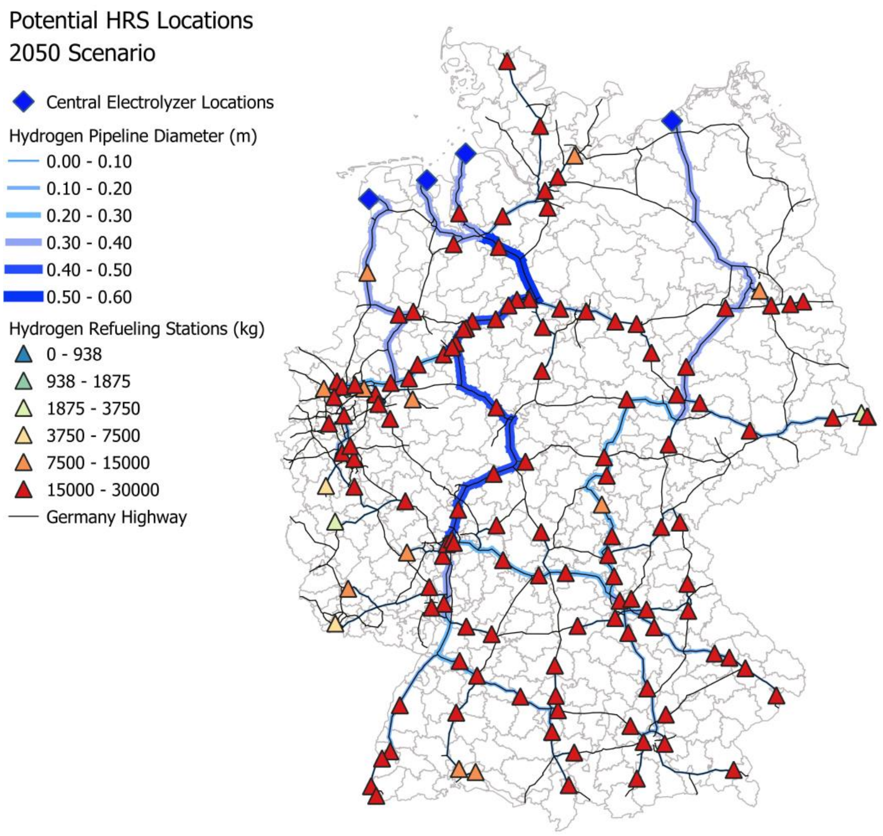


Figure 33: Pipeline network to supply the HDV-HRS network from the reference scenario with hydrogen

5.3 Economic implications: Network cost

This section presents the results of the model-based HDV-HRS network for the reference scenario to understand the economic implications, such as total annual network cost and cost shares of the different components. Further, the four additional scenarios are compared with the reference scenario to gain a more comprehensive understanding of the cost of a potential HDV-HRS network in Germany in 2050.

Three different perspectives are used to appraise and compare the cost of producing and supplying hydrogen via a HDV-HRS network: total annual cost of the network, levelized cost of hydrogen (LCOH) per kilogram hydrogen, and relative network cost per HDV kilometer. The annual network costs comprise the full network life-cycle costs expressed as consistent periodic payments over the lifespan (Wöhe and Döring (2010), which include OPEX and CAPEX[71] for the stations and electrolyzers as well as electricity. Next, the LCOH metric is used, which is conceptionally very similar to the Levelized Cost of Electricity (LCOE). The LCOH determines the full life-cycle costs of hydrogen production up to delivery at the station dispenser and expresses them as costs per unit of hydrogen produced. The LCOH is the annual cost of hydrogen production divided by total hydrogen generation, which can be calculated at station

[71] CAPEX are defined as annuitized investments in this thesis.

level and aggregated or averaged using the annual hydrogen production as a weight. Finally, the relative network cost per HDV kilometer is a metric used within recent HDV infrastructure literature (Wietschel et al., 2017). In this thesis, the relative network cost sets the infrastructure costs in relation to the driven distances on the covered network, i.e. the annual HDV traffic on German highways (cf. section 3.2.1).

These costs were analyzed from a macro-economic perspective, i.e. without levies, taxes or other surcharges. Further, for operating the on-site electrolyzers, the average cost of electricity in the NC-FRLM network cost analysis is 100 €/MWh, taken from the 2050 trend scenario (Schlesinger et al., 2014).[72]

5.3.1 Reference scenario

The reference scenario aims at understanding the economic implications of a HDV-HRS network with default assumptions. These results serve as a starting point to understand the following scenarios and the impact of their variations on the economics. Besides the network design, Table 22 also shows the economic results of the reference scenario including the annual network costs consisting of stations (HRS), electrolyzers, distribution and electricity costs. Due to on-site hydrogen production, the costs of hydrogen distribution are zero in the reference scenario.

The total annual costs of the HDV-HRS network sum up to 8.38 bn€ in 2050. With a network of 137 stations in the reference scenario, an average station would cost 61.2 million euros per annum (€/a) including both infrastructure (station and electrolyzer) and energy costs (hydrogen). With about 86 %, electricity costs account for the majority of the total annual costs (7.19 bn€/a). This indicates the large impact of electricity costs on the total annual network costs. Station costs are the second largest, with about 0.62 bn€/a (about 7 %), which equals about 4.5 million €/a per station. Electrolyzers account for about 50 % of the non-electricity costs (0.57 bn€/a), indicating indicating they and stations are equally relevant as cost drivers.

The average LCOH in the reference scenario is 6.47 €/kg. Of these costs, the electricity costs represent about 5.54 €/kg and are clearly a major cost driver. The pure station costs, on the other hand, account for less than 10 % of the electricity costs at 0.48 €/kg – similar to the electrolyzer costs. Accordingly, a single refill of a FC-HDV with 50 kg hydrogen (cf. section 4.1) costs about 320 euros.

The relative costs per HDV kilometer in the reference scenario sum up to 0.40 €/km. Similar to the previous two metrics, the electricity costs represent the largest proportion of these costs with about 0.34 €/km, and the station and electrolyzer each cost 0.03 €/km.

[72] This electricity price prognosis covers electricity-intensive industries in 2050.

Table 22: Overview of the network design and economic results for the reference scenario

Design results		Unit	Economic results		Unit
Stations	137	#	Network cost	8.38	bn€/a
- XXL	*122*	#	*- HRS*	*0.62*	bn€/a
- XL	*11*	#	*- Electrolyzer*	*0.57*	bn€/a
- M	*2*	#	*- Distribution*	-	bn€/a
- S	*2*	#	*- Electricity*	*7.19*	bn€/a
- XS	-	#	LCOH	6.47	€/kg_{H2}
Utilization	96.5	%	Relative HDV cost	0.40	€/km
HRS electrolyzers	12.62	GW			

5.3.2 Station capacity limit variation scenario

This scenario analyzes the economic impact of varying capacity limitations. More specifically, only a lower capacity limit can be evaluated as stations larger than “XXL” (> 30 t) have not been considered in the station portfolio due to legal limitations (cf. section 4.2.2).

Generally, HDV-HRS networks with lower capacity limits imply higher annual costs. Table 23 shows the results of a network with a capacity limitation of 15 tons (station size “L”). More precisely, the only driver for additional costs compared with the reference scenario are the stations. This is due to the network having more stations at lower capacity limits (cf. 5.2.2), and smaller stations being relatively more costly than larger ones (cf. section 4.2.2). However, the higher utilization rate of networks with lower capacity limits (cf. section 5.2.2) almost offsets these additional station costs, resulting in additional costs of 0.2 % (+16 million €/a). At the same time, the annual costs for electrolyzers and electricity remain constant, due to constant hydrogen demand.

Likewise, the LCOH only increases to a small extent by 0.02 €/kg to 6.49 €/kg. This equals additional costs of about 4 to 5 euros for a single refill. At the same time, the relative network costs increase by less than 0.01 €/km and are thus hardly noticeable.

The capacity variance scenario indicated that higher capacity limits seem preferable from an economic perspective as fewer, larger stations are required. However, this effect is almost compensated by a lower average utilization of the stations. Additionally, building a larger number of smaller stations versus a smaller number of larger stations has additional cost implications that have not been considered in this thesis, such as economies-of-scales resulting from more station installations (which reduces costs), or the more complex management of a larger number of stations (which increases costs).

Table 23: Overview of the network design and economic results for the capacity variation scenario with 15 tons capacity limit

Design results		Unit	Economic results		Unit
Stations	276	#	Network cost	8.40	bn€/a
- XXL	-	#	*- HRS*	*0.64*	bn€/a
- XL	*276*	#	*- Electrolyzer*	*0.57*	bn€/a
- M	-	#	*- Distribution*	-	bn€/a
- S	-	#	*- Electricity*	*7.19*	bn€/a
- XS	-	#	LCOH	6.49	€/kg_{H2}
Utilization	99.8	%	Relative HDV cost	0.40	€/km
HRS electrolyzers	12.62	GW			

5.3.3 Traffic demand variation scenario

To understand the economic implications of reducing traffic demand (which is similar to lowering market diffusion), this scenario analyzes the annual costs of a 60 % traffic scenario. From an economic perspective, this scenario also represents a domestic-only variation as the only difference between a network for domestic traffic only and a network for a total traffic reduction to 60 % is the regional allocation of stations (cf. section 5.2.3).

Table 24 shows the economic results of a 60 % traffic scenario. The annual costs of 4.92 bn€/a are about 3.47 bn€/a lower than the reference scenario. Electricity costs still account for a high share of these costs at about 85 % (4.17 bn€/a).

At the same time, the average utilization is slightly lower than the reference scenario, resulting in about 10 % higher relative costs (LCOH at 6.55 €/kg and kilometer costs of 0.41 €/km) as shown in Table 24. The decrease in utilization is most likely caused by reaching the lower bound of stations required to serve the traffic (set covering approach, cf. section 3.1.3).

Once the lower bound of stations is reached, any further reduction of traffic increases the relative costs exponentially, due to the same number of stations serving a lower volume of traffic (cf. section 5.2.3). This leads to higher LCOH and costs per HDV kilometer. At 40 % traffic, the higher relative costs for smaller stations as well as the lower utilization of the station network increase the average LCOH to 8.05 € per kilogram (24 % increase compared to the reference scenario). Hence, a higher volume of FC-HDV traffic decreases the relative network costs for two reasons: larger stations (with better economies-of-scale per station) and higher utilization, especially for traffic scenarios above 50 % of the total traffic.

Table 24: Overview of the network design and economic results for the traffic variation scenario with only domestic traffic (60 % of the total traffic)

Design results		Unit	Economic results		Unit
Stations	100	#	Network cost	4.92	bn€/a
- XXL	*68*	#	*- HRS*	*0.39*	bn€/a
- XL	*17*	#	*- Electrolyzer*	*0.36*	bn€/a
- M	*8*	#	*- Distribution*	-	bn€/a
- S	*4*	#	*- Electricity*	*4.17*	bn€/a
- XS	*3*	#	LCOH	6.55	€/kg_{H2}
Utilization	83.1	%	Relative HDV cost	0.41	€/km
HRS electrolyzers	7.81	GW			

5.3.4 Vehicle range variation scenario

The previously shown network design results (cf. section 5.2.4) already indicated the low impact of reducing the vehicle range. Hence, the economic implications of varying the vehicle range – e.g. from 800 km to 400 km – are almost negligible.

As shown in Table 25, a network designed for FC-HDVs with 400km range results in total network costs of 8.39 bn€/a, similar to the reference scenario. The changes in the network design (from 137 to 139 stations) add up to less than 5 million €/a, resulting in total station costs of about 624 million €/a. The costs for electrolyzers and electricity are the same as the reference scenario.

Likewise, the relative costs of this vehicle range variation scenario are similar to the reference scenario. The LCOH is 6.47 €/kg and the relative network costs are 0.40 €/km.

Hence, similar to the capacity limitation variation scenarios, the range variation leads to (slightly) more smaller stations and thus increases station costs, while the total hydrogen demand and hence electrolyzer and electricity costs remain constant.

Table 25: Overview of the network design and economic results for the vehicle range variation scenario with 400 km range

Design results		Unit	Economic results		Unit
Stations	139	#	Network cost	8.39	bn€/a
- *XXL*	121	#	- *HRS*	*0.62*	bn€/a
- *XL*	11	#	- *Electrolyzer*	*0.57*	bn€/a
- *M*	1	#	- *Distribution*	-	bn€/a
- *S*	3	#	- *Electricity*	*7.19*	bn€/a
- *XS*	3	#	LCOH	6.47	€/kg_{H2}
Utilization	96.5	%	Relative HDV cost	0.40	€/km
HRS electrolyzers	12.62	GW			

5.3.5 Hydrogen distribution variation scenario

For the pipeline scenario (with centralized hydrogen production), a hydrogen pipeline system is modeled along highways to each HRS in the network (cf. section 5.2.5). Four centralized electrolyzers are assumed close to the German coast due to the lower electricity prices here. In this scenario, 2050 electricity prices for centralized hydrogen production in Germany are based on the work of Robinius (2015) and estimated at 80 €/MWh.

The HDV-HRS network with centralized hydrogen production and a pipeline distribution network results in annual network costs of 7.25 bn€ as shown in Table 26. These costs are about 14 % lower than in the reference scenario. While the cost of stations and electrolyzers are similar to the reference scenario (0.62 bn€/a and 0.57 bn€/a, respectively), there are additional distribution costs for the hydrogen pipeline of 0.31 bn€/a. At the same time, the annual costs for electricity are 20 % lower than in the reference scenario (5.75 bn€/a). In total, the annual network costs are about 13 % lower in the pipeline scenario than in the reference scenario.

Essentially, the additional investments in hydrogen distribution (pipeline) are offset by lower electricity prices, while the other costs (stations and electrolysis) are similar to the reference scenario. As a result, the share of electricity costs decreases from 85 % (reference scenario) to 79 %.

Further, the average LCOH in the pipeline scenario is 5.59 € per kilogram (compared to 6.47 €/kg in the reference scenario). The electricity costs of the LCOH are 4.42 €/kg, i.e. 1.12 €/kg lower than in the reference scenario. The additional costs for the pipeline contribute to 0.24 €/kg. The cost per refill drops by 40 € from 320 € (reference scenario) to 280 € (pipeline scenario).

Likewise, the average HDV-kilometer costs at 0.35 €/km are about 13 % lower than in the reference scenario and thus cheaper by 0.05 €/km. The relativ pipeline costs are about 0.01 €/km.

Table 26: Overview of the network design and economic results for the hydrogen distribution variation scenario with a pipeline

Design results		Unit	Economic results		Unit
Stations	137	#	Network cost	7.25	bn€/a
- XXL	*122*	#	*- HRS*	*0.62*	bn€/a
- XL	*11*	#	*- Electrolyzer*	*0.57*	bn€/a
- M	*2*	#	*- Distribution*	*0.31*	bn€/a
- S	*2*	#	*- Electricity*	*5.75*	bn€/a
- XS	-	#	LCOH	5.59	€/kg_{H2}
Utilization	96.5	%	Relative HDV cost	0.35	€/km
HRS electrolyzers	12.62	GW			

As shown in Figure 34, when comparing the pipeline scenario with the reference scenario, the annual pipeline cost (0.31 bn€/a) is offset by electricity cost savings (1.44 bn€/a). The break-even average electricity price difference between the reference scenario and the pipeline scenario is at 4.31 €/MWh. This indicates that the pipeline scenario triggers fewer annual costs if the electricity costs are lower than in the reference scenario by 0.5 €ct/kWh. This very small difference in electricity prices is subject to high uncertainty until 2050.

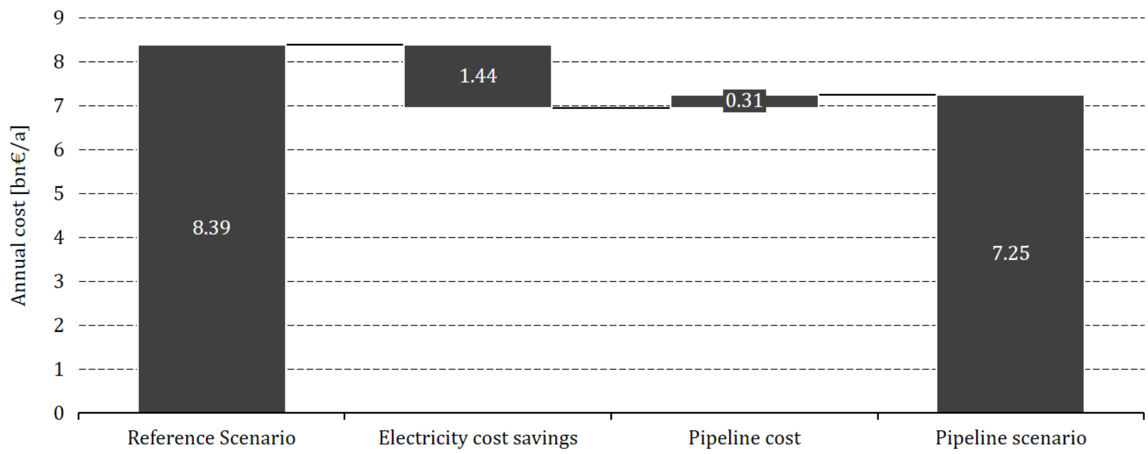


Figure 34: Comparison of total annual costs of reference scenario and pipeline scenario including savings and additional costs

In result, installing a pipeline network to supply hydrogen to the stations seems preferable to on-site production from an economic perspective under current assumptions.

