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Cost of a potential hydrogen-refueling network for heavy-duty vehicles with long-haul application in Germany 2050

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Abstract

Long-distance road-freight transport emits a large share of Germany's greenhouse gas (GHG) emissions. A potential solution for reducing GHG emissions in this sector is to use green hydrogen in fuel cell electric vehicles (FC-HDV) and establish an accompanying hydrogen refueling station (HRS) network. In this paper, we apply an existing refueling network design model to a HDV-HRS network for Germany until 2050 based on German traffic data for heavy-duty trucks and estimate its costs. Comparing different fuel supply scenarios (pipeline vs. on-site), The on-site scenario results show a network consisting of 137 stations at a cost of 8.38 billion € per year in 2050 (0.40 € per vehicle km), while the centralized scenario with the same amount of stations shows a cheaper cost with 7.25 billion euros per year (0.35 € per vehicle km). The hydrogen cost (LCOH) varies from 5.59 €/kg (pipeline) to 6.47 €/kg (on-site) in 2050.

Keywords (max. 6): Long-haul trucks, heavy-duty vehicles, alternative powertrain, fuel cell, green hydrogen, hydrogen refueling network

Word count: 9,614 words

Declaration of interest: none

Abbreviations

AF-HDV	Alternative Fuel Heavy-Duty Vehicle
FC-HDV	Fuel Cell Heavy-Duty Vehicle
BEV	Battery Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FRLM	Flow refueling location model
GHG	Greenhouse Gas
H2	Hydrogen
HDV	Heavy-Duty Vehicle
HRS	Hydrogen Refueling Station
ICE	Internal Combustion Engine
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
NC-FRLM	Node-capacitated flow refueling location model
OD	Origin Destination
OEM	Original Equipment Manufacturer
TCO	Total Cost of Ownership
ttw	Tank-to-wheel
TRL	Technology Readiness Level

1 Introduction

Greenhouse gas (GHG) emissions need to be sharply reduced to minimize the impact of global warming on humans and the environment [1]. The transportation sector is a significant contributor to global energy-related CO_2 emissions, accounting for around 24% in 2019. In particular, heavy-duty vehicles (HDV) amount for a substantial and increasing share of approximately 40% of the transportation sector [2] globally, and about 28% in Germany [3].

One option to reduce GHG is to replace diesel-fueled HDVs, which account for nearly 100% of the current stock of HDVs [4], with Alternative Fuel Heavy-Duty Vehicles (AF-HDVs). Current research within more progressive climate protection scenarios shows that AF-HDVs dominate the market, indicating the positive influence of AF-HDV on CO_2 reductions [5]. Within this segment, the most significant potential for AF-HDV is in vehicles using public refueling infrastructure rather than in closed fleet systems [6].

One option is the utilization of fuel cell electric HDVs (FC-HDVs), which use onboard hydrogen storage generating electricity within a fuel cell. This is one of three main options for carbon-free driving using hydrogen produced from renewable energy. The other two are synthetic fuels and battery electric trucks [69 – 74]. Compared to HDVs using synthetic e-fuels, FC-HDVs are more energy-efficient and would thus require less renewable energy for complete decarbonization. The energy density in an onboard hydrogen tank is lower and they also require a new refueling infrastructure (see e.g. [69]). Compared to battery electric trucks (charged at charging stations or en route via a catenary), FC-HDVs have a lower energy efficiency and would thus require more renewable energy than electric trucks (see e.g. [71]). In contrast, the FC-HDVs obtain a higher gravimetric energy density than battery electric trucks. This paper thus explores more detail on FC-HDVs, specifically on the FC-HDVs specifications and their infrastructure requirements.

Currently, multiple FC-HDVs have been announced or are already in prototype operations in various projects, with the hydrogen usually stored at gaseous state with 350 or 700 bar (see Table 1). Presently, the use of liquified hydrogen (LH2) for trucks is also gaining more attention, however the feasibility of using LH2 is limited to large-scale export (and thus import) option [78]. Other studies also shown that the gaseous hydrogen supply-chain is potentially the cheapest option in Germany [79,80] when disregarding liquid hydrogen imports.

OEM / Chassis	Year announced	Tank volume	Weight (Max.)	Drive Power	Range (max.)	Country	Source
Hyundai	2018	33kg$_{H2}$	34t	350kW	400km	Switzerland	[7]
Iveco	2018	50kg$_{H2}$	36t	400kW	800km	Germany	[8]
Kenworth	2018	50kg$_{H2}$	36t	500kW	800km	USA	[9]
Kenworth	2017	20kg$_{H2}$	36t	415kW	250km	USA	[10]
MAN	2016	35kg$_{H2}$	34t	250kW	400km	Germany	[11]
Nikola Motors	2017	100kg$_{H2}$	36t	735kW	1,600km	USA	[12]
Scania	2018	35kg$_{H2}$	27t	-	500km	Sweden	[13]
VDL	2018	30kg$_{H2}$	44t	160kW	350km	Netherlands	[14]
Mercedes	2019	900kg$_{Diesel}$	40t	460kW	1,200km	Germany	[15]
Mercedes	2020/2021	80kg$_{H2}$	40t	-	1,000km	Germany	[75]
Nikola Motors	2021	-	36t	250kW	805-1,207km	USA	[81]

Table 1: List of current FC-HDV prototype operations including technical details (an average diesel HDV is added in the last line for reference purposes)

Similar to passenger FCEVs, FC-HDVs require an accompanying hydrogen refueling station (HRS) infrastructure. Establishing a novel HRS infrastructure is associated with high investments and low utilization in the early adoption period [16][1]. Conceptualizing optimal HRS network designs helps to overcome these challenges.