5.4 Summary of the HDV-HRS network analysis

In summary, the design and thus the economics of a potential HDV-HRS network depend strongly on the respective scenario. The reference scenario results in a network of 137 stations with annual costs of about 8.39 bn€. Less than 20 % of these costs are not related to electricity, indicating the minor impact of station costs on the final costs. In contrast, more than 80 % of these costs are energy-related, which highlights the overriding importance of electricity prices. The average LCOH at the station is 6.47 €/kg, which can be translated into 0.40 € per HDV kilometer.

Lowering the maximum capacity limit (e.g. from 30 to 15 tons) results in a larger number of stations with higher average utilization. At the same time, changing the capacity limit does not have a significant economic impact on the total annual costs , as a higher station utilization compensates the lower economies-of-scale of a larger number of (smaller) stations.

Further, assuming lower volumes of FC-HDV traffic – corresponding to a lower market diffusion – leads to lower total annual costs but higher relative costs (LCOH, euros per kilometer). This effect mainly results from already reaching the lower bound of 100 stations at less than 60 % HDV traffic.

Varying the vehicle range has almost no impact on either the network design or its annual cost.

Considering centralized hydrogen production instead of on-site electrolysis decreases costs significantly by more than 1 bn€/a, as lower electricity prices outweigh the additional pipeline costs. These results are summarized in Table 27.

Table 27: Summary of the network design and economic results for the reference scenario as well as Scenarios 1 to 4

	Scenario	Reference	S-1	S-2	S-3	S-4	Unit
Input	Station capacity limit	30	15	30	30	30	t_{H2}/d
	Total hydrogen refueling demand	3,557	3,557	2,058	3,557	3,557	t_{H2}/d
	Total hydrogen refueling demand	64.88	64.88	37.62	64.88	64.88	TWh_{el}/a
	HDV range	800	800	800	400	800	km
	Electrolyzer location	Local	Local	Local	Local	Central	-
	Electricity cost	100	100	100	100	80	€/MWh
	HRS electrolyzers capacity factors[73]	90.00	90.00	90.00	90.00	90.00	%
Design results	Stations	137	276	100	139	137	#
	- XXL	*122*	-	*68*	*121*	*122*	*#*
	- XL	*11*	*276*	*17*	*11*	*11*	*#*
	- M	*2*	-	*8*	*1*	*2*	*#*
	- S	*2*	-	*4*	*3*	*2*	*#*
	- XS	-	-	*3*	*3*	-	*#*
	Utilization	96.5	99.8	83.1	96.5	96.5	%
	HRS electrolyzers	12.62	12.62	7.81	12.62	12.62	GW
Economic results	Network cost	8.38	8.40	4.92	8.39	7.25	bn€/a
	- HRS	*0.62*	*0.64*	*0.39*	*0.63*	*0.62*	bn€/a
	- Electrolyzer	*0.57*	*0.57*	*0.36*	*0.57*	*0.57*	bn€/a
	- Distribution	-	-	-	-	*0.31*	bn€/a
	- Electricity	*7.19*	*7.19*	*4.17*	*7.19*	*5.75*	bn€/a
	LCOH	6.47	6.49	6.55	6.47	5.59	€/kg_{H2}
	Relative HDV cost	0.40	0.40	0.41	0.40	0.35	€/km

[73] per definition (cf. section 4.2.3)

6. Interaction of heavy-duty vehicle stations and electricity system[74]

As the previously described potential HDV-HRS network will have impacts on the electricity system and vice versa, the interaction of these two systems is analyzed next. Of particular interest are the HDV-HRS flexibility potentials and their ability to increase the integration of local RE. The subsequent analysis is based on the reference scenario of the previous chapter with on-site hydrogen production. However, the previously external inputs electrolyzer sizes, capacity factors and electricity costs are now part of the optimization.

First, and for reference purposes, the regional electricity demand of the PyPSA-modeled German electricity system (section 6.1) and that of the NC-FRLM-modeled HDV-HRS network (section 6.2) are described separately. These separate results serve as the baseline for comparison with the sector-coupled integration cases. Two sector-coupling scenarios are defined (section 6.3), including a HDV-HRS network cost optimization scenario (section 6.3.1) as well as a total system optimization scenario, i.e. electricity system and HDV-HRS network cost (section 6.3.2). The implications of both scenarios are shown for the HDV-HRS network (section 6.4) and the electricity system (section 6.5). Finally, the last section (section 6.6) summarizes the results of this chapter.

6.1 German electricity system without heavy-duty vehicle stations

In order to obtain a baseline for comparison with the sector-coupling scenarios (section 6.3), PyPSA is used to examine what a minimum cost renewable electricity system could look like in 2050 (without HDV sector coupling). As mentioned in section 4.3, the total electricity demand without a HDV-HRS network represents the present demand and thus sums up to about 509 TWh_{el} in 2050.

The local electricity demand is shown in more detail in Figure 35 for all NUTS3 regions in Germany and correlates strongly with today's regional demand. Most of the electricity demand occurs in western and southern Germany with the three states North Rhine-Westphalia (128 TWh_{el}), Bavaria (88 TWh_{el}) and Baden-Wurttemberg (70 TWh_{el}) accounting for over half of the total national electricity demand. Especially high local electricity demands occur in and around the cities of Berlin, Hamburg, Neuss and Wesel, with each exceeding 10 TWh_{el}.

[74] This chapter is based on Rose and Neumann (2020).

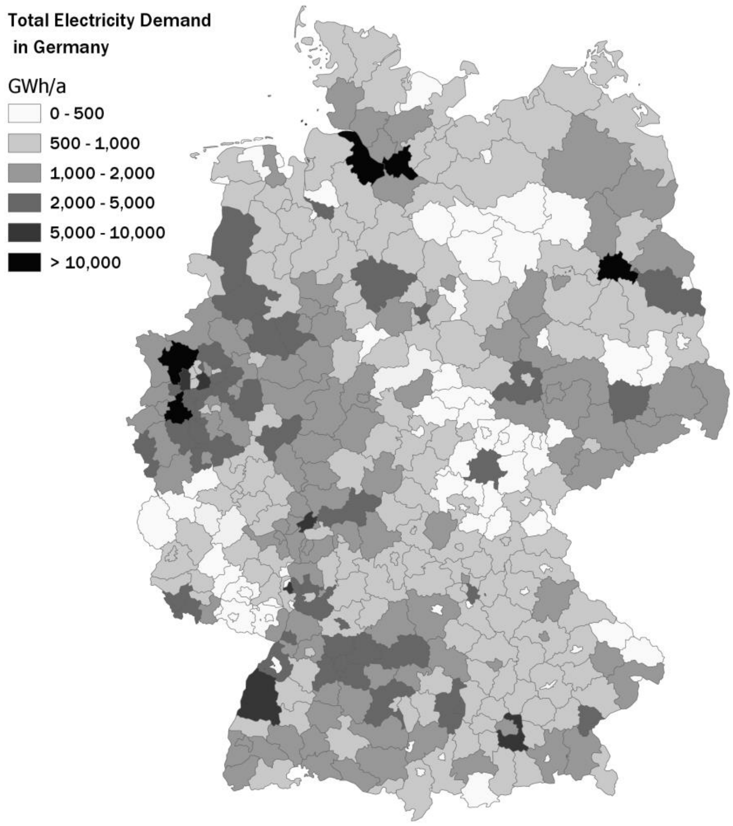


Figure 35: Geographical distribution of electricity demand (without HDV-HRS network)

In sum, the total annual electricity system costs[75] amount to 40.25 billion euros in 2050 as outlined in Figure 36. Of these costs, about 75 % are spent on electricity generation, 20 % on storage infrastructure, and 5 % on transmission infrastructure. These results already indicate the relevance of electricity storage over transmission infrastructure investments. With a total generation of about 550 TWh_{el} (gross electricity generation) and 95 % RE, the relative total annual system costs amount to 73.18 €/MWh.

[75] Annual electricity system costs include operating and capital expenditures for the electricity production capacities (such as wind, solar and run-of-river plants), grid and storages. These costs are analyzed from a macro-economic perspective, i.e. without levies, taxes or other surcharges.

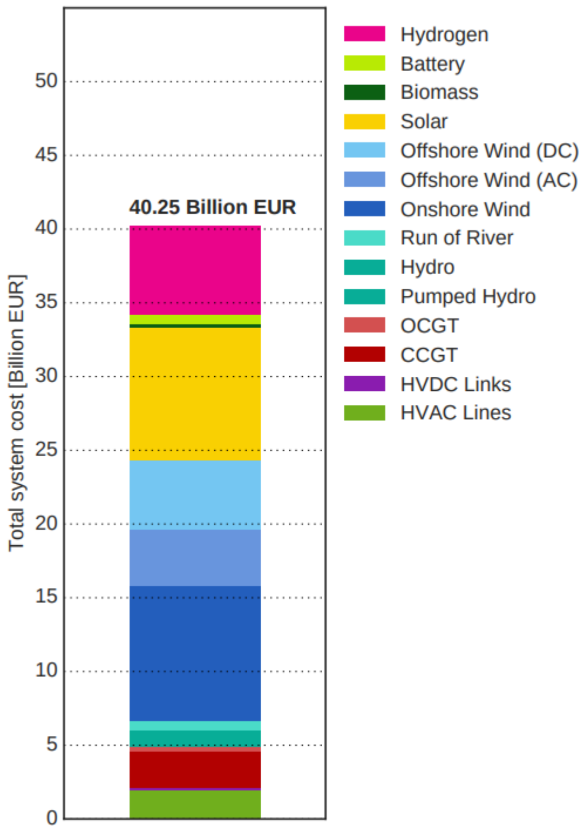


Figure 36: Total system costs in the German electricity system

Looking at the geographical distribution of electricity production capacities, Figure 37 (top) shows that wind turbines dominate the installed capacities and are located predominantly in the north. These wind capacities (both onshore and offshore) produce about 61 % of the total electricity. In general, there is a strong geographical mismatch between electricity generation and demand (load), which is naturally prone to transmission congestion, because load centers are mostly located in Western and Southern Germany (cf. Figure 35), but it is nonetheless the cheapest system layout. The total electricity demand sums up to 509 TWh_{el}, which indicates annual electricity losses of 41 TWh_{el}. These losses are caused by storage inefficiencies to bridge the gap between electricity supply and demand.

The electricity storage capacities are mainly built in the north, too, as also shown in Figure 37 (bottom). In more detail, there is more hydrogen than battery storage deployment. In terms of capital expenditure, the difference amounts to a factor of 10. Hydrogen storage pairs well with locations with high wind power generation (onshore and offshore landing locations), whereas there are only a few, but large battery hubs dispersed across the rest of Germany. These battery storages pair well with the daily fluctuations of solar installations. The most notable battery hub is located near Ingolstadt in the South-East.

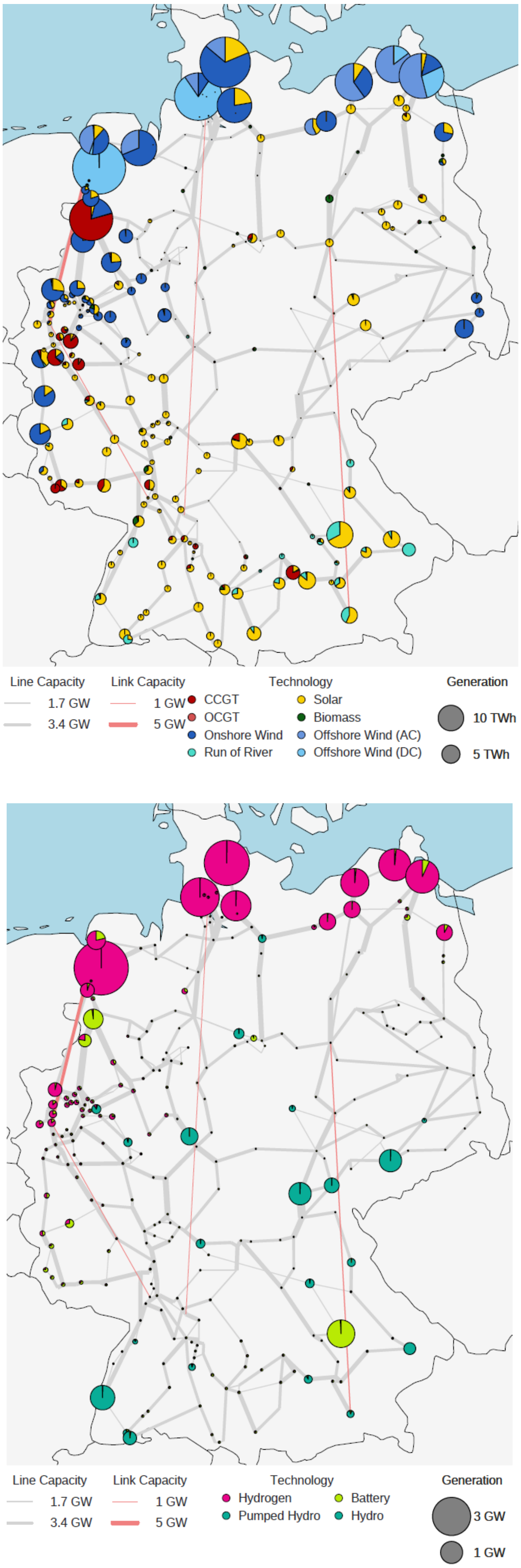


Figure 37: Geographical distribution of electricity production (top) and geographical distribution of storage power capacities (bottom) without HRS network

Further, most of the transmission network expansion is limited to the northern half of Germany and is likewise strongly correlated with wind turbine locations, with lines principally directed south. The total network expansion between today and 2050 is about 8 TWkm[76] (or 18 %), which incurs annual costs of about 1.9 bn€ (cf. Figure 36). From a national perspective, this would be in line with the German network development plan (Netzentwicklungsplan, NEP) of (Rippel et al., 2019), which already aims at an additional 8 % network expansion[77] within the next 11 years (between 2019 and 2030). The remaining 10 % network expansion appears to be modest for the subsequent 20-year period from 2030 to 2050.

The marginal costs that consumers, including hydrogen refueling station operators, pay for electricity (from a macro-economic perspective, without levies, taxes or other surcharges) is another important feature of the optimization results. The local cost of electricity production in the system at a particular point in time is derived from the dual variables of the nodal power balance equations that implement Kirchhoff's current law. The value of these dual variables describes the total system investments' sensitivity to consuming an additional unit of power at one location and at one point in time. This value corresponds to the locational marginal cost (LMC)[78] in an idealized market that implements nodal costs and is capable of factoring in transmission congestion. The increasing deployment of renewables places more strain on the transmission network. This suggests that grid bottlenecks should be taken into account in electricity markets. If congestion occurs, nodal costs will vary in the network, but if there were no transmission limits, the nodal costs would be identical at every location. However, the current market structures in Germany with a single bidding zone do not consider internal transmission congestion in the bidding process. Instead, to ensure that the physical limits of transmission are not exceeded, network operators must re-dispatch power stations and curtail renewables to keep the system balanced. In the future, it is conceivable that re-dispatch will be handled through a nodal market approximating LMC. Since this analysis is interested in the total electricity system cost effects, it is based on an idealized market design, where consumers pay the locational marginal cost, reflecting its impact on total system costs, and excluding levies, taxes or other surcharges.

Figure 38 depicts the median LMC for electricity in combination with average transmission line loadings. There are clear North-South and East-West differentials with median nodal costs ranging between 60 and 165 €/MWh. The lowest LMC is on the Baltic coast (next to the Island of Rügen), followed by Oldenburg and the Müritz area, which have inexpensive RE potentials and low regional electricity demand. In

[76] The quantity of electrical interconnector capacity expansion of an electricity network is commonly expressed as terawatt kilometers (TWkm) representing both its length and its electrical capacity. For example 1 TWkm represents 1,000 km of an interconnector of 1GW capacity.
[77] The NEP considers these investments to be about 1.2 bn€/a.
[78] In this thesis, the locational marginal cost (LMC) is a synonym for the locational marginal price (LMP) due to the macro-economic perspective of this analysis, i.e. without levies, taxes or other surcharges.

contrast to this, high LMCs are observed in the west and south (with the highest LMC in the area around Münster), where the electricity demand is generally higher than average and there are no inexpensive RE potentials. Overall, this suggests that transmission congestion does occur, despite the previously mentioned network capacity expansion, and that this obstructs the flow of low-cost wind power to the south and causes nodal costs to rise, but not to the extent that it proves economical to increase transmission capacities. High line loadings (above 60 %) can be observed, but only in isolated areas (e.g. Cologne, Dortmund and Dresden areas), not throughout the country nor especially in North-South or East-West directions.

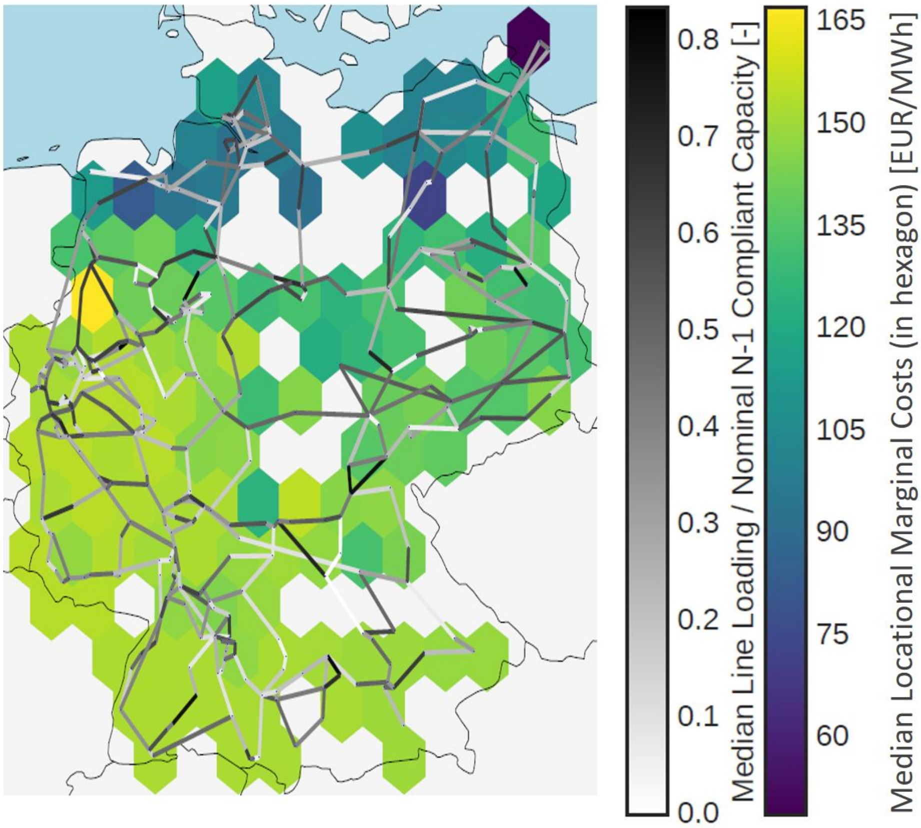


Figure 38: Mean networking loading (left) and local marginal costs of electricity (right)[79]

Having evaluated the future German electricity system from a techno-economic perspective, the next section assesses the new, additional electricity demand of a HDV-HRS network.

6.2 Regional electricity demand of heavy-duty vehicle stations

The additional yearly electricity demand to supply the on-site electrolyzers for the HRS sums up to about 65 TWh_{el} per year in 2050. The electricity demand at HDV-HRS per NUTS3 area is visualized in Figure 39 with the relative electricity demand increase

[79] PyPSA generates tiles to visualize the local marginal costs of electricity based on the nodes of the transmission network.

surplus (top) and the absolute additional electricity demand (bottom) due to the HDV-HRS network. The HRS network is mainly located in rural areas as it is based on traffic demand rather than on population density. Further, the NC-FRLM model-based station allocation naturally limits the regional electricity demand of the HDV-HRS network to only a few areas. Out of 402 NUTS3 areas, 68 have no physical highway and another 222 areas feature highways but no HRS locations. Hence, the additional electricity demand from a HDV-HRS network is focused on only 112 areas along German highways.

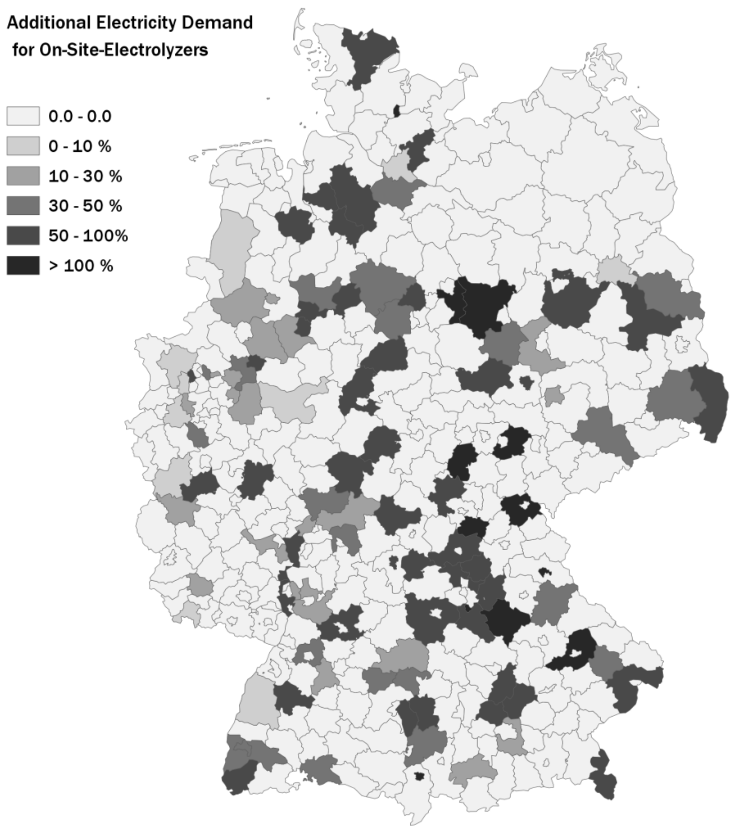
The relative electricity demand increase ranges from zero to 230 % per year. In twelve NUTS3 areas, FC-HDVs account for the largest share in electricity (above 100 % increase). These include seven southern, four central and one northern areas. On the other hand, the electricity demand increase caused by FC-HDV is less than 40 % in 44 areas. Additionally, the largest 50 % of the electricity consuming areas (excluding FC-HDVs) have 31 % demand increase on average caused by FC-HDVs.

In absolute terms, 13 areas[80] are affected by additional demand of more than one TWh_{el} and ten areas[81] with less than 0.2 TWh_{el}. The average additional electricity demand due to HDV-HRS in the 112 affected areas is 0.6 TWh_{el}. The largest impact at state level (NUTS1) is observed in Bavaria (17 TWh_{el}) and North Rhine-Westphalia (12 TWh_{el}) and thus in states, that already have high electricity demand (cf. section 6.1). Only minor impacts occur in most city states (Berlin 0.2 TWh_{el}), Bremen (0 TWh_{el}) and Hamburg (0.5 TWh_{el}) and states with low HDV traffic such as Mecklenburg-Vorpommern.

Having separately evaluated the electricity demand of a potential HDV-HRS network and the layout and annual costs of the German electricity system, the interplay between the two is assessed next. First, two electricity system scenarios are described in section 6.3 before results are presented in sections 6.4 and 6.5.

[80] These 13 areas are Hannover District (1.6 TWh_{el}), Cologne (1.51 TWh_{el}), Frankfurt (1.46 TWh_{el}), Munich District (1.33 TWh_{el}), Bielefeld (1.32 TWh_{el}), Groß-Gerau (1.24 TWh_{el}), Herford (1.21 TWh_{el}), Börde (1.12 TWh_{el}), Ilm (1.07 TWh_{el}), Lörrach (1.06 TWh_{el}), Neumarkt-Oberpfalz (1.03 TWh_{el}), Oder-Spree (1.01 TWh_{el}) and Straubing-Bogen (1.1 TWh_{el}).

[81] These ten areas are Emsland (0.19 TWh_{el}), Berlin (0.19 TWh_{el}), St. Wedel (0.19 TWh_{el}), Hildburghausen (0.18 TWh_{el}), Hochsauerlandkreis (0.17 TWh_{el}), Mainz-Bingen (0.16 TWh_{el}), Herne (0.14 TWh_{el}), Saarbrücken (0.13 TWh_{el}), Euskirchen (0.11 TWh_{el}), Daun (0.67 TWh_{el}).



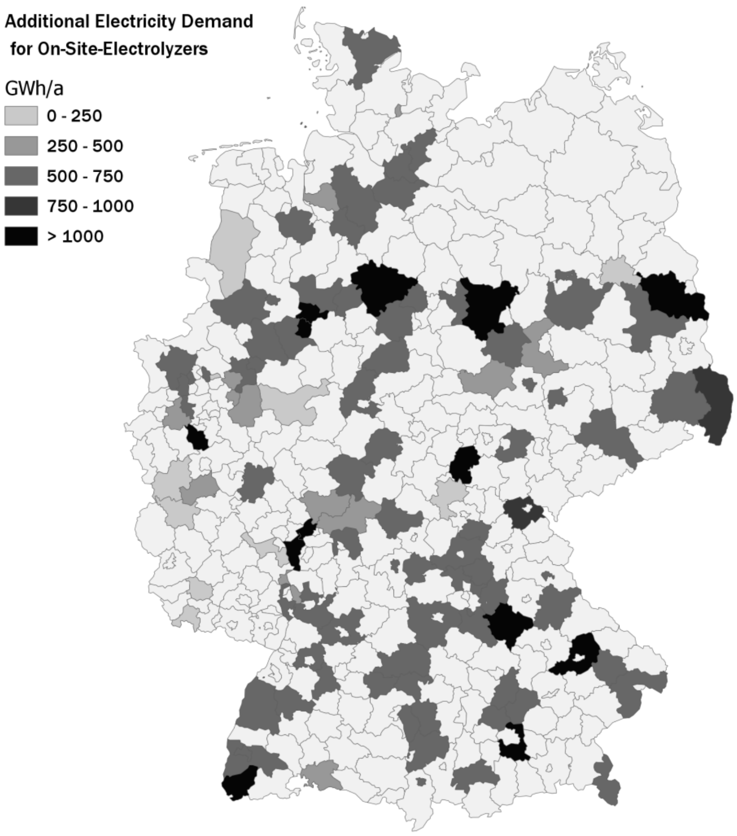


Figure 39: Relative (top) and absolute (bottom) additional electricity demand caused by the on-site electrolyzers of the reference scenario HDV-HRS network in 2050

6.3 Electricity system scenario definition

Two different integration scenarios are defined to investigate the interplay of the hydrogen refueling station network with the electricity system following some general remarks regarding integration.

Station locations are taken from section 5.2.1 and are integrated into the electricity system model. Further, the hydrogen demand time series from section 4.3 includes the hydrogen demand of domestic heavy-duty road vehicles and the required geographical distribution of refueling stations. Figure 40 shows the German power transmission network model overlaid by the German highway network. There are multiple intersections of highway network and high-voltage electricity network all over Germany, especially close to high-populated areas (e.g. Düsseldorf region, Frankfurt region).

Figure 40: Overlay of German highway network (blue lines) and stylized high-voltage transmission electricity network (red lines)

In contrast to section 5.3, no presumptions are made about the HRS portfolio-related capacities and their capacity factors of electrolyzers since these will be re-optimized depending on their interaction with the electricity system. Otherwise, the HRS portfolio-related station configuration (including investments) is the same as in the reference scenario of section 5.3 and feedback from PyPSA on determining locations for stations is excluded.

In the electricity system model, refueling stations are represented by an electrolyzer. Local hydrogen demand must be met by hydrogen produced at the local electrolyzer. Furthermore, while reconverting hydrogen to power is allowed for hydrogen storage options, this is not considered for hydrogen refueling stations. PyPSA-Eur models the electricity system on the transmission level only and HRS are not permitted in direct proximity to the high-voltage grid. Therefore, it is assumed that investments for connecting an electrolyzer to the power grid are proportional to its distance to the nearest high-voltage substation measured as a straight line[82], and are based on the specific costs for transmission level line types in Table 17.

The capital expenditures required for additional components of hydrogen refueling stations that are not linked to the electrolyzer and that do not interact with the electricity system, but are a function of total or peak hydrogen demand, are added ex-post, i.e. after the investment planning problem has been solved. These components are outlined in Table 12. Although these costs are disregarded in investment planning, they constitute a non-negligible cost factor. Investment assumptions for the electrolyzer and grid connection are identical to those presented in Table 17.

In both scenarios, the carbon dioxide emissions for the complete modeled system must not exceed 18 Mt/a. This is approximately equivalent to a 95 % emissions reduction in the power sector compared to 1990 levels in Germany (German Federal Environment Agency, 2019b). It is important to note that additional hydrogen demand from domestic heavy-duty road transport must not incur additional carbon dioxide emissions.

6.3.1 Scenario A: Cost optimization of a heavy-duty vehicle hydrogen refueling station network

In this scenario (scenario A), the individual operators of hydrogen refueling stations can choose how they operate their on-site electrolyzers to minimize the local (and thus total) HRS system costs. Hence, the station configuration is initially determined by locally minimizing the upfront investments in electrolyzers and grid connection to achieve a feasible operation strategy for on-site electrolysis that can supply the hydrogen demand at each point in time under the given storage restrictions. The electricity system costs are optimized subsequently within the global optimization problem, and the previously determined station electrolyzer capacities are taken into account as an input.

[82] As the geography between the electrolyzer and the power grid may not always allow a straight line connection, this assumption can underestimate the investments required. This circumstance is reflected in section 7.1.

6.3.2 Scenario B: Cost optimization of both the electricity system and the heavy-duty vehicle hydrogen refueling station network

In this scenario (scenario B), the individual operators of hydrogen refueling stations aim to minimize the total system costs, i.e. both the electricity system costs and the HDV-HRS network costs at the same time. Therefore, the investment and operation decisions of the operators of hydrogen refueling stations become part of the global optimization problem to minimize total (HRS and electricity) system costs, which determines the station configuration with the lowest costs.

6.4 Implications for the heavy-duty vehicle station network

Figure 41 shows the geographical distribution of the mean LCOH at the stations for both integration scenarios. The LCOH ranges from 5.26 €/kg to 6.74 €/kg in scenario A and from 4.51 €/kg to 5.82 €/kg in scenario B. In both scenarios, hydrogen is more expensive in the south than in the north of Germany because it is closely linked to the average local cost of electricity production as presented in Figure 38. Comparing both scenarios shows that sizing hydrogen refueling stations from a total system perspective (scenario B) can lower the average cost of hydrogen production from 6.43 €/kg to 5.66 €/kg. This corresponds to a significant reduction of 12 %. Seemingly, scenario B either leverages periods of cheap electricity supply better (lower annual electricity system cost), has lower annual costs for the HDV-HRS network or both compared to scenario A. Additionally, smaller stations have a higher average LCOH compared to larger stations in scenario A, especially in Western Germany. In scenario B, however, small stations have smilar LCOH compared to their neighbouring larger stations indicating a disproportional high benefit of scenario B for small stations.

Figure 42 shows the correlation of LCOH with the latitude and mean LMC for both scenarios. Similar to the LMC, there is a strong correlation between LCOH and the latitude (R^2 = 0.7 for scenario A and R^2 = 0.73 for scenario B[83]), i.e. southern stations tend to have a higher LCOH than stations in the north as previously observed in Figure 41. There is an even stronger positive correlation between the LCOH and the mean LMC (R^2=0.99 for scenario A and R^2=0.9 for scenario B), which means that higher LMC imply higher LCOH. As LMC and LCOH have a strong positive correlation, scenario B seemingly leverages periods of cheap electricity supply better (lower annual electricity system costs), leading to lower LCOH than in scenario A.

[83] A high coefficient of determination (R^2), e.g. R^2 = 1, indicates a high correlation of LCOH and mean LMC (while a low R^2, e.g. R^2 = 0.1, indicates a low correlation of the LCOH and LMC).

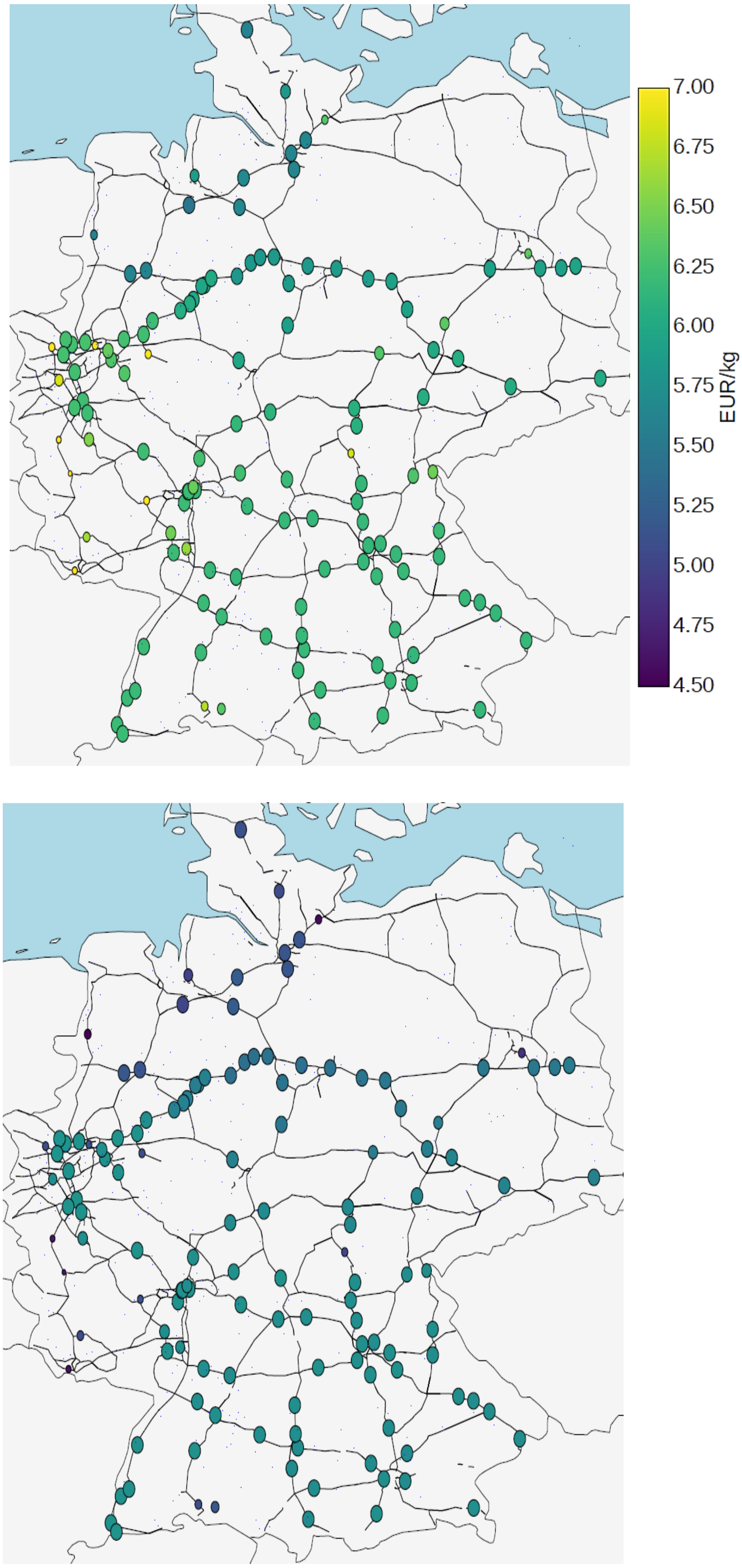


Figure 41: LCOH per station for scenario A (top) and scenario B (bottom) (the size of the spots refers to the station sizes (cf. Figure 28))

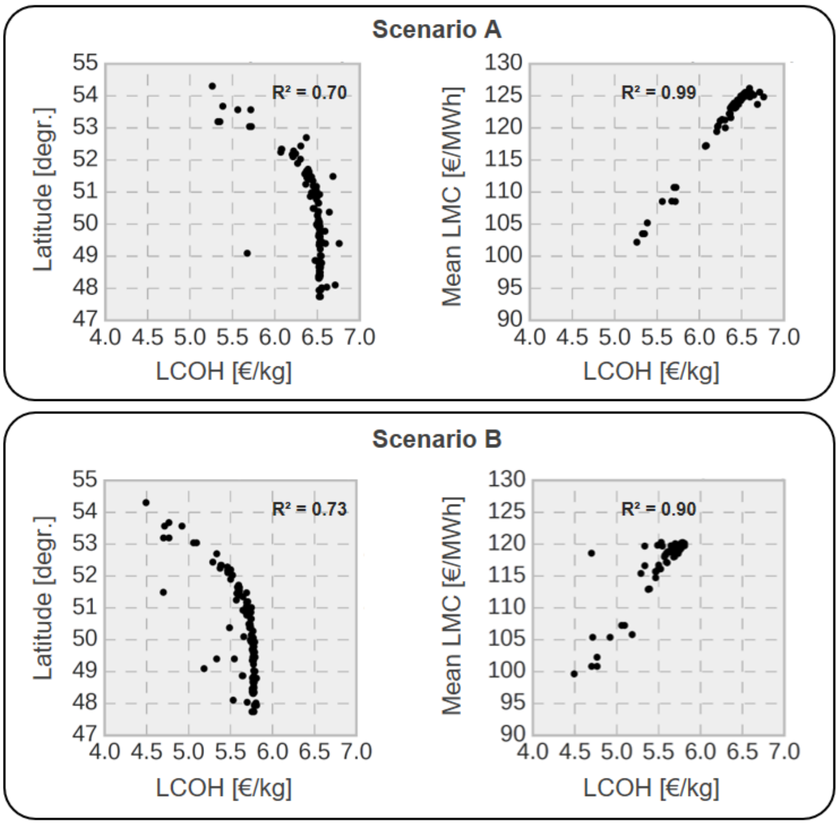


Figure 42: Correlation of LCOH and latitude (left) as well as correlation of LCOH and average cost of electricity production (right) for scenario A (top) and scenario B (bottom)

The histograms in Figure 43 show the electrolyzer capacities per HRS for both scenarios. On average, scenario B shows a 69 % rise in electrolyzer capacities compared with scenario A (165 MW instead of 98 MW). Simultaneously, the capacity factors of the electrolyzers decline from 0.59 on average in scenario A to 0.35 in scenario B (i.e. lower electrolyzer utilization), because the hydrogen demand of HDVs remains constant and therefore the amount of hydrogen produced. These results suggest that it is economical to increase electrolyzer capacities in order to enhance the operational flexibility of stations and support leveraging periods of cheap electricity supply. Furthermore, the flexible electrolyzers in scenario B make better use of the low-pressure hydrogen storages at the stations by leveraging their capacity (see Figure 48 in the Appendix). This context is especially benefitial to small station, which decrease their LCOH disproportionally high by leveraging cheap electricity through oversizing electrolyzer capacities. The overall result, despite lower LCOH, is that scenario B has higher investments in the HDV-HRS network from installing larger electrolyzer capacities running at lower utilization.

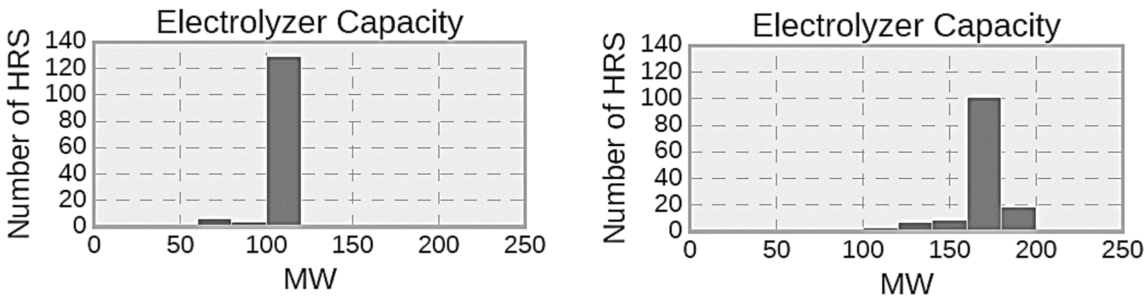


Figure 43: Histograms of electrolyzer capacity for both scenario A (left) and scenario B (right)

This change in station configuration is also reflected in Figure 44, which illustrates the cost share of the individual components. Scenario A shows annual costs of about 8.67 bn€/a, while the annual costs in scenario B accumulate to about 7.70 bn€/a. In both scenarios, there is a predominant cost share of electricity, with about 82 % (scenario A) and about 71 % (scenario B), respectively. Noticeably in scenario B, the annual costs for the electrolyzer increase by 670 million €/a, while the station cost remain constant per definition. The increase of electrolyzer cost as well as the overall cost reduction between scenario A and B raises the annual cost share of the hydrogen refueling infrastructure (stations and electrolyzers) from 18 % to 29 %. This increase is offset by the significant reduction in annual electricity costs of 1.64 bn€/a (from 7.09 bn€/a to 5.45 bn€/a). This highlights that the cost of electricity generation is the main determining factor in the costs of hydrogen production, and that leveraging periods of cheap electricity supply at the expense of oversizing on-site electrolyzers is a sensible economic decision in the assumed market model. Therefore, large electrolyzers are not necessarily a pivotal feature of economic hydrogen refueling stations.

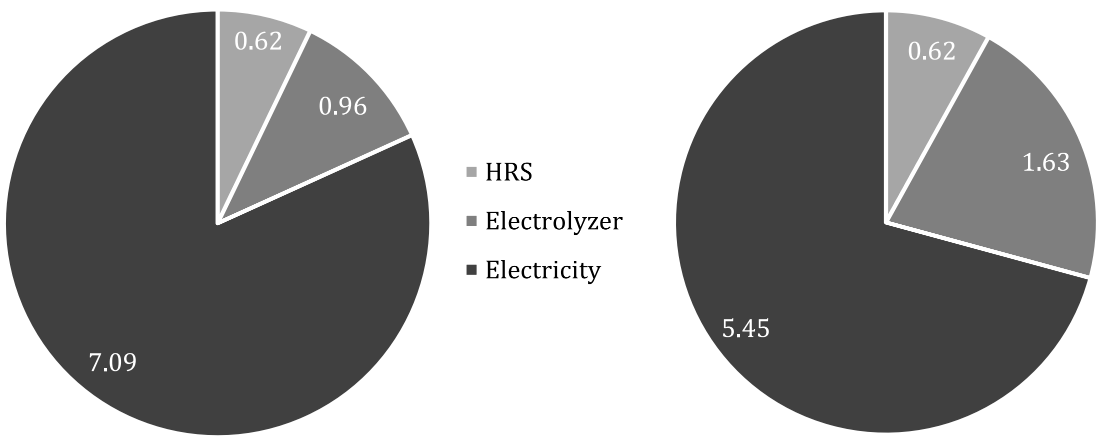


Figure 44: Annual costs[84] of hydrogen refueling infrastructure for scenario A (8.67 bn€/a (left)) and scenario B (7.70 bn€/a (right))

[84] Annual costs include operating and capital expenditures for the HDV-HRS network (electrolyzer, stations) and the electricity required to produce hydrogen (based on LMC). These costs are analyzed from a macro-economic perspective, i.e. without levies, taxes or other surcharges.

6.5 Implications for the electricity system

In both integration scenarios, adding hydrogen refueling stations causes higher total annual system costs in both absolute and relative terms due to the increase in electricity demand of around 65 TWh_{el}. The relative costs of electricity increase because the most productive sites for renewable energy generation have already been exploited to help decarbonize the electricity sector, and additional demand has to be covered by generation at less favorable and therefore less economic locations. The figures referenced in this section are summarized in Table 28 and Table 41 (see Appendix).

In detail, Table 28 shows the main techno-economic results for the (I) stand-alone electricity system without a HRS network, (II) scenario A and (III) scenario B regarding demand, HRS network and the electricity system results. The total annual electricity system demand equals 509 TWh_{el}, and the total annual hydrogen demand sums up to 65 TWh_{el}. Further, the required total electrolyzer capacity in scenario A is around 14 GW, whereas scenario B requires 23.5 GW (+70 %) including a lower capacity factor in scenario B as mentioned in section 6.4. Total electricity production capacities of about 300 GW are required for the stand-alone electricity system, and adding the HRS network requires an additional 60 GW of RE capacities (to cover the additional demand of 65 TWh_{el}). Compared with scenario A, scenario B reduces onshore wind capacity by 12 GW and adds about 10 GW of solar (photovoltaics). This indicates the greater suitability of photovoltaics for flexible hydrogen production compared with other RE potentials.[85]

Table 28 also shows that a considerable line expansion of around 17.9 % of today's volume can be observed even without HRS. Adding HRS increases the necessary grid expansion to more than 21 %, although the grid expansion required in scenario B (9.50 TWkm) is lower than in scenario A (9.69 TWkm). This indicates a better local utilization of local RE potentials in scenario B so that lower electricity network capacities are needed. However, the differences between the two integration scenarios are rather small (less than 2 % difference in absolute volume) and the final regional network loading levels are only marginally different between the considered scenarios. However, adding HRS requires additional network expansion to maintain such loading levels and avoid overexciting network capacities.

Finally, Table 28 also shows the total annual system costs in 2050. Comparing the total annual system costs for scenario B (ca. 48 bn€/a) with scenario A (ca. 49 bn€/a) shows that increasing electrolyzer capacity triggers ca. 0.7 bn€/a savings in other areas. Major savings can be observed in electricity production capacities (ca. 1.0 bn€/a) and electricity system storages (ca. 0.6 bn€/a). Seemingly, a bigger local on-

[85] Details can be found in Table 41 in the Appendix.

site HRS electrolyzer now functions as a storage at times of excess electricity supply from local RE.

Table 28: Summary of annual demand, HRS parameters, electricity system parameters and costs for the German electricity system without HRS, for scenario A and for scenario B in 2050

	Scenario	Without HRS	Scenario A	Scenario B	Unit
Demand	Total annual demand	509.34	574.22	574.22	TWh_{el}
	- Annual electricity demand	*509.34*	*509.34*	*509.34*	*TWh_{el}*
	- Hydrogen refueling demand	*0.00*	*64.88*	*64.88*	*TWh_{el}*
HRS network	HRS electrolyzers	0.00	13.89	23.49	GW
	HRS electrolyzers capacity factors (average)	0	59	35	%
	LCOH (average)	0.00	6.43	5.66	€/kg_{H2}
Electricity system	Electricity capacities	296	363	362	GW
	- Onshore wind	*68*	*97*	*85*	*GW*
	- Solar	*163*	*203*	*213*	*GW*
	Gross electricity generation	550	630	624	TWh_{el}
	Volume of transmission network expansion (relative)	17.9	22.2	21.8	%
	Volume of transmission network expansion (absolute)	7.78	9.69	9.50	TWkm
Annual costs	Total annual system costs (absolute)	40.25	48.92	47.95	bn€/a
	- Electricity capacities	*30.64*	*36.57*	*35.58*	*bn€/a*
	- Electricity storages (battery, hydro & hydrogen)	*7.73*	*8.81*	*8.17*	*bn€/a*
	- Transmission network expansion	*1.88*	*1.96*	*1.95*	*bn€/a*
	- HRS network	*0.00*	*0.62*	*0.62*	*bn€/a*
	- HRS electrolyzers	*0.00*	*0.96*	*1.63*	*bn€/a*
	Total annual system costs (relative)	73.18	77.65	76.84	€/MWh

Figure 45 breaks down these annual costs in more detail, showing the absolute total annual costs as well as the proportions of the transmission network (HV-DC and HC-AC), electricity generation (bio, solar, wind, run-of-river, and hydro), storage (hydrogen and battery), and the HRS network (station and electrolysis). More than 65 % of the total annual system costs consist of solar and wind capacity costs and electricity generation from these sources constitutes the largest absolute cost. Comparing the scenarios shows that a more system-aware planning of HRS can save 2 % of total annual system costs, reducing these from 48.92 bn€/a to 47.95 bn€/a. In relative terms, this corresponds to a reduction in total annual system costs from 77.65 €/MWh to 76.84 €/MWh. However, the differences between scenario A and B are still relatively small in terms of the total annual system costs.[86]

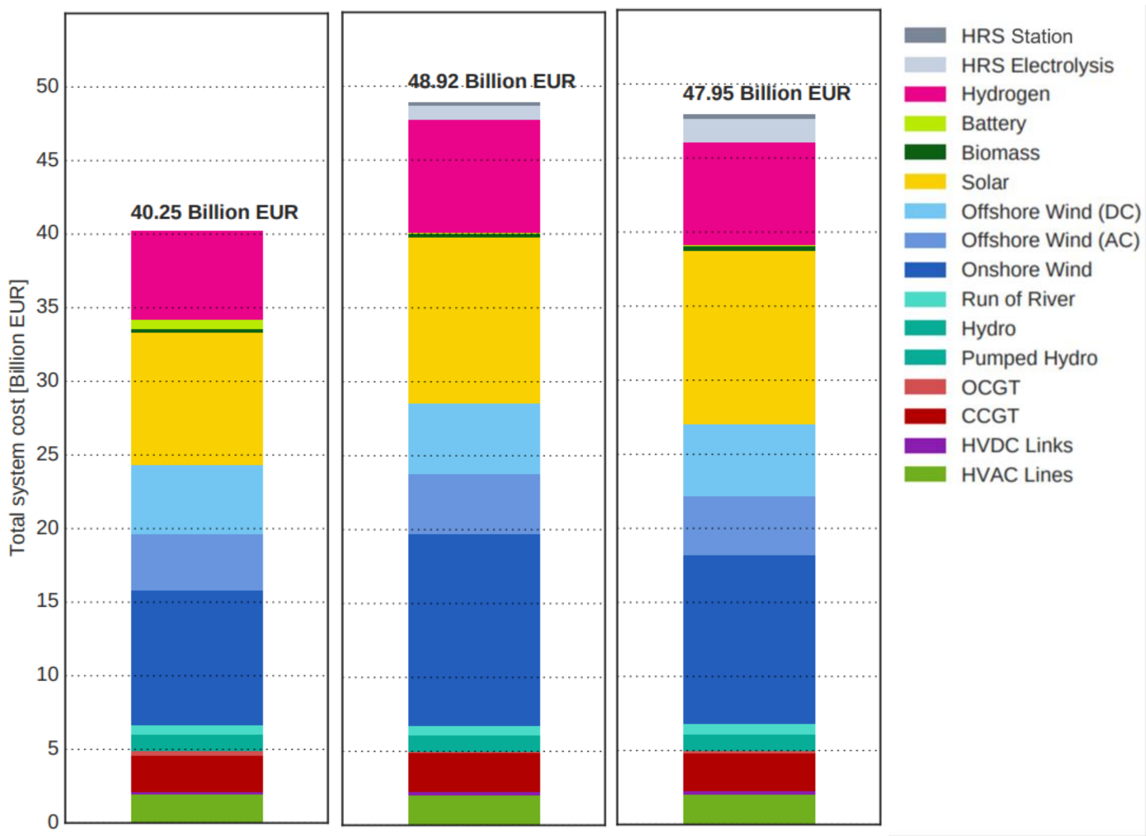


Figure 45: Annual system costs of scenario without HRS (left), scenario A (middle) and scenario B (right)

6.6 Summary of electricity system and station network interaction

This chapter focused on the value of flexibility of a potential HDV-HRS network for the German electricity system in 2050. First and for reference purposes, the electricity-related results of both the NC-FRLM-modeled HDV-HRS network and the PyPSA-modeled German electricity system were described separately. The geo-spatial analysis of the HDV-HRS networks shows strong electricity demand in rural areas, with annually more than one TWh_{el} per NUTS3 area for individual areas. The total electricity demand by the HDV-HRS network sums up to 65 TWh_{el} per year. On the other hand, the electricity system faces an annual electricity demand of 509 TWh_{el}, with large RE capacities in the north and strong demand in the south and west of Germany. Next, the NC-FRLM tool was coupled with the PyPSA tool to quantify the flexibility potential of a HDV-HRS network by deregulating electrolyzer size and operations. The first scenario, an optimization scenario focusing on minimizing HRS

[86] In more detail, especially the annual costs of other storage options can be mitigated by investment planning that takes the entire system into account. These changes can be seen in more detail in Figure 49 in the Appendix.

cost, indicates a high utilization of HRS electrolyzer capacities, but no complete utilization of low-pressure HRS storage capacities. The second scenario, an optimization scenario focusing on minimizing both the HRS network and electricity system cost, shows an oversizing of HRS electrolyzers by about 60 % and intensive utilization of HRS storage capacities. Furthermore, the total system costs in the second scenario are about 1 bn€/a below the first scenario due to the use of larger, flexible electrolyzer capacities leading to better integration of renewable energy, less storage facilities and lower electricity network extension. Finally, the average LCOH at the station are lower in the second optimization scenario by 0.77 €/kg, which is more attractive to users of FC-HDVs.

7. Summary, conclusions and outlook

This chapter gives a summary of the entire thesis. The thesis results are synthesized and conclusions are drawn (section 7.1) followed by a discussion and outlook for future research (section 7.2).

7.1 Summary and conclusions

Heavy-duty traffic is responsible for about eight percent of greenhouse gas (GHG) emissions and is a steadily growing sector. A potential solution to reduce these GHG is to use FC-HDVs powered by hydrogen produced using renewable energy (RE) sources. However, widespread adoption of fuel cell heavy-duty vehicles (FC-HDV) would require a new HRS network and would have major impacts on the electricity sector. This thesis aims at modeling and evaluating a potential hydrogen refueling station (HRS) network for the large-scale adoption of FC-HDVs in Germany in 2050 to answer the research question: *"What is the spatial, technological and economic design of an optimal HDV-HRS network for zero-emission FC-HDVs that meets user requirements and the climate targets for Germany in 2050?"*

A new model-based approach to developing alternative fuel station networks for HDVs is introduced, which generates the required input data and develops a new optimization model. Vehicle and infrastructure user requirements collected for this thesis allow the determination of relevant techno-economic framework parameters, e.g. vehicle efficiency, vehicle range as well as refueling station technical layout and investments. Further, an analysis of several thousand HDV traffic kilometers is conducted to understand current traffic demand and flows. Subsequently, a newly developed NC-FRLM enables the derivation of a potential HRS network. A reference scenario and four scenarios with parameter variations are defined to understand their impact on the design and annual costs[87] of a potential HDV-HRS network for Germany in 2050, e.g. different station capacity limitations, traffic demands, vehicle ranges and different hydrogen distribution options. A link to an open-source electricity model makes it possible to assess what value a flexible hydrogen production for the HDV station network has for the electricity system as a whole.

Using two scenarios, the author aims to understand the value of flexible on-site hydrogen production for integrating growing amounts of RE into an electricity system that meets global climate targets.[88] The following scenario-independent findings refer to the initially proposed research (sub-)questions stated in Chapter 1.

[87] Annual costs include operating and capital expenditures for the stations, electrolyzers and electricity. These costs were analyzed from a macro-economic perspective, i.e. without levies, taxes or other surcharges.
[88] In order to limit global warming to 2°C, GHG emissions must be cut by 95% by 2050 compared with 1990 (IPCC, 2013).

The available literature on HDV decarbonization agrees that, with current policies, the future GHG emissions of the HDV sector will fall short on agreed targets. At the same time, the reviewed literature on HDV decarbonization indicates the need for alternative fuels and powertrains in the HDV stock to meet the GHG emissions targets. This need can be addressed by the introduction of additional (policy) measures supporting the market diffusion of alternative fuels and powertrains in HDVs.

HDV user requirements in Germany are currently rather homogeneous regarding economic and technological requirements but heterogeneous regarding ecological requirements. The collection and analysis of user requirements in expert interviews (n = 15) and an online-survey (n = 63) make it possible to draw conclusions from data, which was not publicly available before. Users unanimously agree on the importance of an economic deployment of their HDVs. Technological requirements, such as range or refueling time, are also considered very relevant. However, ecological requirements are currently less important to users and only considered relevant once they are linked to economic requirements, e.g. GHG emissions and toll charges. Thus, new policy measures that internalize external costs could act as a lever to accelerate the diffusion of AF-HDVs into the (German) market.

HDV-HRS are very different from passenger car HRS in size and expenses. The analysis of user requirements and techno-economic parameters shows that 700 bar hydrogen refueling technology is required for FC-HDVs[89]. In addition, FC-HDVs need about ten times more energy per refuel (50 kg for HDVs vs. 5 kg for passenger cars), which increases the size of the high-pressure hydrogen storage required at the station. Hence, HDV-HRS are generally larger and more expensive than passenger car HRS[90]. Current passenger car HRS are thus not suitable for (a large-scale) market diffusion of FC-HDV.

Modeling alternative fueling infrastructure (AFS) infrastructures for HDVs needs to consider additional requirements compared to passenger car infrastructures. Due to the high energy demand per vehicle, HDV-AFS capacity limitations are inevitable for technological (maximum energy transfer and capacity per station) and legislative reasons (permitted energy storage installations). This new capacity limitation triggers additional adjustments compared with previous passenger car AFS modeling approaches (e.g. a new formulation of path distances and a new formulation of the potential candidate set). Furthermore, due to the long distances driven by HDVs, modeling HDV infrastructure networks preferably spans large node networks (>1,000 nodes) compared with passenger cars AFS, which usually contain smaller networks (<100 nodes).[91]

[89] In order to accomplish the user-required range of 800km for a fully loaded HDV.
[90] HDV-HRS are more expensive than passenger car HRS by a factor of three to five. For example, a size "S" HRS (serving about 40 vehicles per day) requires a total investment of about one million euros for fuel-cell passenger cars and 3.6 million euros for FC-HDVs.
[91] Short trips can be excluded from the analysis as they may not use HDV networks, i.e. highways.

A HDV-HRS network in Germany in 2050 to service 72 million driven HDV kilometers per day has about 140 stations. Considering virtually zero-emission truck traffic in 2050[92] (thus assuming 100 % FC-HDV market diffusion) combined with current legal restrictions (a daily demand cap of 30 tons of hydrogen per location), a potential HRS station network for HDVs would be twice as large as the current passenger car HRS network in Germany, or one third of the number of conventional fueling stations on German highways. As the potential HDV-HRS network is located along highways and mainly in rural areas, it would largely complement the existing passenger car HRS network, as the latter is mainly focused on metropolitan areas.

A station capacity limit lower than 30 tons triggers more homogeneous station sizes to cover the network. Lowering the daily demand cap of 30 tons of hydrogen per location has two effects: First, the network modeling results indicate a negative correlation between capacity limit and the number of stations in the network, i.e. the number of stations increases with lower capacity limits. Second, lowering the capacity limit also triggers a more homogeneous station portfolio, e.g. a 30 tons capacity limit results in a network with almost all sizes from XS to XXL (with 140 stations), while a 7.5 tons capacity limit features only one HDV-HRS station type: size L (with 550 stations).

At low market diffusion of FC-HDV, the relative annual network costs increase significantly.[93] The results show a lower bound of stations – here 100 stations – to serve the given HDV traffic assuming a set-covering approach. With 60 % market diffusion or more, the relative costs of HDV-HRS network remain almost constant ("steady state"). However, with less traffic on the highway network, the lower bound of stations leads to lower utilization of the station network and thus to higher relative costs. Already at 40 % market diffusion, the levelized cost of hydrogen (LCOH) increases by about 1.60 €/kg (or 24 %) compared with 100 % FC-HDV market diffusion (6.50 €/kg).

A potential HDV-HRS network in Germany in 2050 would have total costs[94] of about nine billion euros per year (bn€/a). The actual station and electrolyzer operating and capital expenditures only make up a minor share of the total costs (below 20 %) compared to the cost of providing the electricity to produce the required hydrogen (above 80 %). The resulting average LCOH at the station is about 6.50 €/kg, thereof about 1 €/kg for the station network including electrolysis. The construction and operation of a pipeline network with centralized hydrogen production instead of on-site production could generate savings of about 1 bn€/a, reducing the average LCOH to about 5.60 €/kg, but only if the locational marginal electricity cost (LMC) for centralized hydrogen production could be reduced from 100 to 80 €/MWh or be at least

[92] The national GHG reduction targets in Germany state a 95% GHG emission reduction in 2050 compared with 1990 levels (German Federal Environment Agency, 2019b).
[93] In this context, market diffusion means the actual share of hydrogen demand by FC-HDVs versus the theoretical hydrogen demand if all HDV traffic on German highways ran on hydrogen in FC-HDVs.
[94] Annual costs include operating and capital expenditures for the stations, electrolyzers and electricity. These costs are analyzed from a macro-economic perspective, i.e. without levies, taxes or other surcharges.

20 €/MWh cheaper, respectively. Producing hydrogen at centralized locations and distributing it to the stations via pipelines is a favorable scenario for a high market diffusion of FC-HDVs. This assumes LMC are low and reliable and does not consider the interaction of the HDV-HRS network with the electricity system.

Coupling the HDV-HRS network with the electricity system could reduce the total annual costs by about 1 bn€/a due to the increased flexibility for the station network offered by on-site hydrogen production. Linking the potential HDV-HRS network to an open-source electricity model makes it possible to evaluate the flexibility value of hydrogen production (via electrolysis) for the electricity system. This network adds 65 TWh_{el} demand to the electricity system, amounting to an additional 13 % on top of the current German electricity demand. The results of integrating the potential HDV-HRS network into the electricity system ("sector coupling") indicate oversizing electrolysis capacities in order to minimize the electricity investments needed for the electricity system. In other words, higher investments for electrolysis (about 0.6 bn€/a) are overcompensated by lowering the investments in electricity storages, production capacities and grid expansion and thus electricity costs (about 1.6 bn€/a). This cost reduction due to decentralized flexible hydrogen production is in the same order of magnitude as the centralized hydrogen production previously described.

7.2 Discussion and further research

Comparing the design of the HRS network determined in this thesis with potential passenger car HRS networks for Germany, the author finds a notably smaller network for HDVs, with only about 1 % of the number of stations required (about 140 HRS in this thesis for HDVs vs. 10,500 HRS (cf. Seydel, 2008) and 10,000 HRS (cf. Robinius, 2015; for cars). However, the total hydrogen demand is only 2.3 times higher for passenger cars (65 TWh_{el} for HDVs vs. 150 TWh_{el} for cars (cf. Robinius, 2015)[95]). As a result, there are lower economies of scale for the on-site production of hydrogen at passenger car HRS than for HDV-HRS, and on-site production might be more reasonable for HDV-HRS than for passenger car HRS. On a side note, considering the minor share of 10 % passenger car trips on highways (Altmann et al., 2017), the additional demand due to passenger cars on the HDV-HRS network would increase hydrogen demand by 25 % and thus the HDV-HRS network, too. Furthermore, excluding some origin-destination paths (< 50 km) and isolated highways nodes (e.g. A44 Waldkappel) resulted in a smaller HDV-HRS network. However, as these paths and nodes represent less than 10 % of all nodes and paths, the effect is assumed to be minor.

The average LCOH determined in this thesis (between 5.60 and 6.50 €/kg) are roughly comparable to the LCOHs in other studies of potential passenger car HRS networks in Germany in 2050. These LCOH range from 4.40 €/kg at the lower end (Welder et al.,

[95] This equals about 1.3 million tons hydrogen per year for HDVs or about 3 million tons hydrogen for passenger cars.

2018) through 5.60 €/kg (Robinius et al., 2017b) to 6.80 €/kg at the upper end (Emonts et al., 2019). However, the resulting cost share for the pure station network (about 0.6 bn€/a, without electrolyzer and electricity) in this thesis is significantly lower than in previous studies – by up to a factor of four (Robinius, 2015). This is due to the smaller number of stations required to supply the FC-HDV stock combined with disproportionately lower average costs per station to supply a national HDV fleet versus a passenger car fleet. Furthermore, the low share of infrastructure costs (hydrogen stations and electrolysis) of below 20 % versus the high share of energy costs in the final cost of alternative fuels for HDV applications is in line with previous HDV infrastructure publications on other technologies (Connolly, 2017; Fan et al., 2017; Wietschel et al., 2017).

The results indicate the significant value of integrating a potential HDV-HRS network into the electricity system by showing the relevance of electricity storage compared to transmission infrastructure cost. However, this is only applicable if regulatory approval procedures for on-site hydrogen production are lifted in Germany (BImSchV) and the German single-bidding zone shifts towards a market that implements nodal pricing and is capable of factoring in transmission congestion. If these prerequisites are fulfilled, FC-HDVs (and thus HDV-HRS) have the potential to become one of the largest electricity consumers in Germany.

Other studies (Robinius, 2015; Welder et al., 2018; Emonts et al., 2019) dedicate the most attractive renewable capacities to centralized hydrogen production distributed via pipelines. This thesis contains an additional option: on-site hydrogen production in the context of concurrently decarbonizing the total electricity sector. Comparing these two options, the author finds that both offer similar cost savings of about one billion euros annually. However, flexible on-site hydrogen production enables a better integration of local RE potentials than centralized hydrogen production. Local RE integration is likley to offer increasing benefits when coupling additional sectors with the electricity system (e.g. heating) and thus further driving the demand for RE sources.

Furthermore, the author concludes that total electrification of road-based transport (both road-freight vehicles and passenger vehicles) using hydrogen would require significantly more hydrogen to be produced from electricity. Accordingly, the LCOH could either benefit from (HDV-)HRS economies of scale (although station costs only account for 15-20 % of the LCOH) or from better technology efficiencies (e.g. using high-temperature electrolysis). However, the LCOH could also become more expensive if the marginal cost of electricity from RE increased in Germany, which would lead to higher energy costs, that account for 80 % to 85 % of the LCOH. It is therefore likely that the LCOH determined in this thesis is in a lower range estimate when considering the electrification of other transport modes and other sectors as well as the dominance of electricity consumption costs over initial investments. Other external factors could lead to either an increasing demand for domestically produced hydrogen (e.g. using green hydrogen for the chemical industry) or an increasing supply of hydrogen imports (e.g. from the MENA region). In any case, the co-optimization of multiple energy sectors is important for investment planning in the electricity system, and promises to exploit synergies and offer cost reduction potentials if its components act in concert.

This thesis aimed at modeling and analyzing an optimal HDV-HRS network in Germany in 2050. While the author focused on answering this question, several further fields of research could be identified.

To determine a suitable HRS network and its impacts on the electricity system, better data on the driving and refueling profiles of heavy-duty trucks at national level would certainly improve the model. This involves decoupling driving patterns from consumption patterns as well as retrieving information from a regionally more disaggregated traffic census than the currently available data sets. Further, the traffic data sets with separate HDV coverage are from about a decade ago. More recent data on national and international HDV traffic flows could improve the results.

Moreover, modeling HDV-HRS infrastructure in this thesis uses a perfect foresight approach, which by definition determines the lower limit for investments (cf. chapter 3). Hence, real-life investments may be higher due to unexpected developments during the HRS network ramp-up. Further, the market diffusion of FC-HDVs is assumed to be spatially homogeneous along the origin-destination paths, which may not be the case in real life as some regions or hotspots may feature early adopters. Also, the link to the open-source electricity system tool PyPSA assumes a Brownfield approach for modeling the electricity grid, but a Greenfield approach for future RE power generation (and hence neglects the path towards it). An interesting research topic could be to compare the results of this thesis with an evolutionary ramp-up approach, which considers the path from today to 2050 as well as potential market diffusion hotspots. Furthermore, adding hydrogen pipeline networks directly into the PyPSA asset portfolio and allowing direct competition between electricity grid and hydrogen pipeline capacities could further strengthen the results of this analysis.

Future research could also consider other factors influencing the hydrogen cost at the stations. First, a refined hydrogen supply hub system (consisting of a pipeline network for HRS along main corridors and on-site production for any remaining HRS) could influence the LCOH by exploiting the advantages of both pipelines and local RE integration. In addition, pipeline modeling as well as modeling the connection between the transmission grid and the HRS could be refined in terms of considering existing infrastructures and geography.

Finally, as yet unexplored fields of research could be integrated by broadining the view of the analysis beyond hydrogen-based FC-HDVs, the transport sector and Germany. First, analyzing other alternative fuel and powertrain technologies for HDVs (e.g. battery electric vehicles), their infrastructure and interaction with the electricity system would enhance the understanding of different vehicle technologies and allow a comparison of their potentials. Second, as the electrification of other sectors (such as heating or industry) is not considered, the total electricity demand is a lower bound. In a fully sector-coupled model, the electricity demand of hydrogen refueling stations would be affected by the additional electricity demand resulting from the electrification of other energy sectors. Since all these sectors potentially have to share Germany's geographical power generation potentials and as electricity demand increases, less favorable RE generation sites are also developed, which means the cost of electricity production could rise. Third, extending the infrastructure analysis towards a pan-European observation seems beneficial for two reasons. On the one hand, the thesis results indicate only a minor impact of vehicle range on the potential German HDV-HRS network due to relatively short origin-destination paths. As origin-destination path lengths determine the impact of vehicle range on the station network, longer paths – e.g. in a European analysis – could reveal that vehicle range has a larger impact on the AFS network. On the other hand, the current geographical restriction to Germany may underestimate the required transmission network expansion and overestimate storage expansion due to excluding benefits of power exchange between neighboring countries and continental smoothing of renewable feed-in.

Appendix

Table 29a: Overview of literature model design, scenarios and other model attributes

Author	Model name	Model type	Modeled scenarios
(Ambel, 2017)	EUTRM	Accounting	4 scenarios (BAU, low hanging fruit, LHF + partial, LHF + full)
(Askin et al., 2015)	(no name)	Simulation	2 scenarios (baseline, exaggerated)
(Bahn et al., 2013)	TIMES-Canada	Optimization	3 scenarios (baseline, energy policy, climate policy)
(Bründlinger et al., 2018)	DIMENSION+	Optimization	5 scenarios (Reference, matrix of electrification and
(Çabukoglu et al., 2018)	(no name)	Accounting	3 scenarios (current tech, max. potential, battery swapping)
(Capros et al., 2016)	PRIMES	Simulation	1 scenario (reference)
(Gambhir et al., 2015)	(no name)	Optimization	2 scenarios (BAU, low-carbon)
(Gerbert et al., 2018)	VIEW	Simulation	5 scenarios (reference, matrix of national go-it-alone and
(Kasten et al., 2016)	TEMPS	Accounting	4 scenarios (FI+, E+, CH4+, H2+)
(Liimatainen et al., 2019)	(no name)	Accounting	4 Scenarios (current technology, vehicles, IV & charging, full)
(Mai et al., 2018)	EnergyPathway	Accounting	3 scenarios (reference, medium, high)
(Mulholland et al., 2018)	MoMo	Simulation	2 scenarios (COP21, modern)
(Naceur et al., 2017)	ETP model	Optimization	3 scenarios (RTS, 2DS, B2DS)
(Özdemir, 2011)	TIMES-D	Simulation	4 scenarios (baseline, free market, GHG restriction,
(Plötz et al., 2019)	PERSEUS-EU	Simulation	4 scenarios (matrix of optimistic with pessimistic)
(Repenning et al., 2015)	TEMPS, ASTRA-	Accounting	3 scenarios (baseline, 80%, 95%)
(Seitz, 2015)	(no name)	Simulation	4 scenarios (baseline, CO_2-policy, e-mobility, recession)
(Siegemund et al., 2017)	[none]	[no info]	3 scenarios (PtL, PtG, eDrive)
(Talebian et al., 2018)	(no name)	Accounting	2 scenarios (BAU, CLF)

Table 29b: Overview of literature model design, scenarios and other model attributes

Author	Scenario classification	Other transport modes included?	Macro-economic perspective?
(Ambel, 2017)	BAU scenario is explorative, other 3 are normative	No	Yes
(Askin et al., 2015)	Both scenarios are explorative	No	No
(Bahn et al., 2013)	BAU scenario is explorative, other 2 are normative	Yes	Yes
(Bründlinger et al., 2018)	Reference scenario is explorative, other 4 scenarios are normative	Yes	Yes
(Çabukoglu et al., 2018)	Current technologies scenario is explorative, other 2 are .	Yes	Yes
(Capros et al., 2016)	Reference scenario is explorative	Yes	Yes
(Gambhir et al., 2015)	Both scenarios are normative	Yes	unclear
(Gerbert et al., 2018)	Reference scenario is explorative, other 2 scenarios are normative	Yes	Yes
(Kasten et al., 2016)	All 4 scenarios are normative	Yes	Yes
(Liimatainen et al., 2019)	Current technologies scenario is explorative, other 3 are .	Yes	Yes
(Mai et al., 2018)	Reference scenario is explorative, other 2 are normative	Yes	Yes
(Mulholland et al., 2018)	Reference scenario is explorative, other scenario is normative	No	Yes
(Naceur et al., 2017)	RTS scenario is explorative, other 2 scenarios are normative	Yes	Yes
(Özdemir, 2011)	Base scenario is explorative	Yes	Yes
(Plötz et al., 2019)	Both scenarios are explorative	No	Yes
(Repenning et al., 2015)	Reference scenario is explorative, other 2 scenarios are normative	Yes	No
(Seitz, 2015)	All 4 scenarios are explorative	No	unclear
(Siegemund et al., 2017)	All 3 scenarios are normative	Yes	Yes
(Talebian et al., 2018)	Both scenarios are normative	No	Yes

Table 30: Policy level consideration

Author	Policy level consideration
(Ambel, 2017)	yes, CO_2 emission regulations (no specification)
(Askin et al., 2015)	yes, CO_2 emission regulations (vehicle efficiency) and local pollution (particular matter)
(Bahn et al., 2013)	yes, CO_2 emission regulations and e-vehicle market diffusion regulations
(Bründlinger et al., 2018)	no
(Çabukoglu et al., 2018)	yes, CO_2 emission regulations (no specification)
(Capros et al., 2016)	yes, CO_2 emission regulations (no specification)
(Gambhir et al., 2015)	no
(Gerbert et al., 2018)	yes, CO_2 emission regulations (no specification)
(Kasten et al., 2016)	no
(Liimatainen et al., 2019)	yes, CO_2 emission regulations (no specification)
(Mai et al., 2018)	yes, CO_2 emission regulations (no specification)
(Mulholland et al., 2018)	yes, CO_2 emission regulations (fuel economy regulations, carbon taxes on transport fuels) and local pollution (particular matter)
(Naceur et al., 2017)	yes, CO_2 emission regulations (no specification)
(Özdemir, 2011)	yes, CO_2 emission regulations (no specification)
(Plötz et al., 2019)	yes, CO_2 emission regulations (CO_2-certificate prices, fuel prices)
(Repenning et al., 2015)	yes, CO_2 emission regulations (no specification)
(Seitz, 2015)	yes, CO_2 emission regulations (CO_2-certificate prices)
(Siegemund et al., 2017)	yes, CO_2 emission regulations (no specification)
(Talebian et al., 2018)	yes, CO_2 emission regulations (no specification)

Table 31: Considered AFPs within reviewed literature

Author	Diesel	BEV	BIO	CAT	CNG	eMET	eSYN	FCEV	HEV	LNG	LPG
(Ambel, 2017)	√	√	-	√	-	-	-	√	-	-	-
(Askin et al., 2015)	√	-	-	-	√	-	-	-	-	√	-
(Bahn et al., 2013)	√	-	√	-	-	-	√	√	√	-	-
(Bründlinger et al., 2018)	√	√	-	-	√	√	-	√	√	√	-
(Çabukoglu et al., 2018)	√	√	-	-	-	-	-	-	-	-	-
(Capros et al., 2016)	√	-	-	-	-	-	-	-	-	√	-
(Gambhir et al., 2015)	√	√	-	-	√	-	√	√	√	√	√
(Gerbert et al., 2018)	√	-	-	√	√	-	-	√	√	√	-
(Kasten et al., 2016)	√	√	-	-	-	√	-	√	-	√	-
(Liimatainen et al., 2019)	√	√	-	-	-	-	-	-	-	-	-
(Mai et al., 2018)	√	√	-	-	-	√	-	-	-	-	-
(Mulholland et al., 2018)	√	-	√	√	√	-	-	-	√	√	-
(Naceur et al., 2017)	√	-	-	√	√	-	-	-	√	-	√
(Özdemir, 2011)	√	-	√	-	√	-	-	-	√	-	-
(Plötz et al., 2019)	√	-	-	√	-	-	-	-	-	-	-
(Repenning et al., 2015)	√	-	√	√	√	-	-	-	√	-	-
(Seitz, 2015)	√	√	-	-	√	-	-	-	-	√	-
(Siegemund et al., 2017)	√	-	-	-	-	-	-	√	-	-	-
(Talebian et al., 2018)	√	√	-	-	-	-	-	√	-	-	-
Total	19/19	10/19	4/19	6/19	9/19	4/19	2/19	8/19	8/19	5/19	2/19

Table 32: Market share of AFP in reference scenarios and most competitive AFP

Author	Focus region	Name of reference scenario	AFP share in % (reference scenario)					Most competitive AFP (reference scenario)
		(explorative goal)	2020	2030	2040	2050	2060	
(Ambel, 2017)	EU-28	Business-as-usual	-	-	-	-	-	[none]
(Askin et al., 2015)	USA	Reference	-	3	6	11	-	NGV
(Bahn et al., 2013)	CA	Business-as-usual	-	-	-	-	-	BIO
(Bründlinger et al., 2018)	DE	Reference	-	-	-	-	-	FCEV
(Çabukoglu et al., 2018)	CH	Current technologies	-	-	-	-	-	[none]
(Capros et al., 2016)	EU-28	Reference	0	3	-	8	-	LNG
(Gambhir et al., 2015)	CN	Business-as-usual	0	-	-	20	-	HEV
(Gerbert et al., 2018, 2018)	DE	Reference	0	2	5	9	-	HEV
(Kasten et al., 2016)	DE	Baseline	0	-	-	30	-	HEV or CAT
(Liimatainen et al., 2019)	FIN & CH	Current technologies	-	2	-	-	-	[none]
(Mai et al., 2018)	USA	Reference	-	-	-	0	-	[none]
(Mulholland et al., 2018)	Global	Reference	-	2	-	6	-	HEV
(Naceur et al., 2017)	Global	RTS	-	-	-	-	17	HEV
(Özdemir, 2011)	DE	Baseline	0	0	-	-	-	[none]
(Plötz et al., 2019)	EU-28	Pessimistic	0	17	39	-	-	CAT
(Repenning et al., 2015)	DE	[none]	-	-	-	30	-	BIO
(Seitz, 2015)	DE	Non-intervention	-	-	-	-	-	[none]
(Siegemund et al., 2017)	EU-28	PtL	1	5	10	15	-	eMET
(Talebian et al., 2018)	CA	CLF	0	-	70	-	-	BEV or FCEV

Table 33: Market share of AFP in climate protection scenarios and most competitive AFP. The normative goal describes the objective that is set by the study authors until their final year of forecast, e.g. a 95 % GHG emission reduction (*-95 % CO_2*)

Author	Focus region	Name of climate protection scenario *(normative goal)*	AFP share in % (climate protection scenario) 2020	2030	2040	2050	2060	Most competitive AFP (climate protection scenario)
(Ambel, 2017)	EU-28	LFH + full electrification	1	40	-	-	-	BEV
(Askin et al., 2015)	USA	Exaggerated *(no information)*	-	25	55	60	-	NGV
(Bahn et al., 2013)	CA	CLIM *(-50% CO_2)*	26	-	-	64	-	BIO
(Bründlinger et al., 2018)	DE	EL95 *(-95% CO_2)*	-	31	-	94	-	FCEV
(Çabukoglu et al., 2018)	CH	Battery swapping	1	-	-	100	-	BEV
(Capros et al., 2016, 2016)	EU-28	[none]	0	-	-	-	-	LNG
(Gambhir et al., 2015)	CN	95% Target *(-95% CO_2)*	0	-	-	80	-	HEV
(Gerbert et al., 2018)	DE	95% Target *(-95% CO_2)*	0	25	57	85	-	CAT
(Kasten et al., 2016)	DE	95% Target *(-95% CO_2)*	0	0	80	95	-	CAT
(Liimatainen et al., 2019)	FIN & CH	Towards full electrification	-	-	-	68	-	BEV
(Mai et al., 2018)	USA	High	-	-	-	41	-	BEV
(Mulholland et al., 2018)	Global	Modern *(-95% CO_2)*	-	6	-	70	-	CAT
(Naceur et al., 2017)	Global	B2DS *(-95% CO_2)*	-	-	-	-	91	HEV or CAT
(Özdemir, 2011)	DE	GHG *(-53% CO_2)*	0	3	-	-	-	CNG
(Plötz et al., 2019)	EU-28	Optimistic	0	18	49	-	-	CAT
(Repenning et al., 2015)	DE	All scenarios *(-95% CO_2)*	0	76	100	100	-	CAT
(Seitz, 2015)	DE	[none]	0	15	-	-	-	HEV
(Siegemund et al., 2017)	EU-28	eDrive *(-95% CO_2)*	2	20	55	95	-	FCEV
(Talebian et al., 2018)	CA	Business-as-usual *(-64% CO_2)*	0	-	85	-	-	BEV or FCEV

Expert Interview Guideline

a) Basics:

- Agreed with recording? (Name/Company)
- What is your position/activity in the company?

b) Business:

- In which industry?
- Size of the fleet of heavy trucks (>12t)
- Kilometer driven per year (approx.)?

c) Key questions:

- Do you buy or lease your trucks?
- How long are heavy trucks on average in your traffic?
- What user requirements do you place on a heavy truck? (assuming the diesel truck would be off the market)
- Which requirements must be fulfilled? Which more "Nice-to-have"?
    - What is the minimum range?
    - What power (kW/torque/final speed)?
    - What is the maximum tank duration?
    - What is the minimum payload/capacity?
- [If you could determine three characteristics yourself, what would they be and what would they look like?]
- Rather volume (80%) or weight the decisive residual friction for you (when loading)?
- What role do emission values play in the choice?
- What role does public opinion play in fleet procurement?
- Do you operate trucks with alternative drive systems? If No: Under what conditions would you choose a truck with alternative drive or alternative fuel?
- Have you already decided in favor of alternative drive systems? If so, how far away?
- Would you accept higher costs to reduce the CO2 emissions of your fleet?
- In your opinion, how could you make trucks with alternative drives more interesting?
- What do you think of the offer to make trucks with alternative drives longer?
- What do you think of incentive systems such as: No tolls for electric trucks
- In your opinion, what are the influencing factors for changing user requirements? (e.g. politics, clients)

d) assessment:

- In your opinion, what is the future of heavy long-distance freight transport like? (How would you like to see the future?)
- In your opinion, what are the biggest challenges for alternative drives?

Figure 46: Interview guideline for face-to-face expert interviews

Questionnaire Online Survey Interview Guideline

Welcome to the scientific study of the Fraunhofer Institute in cooperation with the Karlsruhe Institute of Technology on "User requirements in road-bound heavy goods traffic".

We are pleased that you are taking part in the survey! The purpose of the survey is to identify the current requirements of the logistics and freight forwarding industry. These can then be used in the development of innovative drive technologies.

It will take about 20 minutes to complete the survey. Your personal opinion is asked, there are no right or wrong answers. We are looking forward to conscientiously answered questions, as this is the only way to obtain complete and exact research results. If you are interested in the results, we will be happy to send them to you. Simply send us a short e-mail.

The data will of course be treated confidentially, your details will be evaluated anonymously and the results will not allow any conclusions to be drawn about you or your company. Participation in the study is of course voluntary.

Part I: Basic information

1. Does your company use heavy commercial vehicles (with a permissible weight of more than 12 tonnes)?
   a. Yes
   b. no--> Filter: if no do not participate in survey
2. How many commercial vehicles does your company have in its fleet? (Here is the total number of vehicles in all weight classes.)
   a. ___
3. How many commercial vehicles does your company's fleet comprise in the following approximate weight classes? (Here the number of vehicles divided by weight class is to be mentioned.)
   a. Light commercial vehicles <3.5 t___
   b. Medium-duty commercial vehicles 3.5-12t___
   c. Heavy commercial vehicles >12t___

   Info: The questions in the remaining part of the questionnaire relate exclusively to heavy goods vehicles (>12t). As a reminder, this is also pointed out in some places.
4. How are the heavy commercial vehicles (>12t) predominantly procured?
   a. Cash purchase
   b. Financing
   c. Leasing
   d. Rent
5. How many km is the minimum, average and maximum daily mileage of heavy goods vehicles (>12t) approximately?

	0-100km	100-400km	400-800km	>800km	No answer
Min Distance	☐	☐	☐	☐	☐
Max Distance	☐	☐	☐	☐	☐
Average Distance	☐	☐	☐	☐	☐

Figure 47a: Questionnaire of online survey

6. Over what average period do you use the heavy commercial vehicles (>12t)?
    a. <3 years
    b. 3-5 years
    c. >5 years
7. what types of transport tasks does your company carry out mainly with heavy commercial vehicles?
    a. Local freight transport (delivery tours within a certain radius of a location)
    b. Tramp transport (journeys across Germany and Europe; spontaneous route determination through short-term transport orders from the spot market)
    c. Regular services (scheduled departures on fixed routes)
    d. Encounter traffic (two vehicles travelling in the opposite direction on a route meet in the middle, exchange transport containers and drive back to the starting point)
    e. Shuttle traffic (regular short-haul traffic e.g. between two production sites)
    f. Roundabout traffic (fully loaded traffic between two points)
    g. Mixed form of several transport tasks, namely: ____________
    h. Not specified
8. Does the work take place in shifts?
    a. No
    b. Two-shift operation
    c. Three-shift operation
9. How many hours per day do your vehicles stand?
    a. 0-4h
    b. 4-8h
    c. 8-12h
10. The transport takes place predominantly
    a. Regional
    b. National
    c. International
    d. Mixed form, namely __________
11. The following statements in connection with alternative drive and fuel variants apply to me and my company (*Please tick the appropriate drive or fuel variant)*:

	No, never heard	Yes, already heard, but know nothing / hardly anything about it	Yes, already heard and know some / much about	No answer
Catenary-Hybrid-HDV (CAT)	☐	☐	☐	☐
Battery HDV (BEV)	☐	☐	☐	☐
Fuel Cell HDV (FCEV)	☐	☐	☐	☐
Power-to-Gas (PtG)	☐	☐	☐	☐
Natural Gas HDV (CNG and LNG)	☐	☐	☐	☐

Figure 47b: Questionnaire of online survey

Part II: Prioritization via matrix question

1. How important are the following aspects to you in connection with the heavy trucks (>12t) of your fleet? *(Please distinguish on a scale from "important" to "not important"):*

	Important 1	Rather imporant 2	Indifferent 3	Rather not important 4	Not important 5
a. Total-Cost-of-Ownership (TCO)	☐	☐	☐	☐	☐
b. Invest	☐	☐	☐	☐	☐
c. Reliability	☐	☐	☐	☐	☐
d. Fuel consumption	☐	☐	☐	☐	☐
e. Range	☐	☐	☐	☐	☐
f. Infrastructure	☐	☐	☐	☐	☐
g. Loading capacity	☐	☐	☐	☐	☐
h. Interior	☐	☐	☐	☐	☐
i. Power	☐	☐	☐	☐	☐
j. Fueling time	☐	☐	☐	☐	☐
k. Assistance systems	☐	☐	☐	☐	☐
l. Toll classification	☐	☐	☐	☐	☐
m. Environmental protection	☐	☐	☐	☐	☐
n. Avoidance of driving bans	☐	☐	☐	☐	☐
o. Image/Marketing	☐	☐	☐	☐	☐
p. Pressure by client					
q. Other: ___	☐	☐	☐	☐	☐

Figure 47c: Questionnaire of online survey

2. Of the aspects just mentioned, the following five aspects relating to the heavy trucks (>12t) of my fleet are most important to me *(Please select five aspects)*:

r. Total-Cost-of-Ownership (TCO)	☐
s. Invest	☐
t. Reliability	☐
u. Fuel consumption	☐
v. Range	☐
w. Infrastructure	☐
x. Loading capacity	☐
y. Interior	☐
z. Power	☐
aa. Fueling time	☐
bb. Assistance systems	☐
cc. Toll classification	☐
dd. Environmental protection	☐
ee. Avoidance of driving bans	☐
ff. Image/Marketing	☐
gg. Pressure by client	
a. Other: __	☐

Figure 47d: Questionnaire of online survey

Part III: Prioritisation via statements

1. Please indicate below to what extent you agree or disagree with the respective statement from the point of view of your company. Distinguish the degree of agreement on a scale from "do not agree at all" to "fully agree".

	Agree 1	Rather agree 2	Indifferent 3	Rather not agree 4	Not agree 5
a. There is a great willingness in our company to switch to commercial vehicles with alternative drive systems..	☐	☐	☐	☐	☐
b. Consumption values are particularly taken into account when selecting a drive.	☐	☐	☐	☐	☐
c. The failure susceptibility of our commercial vehicles is increased by the use of alternative drives.	☐	☐	☐	☐	☐
d. Low-emission drive technologies are of particular interest to our company for climate protection reasons.	☐	☐	☐	☐	☐
e. The use of alternative drives is good for the image of our company.	☐	☐	☐	☐	☐
f. The current infrastructure of alternative drives impairs the fulfilment of our transport tasks.	☐	☐	☐	☐	☐
g. The tank or loading times of alternative drives have disadvantages in fulfilling our transport tasks.	☐	☐	☐	☐	☐

Figure 47e: Questionnaire of online survey

Part IV: Characteristics of technical requirements

The following section deals with your attitude towards technical aspects related to alternatively powered heavy trucks. Please provide the following information from your company's point of view in relation to heavy trucks in your own fleet.

1. The willingness to make detours due to insufficiently developed infrastructure (petrol stations, overhead lines, charging points) is limited to ... km per journey.
2. The minimum power of a truck should be ...kW or PSe (taking into account increasing vehicle investments with increasing power).
3. A refuelling process should not exceed ... min.
4. The minimum range of a truck should be at least ... km (taking into account increasing vehicle investments with increasing range).
5. Please indicate below to what extent you agree or disagree with the respective statement from your company's point of view. Distinguish the degree of agreement on a scale from "fully agree" to "disagree at all".

	Agree 1	Rather agree 2	Indifferent 3	Rather not agree 4	Not agree 5	I don't know 6
a. Today, fuel is mainly supplied at public petrol stations on the motorway and not at the starting point or destination of the delivery journey.	☐	☐	☐	☐	☐	☐
FILTER: 1.1 If not on the motorway where else? ___						
b. The current number of petrol stations (diesel/petrol) is sufficient.	☐	☐	☐	☐	☐	☐
c. A delivery journey (warehouse - customer - warehouse) is usually shorter than the range of my current heavy trucks.	☐	☐	☐	☐	☐	☐
d. Most drivers know the locations of petrol stations on their way.	☐	☐	☐	☐	☐	☐
e. Most drivers refuel strategically during their breaks.	☐	☐	☐	☐	☐	☐
f. Most drivers refuel strategically during idle times between shifts.	☐	☐	☐	☐	☐	☐
g. Most drivers refuel strategically depending on the conditions of the fuel card used.	☐	☐	☐	☐	☐	☐
h. The number of dispensers is not a relevant aspect when searching for a petrol station.	☐	☐	☐	☐	☐	☐
i. At least one service station should be available directly on the way per delivery journey on a motorway.	☐	☐	☐	☐	☐	☐
j. The loading volume is utilised to the maximum on most journeys.	☐	☐	☐	☐	☐	☐
k. In most cases, the trucks are loaded up to the maximum payload.	☐	☐	☐	☐	☐	☐

Figure 47f: Questionnaire of online survey

Part V: Sensitive basic information

1. The decisive restriction in my industry is above all the...
   a. Volume
   b. Weight
   c. Other, namely: ______
   d. Not specified
2. How many employees does your company currently have?
   a. 1-10
   b. 11-50
   c. 51-100
   d. 101-200
   e. 201-3000
   f. Over 3000
   g. Not specified
3. What type of goods does your company predominantly transport?
   a. No goods
   b. Bulk goods (unpacked)
   c. Container/swap body
   d. Vehicles
   e. Palletized goods
   f. Non-palletized goods
   g. Bound goods
   h. Other forms of cargo, namely:___
4. My personal job description is most likely to apply to the following:
   a. Managing Director
   b. Fleet manager
   c. Tour dispatcher
   d. Driver
   e. Not specified

Figure 47g: Questionnaire of online survey

Table 34: Details on company and fleet characteristics

Question item	Antwortoption	Number	Share in %
Job description	Managing Director	38	60,3
	Fleet Manager	10	15,9
	Tour Dispatcher	3	4,8
	Driver	3	4,8
	No info	9	14,4
Number employees	1 to 10	6	9,5
	11 to 50	16	25,4
	51 to 100	15	23,8
	101 to 200	14	22,2
	201 to 3000	11	17,5
	above 3000	1	1,6
Type of goods	No goods	2	3,2
	Bulk goods (unpacked)	7	11,1
	Container/swap body	3	4,8
	vehicles	0	0,0
	Palletized goods	37	58,7
	Non-palletized goods	3	4,8
	Bound property	0	0,0
	Other forms of cargo	9	14,3
HDV procurement	cash purchase	12	19,0
	funding	28	44,4
	leasing	20	31,7
	rent	3	4,8
Transportation tasks	local freight transport	7	11,1
	tramp traffic	13	20,6
	regular service	7	11,1
	shuttle service	1	1,6
	circular traffic	5	7,9
	hybrid	29	46,0
	not specified	1	1,6

Table 35: Details on expert interviews

Interview Partner Subject - ID Fleet Size of the Company*	Interview Partner Subject - ID Fleet Size of the Company*	Interview Partner Subject - ID Fleet Size of the Company
Managing Director:	S-ID 3	40
	S-ID 7	150
	S-ID 9	154
	S-ID 1	170
	S-ID 10	200
	S-ID 15	400
Senior executives:	S-ID 4	40
	S-ID 2	285
Including fleet management:	S-ID 8	11
	S-D 12	24
	S-ID 5	33
	S-ID 6	43
	S-ID 11	62
	S-ID 13	100
Driver:	S-ID 14	40

Table 36: Exemplary projects of PEM electrolyzers

Project Name	Type	Power [MW]	Hydrogen per day [kg]	Consumption [kWh/Nm^3]	Efficiency [%]	Production Rate [Nm^3/h]	Production Rate [kg/MW]
Nikola HRS (small)	PEM	2	1,000	[unknown]	[unknown]	[unknown]	454.5
Energy Park Mainz	PEM	6	2,031	5.5	50	1006	338.4
REFHYNE	PEM	10	3,500	3.78	79	2160	350.0
HyLYZER	PEM	25	10,092	5	[unknown]	5000	403.6
Nikola HRS (large)	PEM	66	30,000	[unknown]	[unknown]	[unknown]	454.5
HYBRIDGE	PEM	100	34,000	[unknown]	[unknown]	[unknown]	[unknown]

Table 37: Input parameters for mass flow calculation based on (Krieg, 2014)

Parameter	Unit	Value
Density at 9,5°C	[kg/m^3]	5.96
Flow rate	[kg/s]	2.08
Pressure	[bar]	70.00
Speed	[m/s]	15.00

Table 38a: Reference scenario HDV-HRS stations including their location, size and utilization rate

#	Node	Location	Demand [kg]	Capacity [kg]	Utilization [%]
1	93	AS Kodersdorf (93)	3,328	3,750	89
2	1885	Gerolstein	3,619	3,750	96
3	924	AS Mechernich (112)	5,432	7,500	72
4	755	AS Saarbrücken-Gersweiler (12)	6,258	7,500	83
5	1128	AS Bochum-Riemke (16)	7,658	15,000	51
6	18	AS Bingen-Ost (13)	7,658	15,000	51
7	2150	AS Asdonkshof (7a)	8,369	15,000	56
8	911	AS Neheim-Süd (63)	8,755	15,000	58
9	710	AS Schleusingen (4)	8,775	15,000	58
10	2360	AS Reinfeld (25)	9,290	15,000	62
11	776	AS Engen (39)	10,315	15,000	69
12	978	AS Britzer Damm (23)	10,356	15,000	69
13	857	AS Nohfelden-Türkismühle (3)	10,443	15,000	70
14	158	AS Geeste (23)	10,508	15,000	70
15	1250	AK Hegau (A 81)	13,975	15,000	93
16	2369	AS Neuss-Reuschenberg (21)	15,062	30,000	50
17	1336	AS Ihlpohl (15)	17,303	30,000	58
18	392	AN (1)	17,913	30,000	60
19	1830	AS Dessau-Süd (11)	18,176	30,000	61
20	2333	AS Görlitz (94)	18,400	30,000	61
21	1143	AS Sangerhausen-Süd (16)	19,450	30,000	65
22	2159	AK Meckenheim (A 565)	20,037	30,000	67
23	952	AS Rehau-Süd (6)	20,820	30,000	69
24	1426	AK Westkreuz Frankfurt (A 648)	21,647	30,000	72
25	884	AS Worms/Mörstadt (57)	21,763	30,000	73
26	2219	AS Neumünster-Nord (13)	21,856	30,000	73
27	40	AK Dortmund/Witten (A 45/A 44)	24,033	30,000	80
28	1893	AS Hof-West (34)	25,253	30,000	84
29	1817	AS Hagen-West (88)	26,637	30,000	89
30	1020	AS Lüdenscheid-Süd (15)	27,122	30,000	90
31	2319	AS Bad Soden-Salmünster (46)	27,507	30,000	92

Table 38b: Reference scenario HDV-HRS stations including their location, size and utilization rate

#	Node	Location	Demand [kg]	Capacity [kg]	Utilization [%]
32	1339	AS Ober-Mörlen (14)	27,811	30,000	93
33	1602	AS Weiden-Frauenricht (24)	28,297	30,000	94
34	903	AS Alsfeld-Ost (2)	28,335	30,000	94
35	1848	AS Buttenheim (26)	29,445	30,000	98
36	1689	AS Walsrode-West (27)	29,784	30,000	99
37	1440	AS Köln-Wahn (35)	29,835	30,000	99
38	489	AS Arnstadt-Süd (14)	29,864	30,000	100
39	506	AS Köln-Klettenberg (11a)	29,906	30,000	100
40	1081	AS Storkow (3)	29,984	30,000	100
41	1386	AS Porta Westfalica (33)	30,000	30,000	100
42	1237	AK Bielefeld (A 2/A 33)	30,000	30,000	100
43	607	AS Freiburg-Mitte (62)	30,000	30,000	100
44	1688	AS Oelde (21)	30,000	30,000	100
45	616	AS Fürstenwalde-Ost (5)	30,000	30,000	100
46	771	AS Königs Wusterhausen (10)	30,000	30,000	100
47	1312	AK Kamener Kreuz (A 1)	30,000	30,000	100
48	162	AS F-Flughafen (50)	30,000	30,000	100
49	733	AD Potsdam (A 9)	30,000	30,000	100
50	1877	AS Bielefeld-Süd (26)	30,000	30,000	100
51	440	AS Garbsen (41)	30,000	30,000	100
52	867	AS Bockel (49)	30,000	30,000	100
53	1185	AS Leipzig-Nordost (25)	30,000	30,000	100
54	1283	AK Lotte/Osnabrück (A 30)	30,000	30,000	100
55	429	AD Leonberg (A 81)	30,000	30,000	100
56	260	AS Rehren (36)	30,000	30,000	100
57	2012	AS Herten (7)	30,000	30,000	100
58	167	AS Pforzheim-Ost (45a)	30,000	30,000	100
59	2042	AS Nossen-Nord (36)	30,000	30,000	100
60	2351	AS Hamburg-Stillhorn (37)	30,000	30,000	100
61	2086	AS Köln-Dellbrück (26)	30,000	30,000	100
62	1529	AS Bielefeld-Ost (27)	30,000	30,000	100

Table 38c: Reference scenario HDV-HRS stations including their location, size and utilization rate

#	Node	Location	Demand [kg]	Capacity [kg]	Utilization [%]
63	2152	AS Bad Krozingen	30,000	30,000	100
64	988	AS Halle-Ost (18)	30,000	30,000	100
65	2139	AS Passau-Süd (117)	30,000	30,000	100
66	743	AS Groß Ippener (59)	30,000	30,000	100
67	2095	AS Roth (57)	30,000	30,000	100
68	388	AS Mühlhausen (59)	30,000	30,000	100
69	2188	AS Bad Hersfeld (32)	30,000	30,000	100
70	161	AS Hildesheim-Drispenstedt (61)	30,000	30,000	100
71	2237	AS Aalen/Oberkochen (115)	30,000	30,000	100
72	416	AS Schnaittach (48)	30,000	30,000	100
73	699	AS Appenweier (54)	30,000	30,000	100
74	803	AS Velburg (93)	30,000	30,000	100
75	181	AS Bautzen-West (89)	30,000	30,000	100
76	400	AS Manching (63)	30,000	30,000	100
77	562	AS Kelsterbach (49)	30,000	30,000	100
78	2378	AS Weil am Rhein/Hüningen (69)	30,000	30,000	100
79	2317	AS Dachau/Fürstenfeldbruck (78)	30,000	30,000	100
80	2134	AS Scheßlitz (18)	30,000	30,000	100
81	2207	AS Neukirchen (113)	30,000	30,000	100
82	2272	AS Ellwangen (113)	30,000	30,000	100
83	145	AS Alfeld (63)	30,000	30,000	100
84	1979	AS Lichtenfels-Nord (12)	30,000	30,000	100
85	1249	AK Deggendorf (A 92)	30,000	30,000	100
86	112	AS Erlangen-Tennenlohe (84)	30,000	30,000	100
87	713	AS Northeim-Nord (69)	30,000	30,000	100
88	893	AS Stetten (18)	30,000	30,000	100
89	1072	AS Weißenfels (20)	30,000	30,000	100
90	1665	LG (BW/BY)	30,000	30,000	100
91	645	AK Mutterstadt (A 65)	30,000	30,000	100
92	5	AS Sinsheim (33)	30,000	30,000	100
93	230	AD Rüsselsheimer Dreieck (A 60)	30,000	30,000	100
94	250	AK München-Ost (A 94)	30,000	30,000	100

Table 38d: Reference scenario HDV-HRS stations including their location, size and utilization rate

#	Node	Location	Demand [kg]	Capacity [kg]	Utilization [%]
95	1092	AS Zierenberg (67)	30,000	30,000	100
96	21	AS Hannover-Bothfeld (45)	30,000	30,000	100
97	1205	AS Freising-Mitte (7)	30,000	30,000	100
98	1965	AS Würzburg-Heidingsfeld (70)	30,000	30,000	100
99	1717	AS Wiesentheid (75)	30,000	30,000	100
100	1108	AS Vöhringen (123)	30,000	30,000	100
101	2305	AS Betzigau (135)	30,000	30,000	100
102	1211	AS Straubing (106)	30,000	30,000	100
103	1862	AS Flensburg (3)	30,000	30,000	100
104	389	AS Wörth a.d. Donau-Ost (104b)	30,000	30,000	100
105	265	AS Rottenburg (29)	30,000	30,000	100
106	601	AS Nabburg (30)	30,000	30,000	100
107	975	AS Neudietendorf (44)	30,000	30,000	100
108	1759	AS Heilbronn/Untereisesheim (36)	30,000	30,000	100
109	1507	AS Garlstorf (40)	30,000	30,000	100
110	870	AS Rohrbrunn (64)	30,000	30,000	100
111	1192	AS Herrieden (51)	30,000	30,000	100
112	2151	AS Gräfelfing (36b)	30,000	30,000	100
113	1288	AS Allersberg (55)	30,000	30,000	100
114	2332	AS DU-Häfen (12) (Am Schlütershof)	30,000	30,000	100
115	1311	AS Seeshaupt (7)	30,000	30,000	100
116	223	AS Bad Brückenau/Wildflecken (95)	30,000	30,000	100
117	1883	Grenze Görlitz (95)	30,000	30,000	100
118	1374	AS Hünxe (7)	30,000	30,000	100
119	1504	AS Hamm (18)	30,000	30,000	100
120	1774	AS Oberhausen-Königshardt (2)	30,000	30,000	100
121	1664	AK Bad Oeynhausen (A2/A 30)	30,000	30,000	100
122	2162	AS Herford-Ost (30)	30,000	30,000	100
123	1551	AS Peine (52)	30,000	30,000	100
124	1575	AS Ibbenbüren (11b)	30,000	30,000	100
125	2136	AK Ratingen-Ost (A 44)	30,000	30,000	100

Table 38e: Reference scenario HDV-HRS stations including their location, size and utilization rate

#	Node	Location	Demand [kg]	Capacity [kg]	Utilization [%]
126	955	AS Stapelfeld (29)	30,000	30,000	100
127	1243	AS Calbe (8)	30,000	30,000	100
128	813	AD Neuenburg (A 5)	30,000	30,000	100
129	1291	AD Dernbach (A 48)	30,000	30,000	100
130	1511	AS F-Süd (51)	30,000	30,000	100
131	1949	AS Alleringersleben (64)	30,000	30,000	100
132	716	AS Braunschweig-Ost (57)	30,000	30,000	100
133	1681	AS Wunstorf-Kolenfeld (39)	30,000	30,000	100
134	2311	AS Irxleben (67)	30,000	30,000	100
135	800	AS Dreieck Hittistetten (122)	30,000	30,000	100
136	648	AS Hengersberg (111)	30,000	30,000	100
137	2117	AK Offenbacher Kreuz (A 661)	30,000	30,000	100

Table 39: The effect of node-capacity limit on traffic flow (100 %, 80 %, 60 % and 40 %) regarding HRS portfolio composition; colors: green indicate fewer stations, while red indicates more stations

Capacity Limit	**Traffic Demand**	**HRS Size**							**∑ *HRS***
		> XXL	**XXL**	**XL**	**L**	**M**	**S**	**XS**	
No limit	100 %	51	20	13	12	2	1	1	***100***
	80 %	40	17	26	9	3	2	3	***100***
	60 %	32	22	23	13	4	5	1	***100***
	40 %	20	21	16	23	9	7	4	***100***
60	100 %	66	19	11	2	1	1	-	***100***
	80 %	52	23	12	7	3	3	-	***100***
	60 %	38	21	19	12	8	1	1	***100***
	40 %	19	22	21	18	14	3	3	***100***
30	100 %	-	121	12	2	2	-	-	***137***
	80 %	-	104	13	2	2	-	-	***121***
	60 %	-	84	15	2	3	-	-	***104***
	40 %	-	60	21	11	6	2	-	***100***
15	100 %	-	-	276	-	-	-	-	***276***
	80 %	-	-	222	-	-	-	-	***222***
	60 %	-	-	168	-	-	-	-	***168***
	40 %	-	-	114	6	1	-	-	***121***
7.5	100 %	-	-	-	552	-	-	-	***552***
	80 %	-	-	-	443	-	-	-	***443***
	60 %	-	-	-	333	-	-	-	***333***
	40 %	-	-	-	222	-	-	-	***222***

Table 40: The effect of node-capacity limit, vehicle range (400km, 600km, 800km and 1,000km) and traffic flow (100 %, 80 %, 60 % and 40 %) on HRS portfolio composition; colors: green indicate fewer stations, while red indicates more stations

			Vehicle range and traffic flow															
			400km				600km				800km				1000km			
			100%	80%	60%	40%	100%	80%	60%	40%	100%	80%	60%	40%	100%	80%	60%	40%
Capacity limit and HRS portfolio	no limit	> XXL	54	43	23	11	46	37	30	17	51	40	32	20	48	41	29	16
		XXL	43	42	40	23	26	26	24	23	20	17	22	21	22	19	20	25
		XL	20	30	43	35	24	21	19	24	13	26	23	16	10	15	25	23
		L	12	12	15	41	6	14	20	19	12	9	13	23	11	15	12	16
		M	3	4	9	13	2	4	5	11	2	3	4	9	5	8	6	10
		S	1	1	2	6	1	2	3	6	1	2	5	7	3	2	5	7
		XS	-	1	1	4	1	2	5	6	1	3	1	4	1	-	3	3
		∑ HRS	***133***	***133***	***133***	***133***	***106***	***106***	***106***	***106***	***100***	***100***	***100***	***100***	***100***	***100***	***100***	***100***
	60	> XXL	62	45	25	12	64	53	38	14	66	54	38	19	65	52	37	18
		XXL	42	37	36	24	26	28	24	33	20	24	21	22	24	25	22	23
		XL	18	35	35	39	10	16	20	21	12	12	19	21	7	12	20	22
		L	8	8	17	35	4	4	15	21	2	10	12	18	4	11	13	21
		M	2	6	10	11	1	2	5	11	-	-	8	14	-	-	6	9
		S	1	1	7	8	1	2	3	1	-	-	1	3	-	-	1	4
		XS	-	1	3	4	-	1	1	5	-	-	1	3	-	-	1	3
		∑ HRS	***133***	***133***	***133***	***133***	***106***	***106***	***106***	***106***	***100***	***100***	***100***	***100***	***100***	***100***	***100***	***100***
	30	XXL	121	109	72	44	121	115	81	54	121	104	84	60	121	113	85	61
		XL	11	17	39	40	11	8	20	25	12	13	15	21	12	6	11	18
		L	3	5	15	22	2	-	5	22	2	2	2	11	2	1	5	13
		M	3	4	6	17	2	-	1	4	2	2	3	6	2	1	3	6
		S	1	2	2	8	1	-	1	1	-	-	-	2	-	-	-	2
		XS	-	-	1	5	-	-	-	-	-	-	-	-	-	-	-	-
		∑ HRS	***139***	***137***	***135***	***136***	***137***	***123***	***108***	***106***	***137***	***121***	***104***	***100***	***137***	***121***	***104***	***100***
	15	XXL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		XL	277	220	164	113	276	223	169	115	276	222	168	114	276	222	168	114
		L	1	2	8	20	-	-	-	6	-	-	-	6	-	-	-	6
		M	-	-	1	5	-	-	-	2	-	-	-	1	-	-	-	1
		S	-	-	-	1		-	-	-	-	-	-	-	-	-	-	-
		XS	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-
		∑ HRS	***278***	***222***	***173***	***141***	***276***	***223***	***169***	***123***	***276***	***222***	***168***	***121***	***276***	***222***	***168***	***121***
	7.5	XXL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		XL	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		L	554	442	332	221	552	443	333	223	552	443	333	222	552	443	333	222
		M	-	2	2	3	-	-	-	-	-	-	-	-	-	-	-	-
		S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		XS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		∑ HRS	***554***	***444***	***334***	***224***	***552***	***443***	***333***	***223***	***552***	***443***	***333***	***222***	***552***	***443***	***333***	***222***

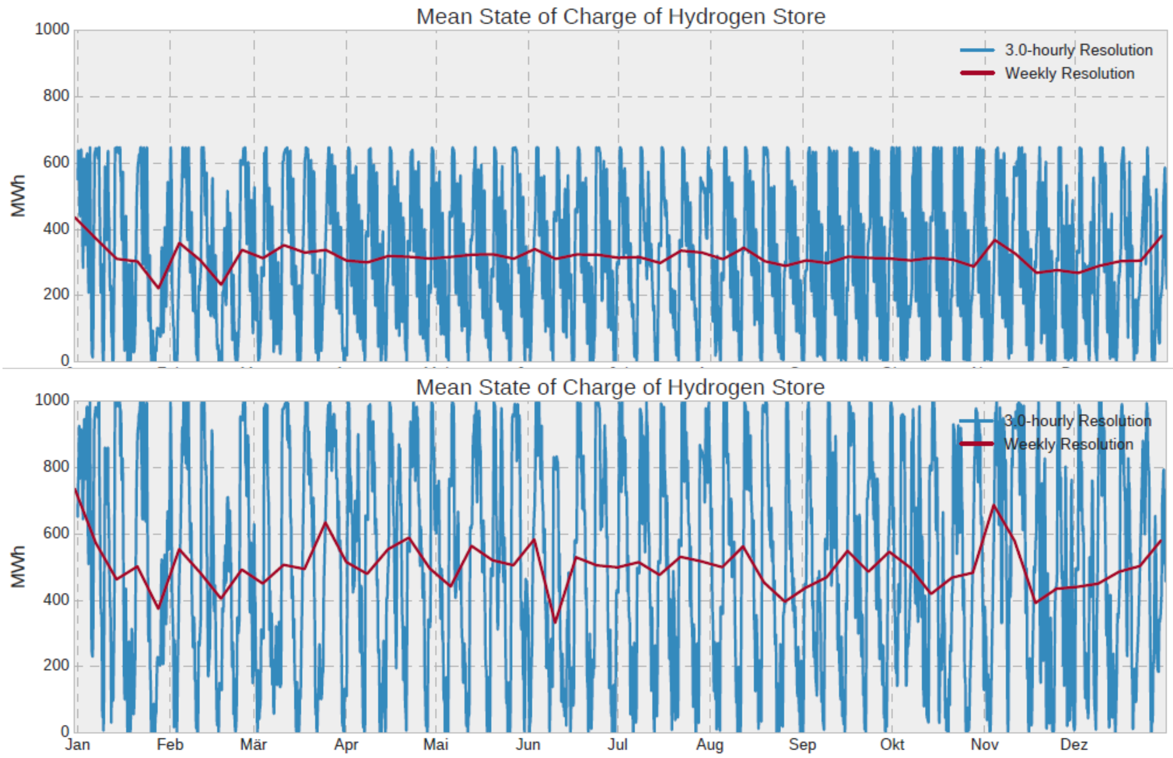


Figure 48: Mean state of charge of LP hydrogen storages at the HRS for scenario A (top) and scenario B (bottom)

Table 41: Overview of capacities and energy demand per source of renewable energy for the German electricity system without HRS, for scenario A and scenario B for Germany in 2050

	Without HRS			Scenario A			Scenario B		
	Capacity [GW]	Energy [TWh_{el}]	Energy [%]	Capacity [GW]	Energy [TWh_{el}]	Energy [%]	Capacity [GW]	Energy [TWh_{el}]	Energy [%]
CCGT	16	45	8.6	18	48	7.9	17	46	7.8
OCGT	6	3	0.5	1	0	0.1	3	2	0.3
Biomass	1	6	1.1	1	6	0.9	1	6	0.9
Offshore wind (AC)	19	72	14	20	74	12.3	20	75	12.6
Offshore wind (DC)	20	86	16.5	20	84	14	20	85	14.3
Onshore wind	68	177	30.2	97	223	33.8	85	216	31.3
Run-of-river	3	18	3.5	3	18	3	3	18	3.1
Solar	163	143	25.7	203	177	27.9	213	186	29.7
Total	296	550	100	363	630	100	362	624	100

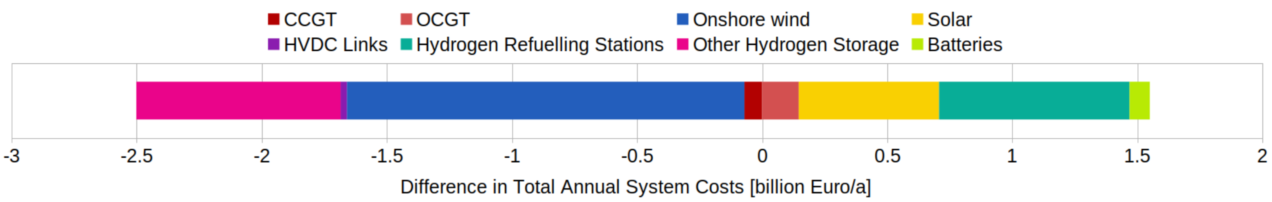


Figure 49: Difference in total annual system cost (scenario B compared to scenario A)

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