As the diffusion of FC-HDVs is a potential lever for significant CO_2 reductions and fuel cell technology may be a path towards HDV decarbonization, analyzing the cost of a public refueling infrastructure is beneficial for future research and fuel cell truck deployment. To the best of our knowledge, this work is the first to analyze a potential hydrogen supply and to provide a cost analysis of a public HRS infrastructure for the HDV sector on a national level.

This work aims to determine the cost of a HDV-HRS network in Germany using a two-step approach and addresses the following research questions:

- Where should HDV-HRS be located on German highways? We aim at determining the optimal refueling station locations and their size in order to meet the demand of total (domestic and international) HDV traffic in Germany.
- What are the costs of a potential German HDV-HRS infrastructure? Based on the determined optimal locations, we aim at deriving the HRS cost per location.
- What is the most cost-efficient way to produce green hydrogen (central vs. local)? Comparing different scenarios of hydrogen production and distribution (pipeline vs. on-site) helps us to determine the most cost-effective hydrogen supply for the HRS network.

The scope of our work is focused on gaseous hydrogen that is locally produced in Germany (excluding the import of hydrogen from other countries). The work is structured as follows: First, we provide a literature review in Section 2 before we introduce our technical approach in Section 3. We describe the data sources, data collection, and processing procedure in

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[1] This may be different in a place like China, which dictates a certain number of FC buses (or HDVs) in the future. As a result, utilization is higher here than it would be in a "free market" system.

Section 4. Section 5 contains our results. We close with conclusions and suggestions for further research in Section 6.

2 Literature Review

This work is different from others in each of the three following categories: method, transport segment, and technology. Hence, we subsequently consider the current literature in these fields.

Based on the modeling of AFS infrastructure studies, weekly energy transfer can be better performed using demand-driven location methods rather than strategic location methods [17]. Thus, the research on infrastructure cost modeling focuses on demand-driven facility location problems. The facility location problem can be classified into seven research streams: p-median, set covering problem, maximal covering location problem, flow interception location problem, flow refueling location problem, network interdiction problem, and sensor problem [18]. The flow refueling location problem is common in the road transportation sector, and often solved using the flow refueling location model (FRLM) [19]. The FRLM is based on the flow capturing location model (FCLM) [20], which uses Origin-Destination (OD) trips to depict the demand flow within the network. Compared to the FCLM, the FRLM takes into account the maximum driving range of vehicles [18,19,21], which is an important factor for alternative-fueled vehicles. The objective of FRLM can be either to maximize the number of trips covered (maximum covering), or to minimize the required facilities to serve the given demand (set covering) [22]. Current studies have extended the FRLM to solve more complex issues in AFS network development, including our previous work that addresses the problem of maximum capacity restriction to build a single HRS in a single node and solves the problem using an extension of FRLM called NC-FRLM [23].

Despite a growing interest in AF-HDVs as an alternative to diesel trucks, the literature on HDV refueling infrastructure research is limited. Fan et al. analyze the potential liquefied natural gas (LNG) infrastructure for HDVs in the US and recommend focusing initially on the highest volume freight routes when promoting an AF [24]. Within a set covering approach, they determine the most profitable HDV-LNG network and discover only a minimal number of stations to be useful. 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 the required station availability to serve a significant amount of HDV traffic demand suggest that infrastructure development needs to be pre-funded by public authorities or a public-private partnership in order to evolve. The study gives neither a detailed analysis of the overall cost of the HDV-LNG infrastructure nor the individual cost per charge or km. Wietschel et al. determine infrastructure build-up and market diffusion for catenary HDVs in Germany [3]. They use a set covering approach, defining highway corridors with similar traffic demand that are to be equipped with catenary lines. Even though the technology is found to be the most efficient way to decarbonize HDV traffic, Wietschel et al. also conclude that the large upfront infrastructure investments represent a high barrier to market entry. In sum, they calculate the infrastructure installation costs at about two to 23 billion euros, with an additional maintenance cost of about 40 to 400 million euros per year. Conolly also analyzes the catenary technology (he calls this "eRoads," meaning the power cables could be installed either above or below the vehicle), and determines its cost for the Danish passenger and freight vehicle market [25]. He also follows a maximum coverage approach, assuming an eRoad infrastructure network of 2,700km. Conolly finds eRoad infrastructure to be cheaper than conductive charging infrastructure for Battery Electric Vehicles (BEV) with installation investments of 4 billion euros and annual costs of 80 to 850 million euros (covering installation and maintenance). Further, Kuby et al. modeled an optimal European network of LNG-HDV stations and find the most effective station allocation to be a cluster in Germany due to the high traffic flow density here [26]. However, none of the existing studies has determined the design or the cost of national FC-HDV infrastructure (cf. Table 2).

Author	*Covering type*	*Sector*	*Technology*	*Country*	*Infrastructure amount*	*Source*
Fan et al. 2017	*Set covering*	*Only HDV*	*Natural Gas*	*US*	*6 - 80 stations [highways]*	*[24]*
Wietschel et al. 2017	*Maximum covering*	*Only HDV*	*Catenary*	*GER*	*1,000 - 8,000 km [highways]*	*[3]*
Conolly 2017	*Maximum covering*	*All passenger and freight vehicles incl. HDV*	*eRoads*	*DK*	*2,700km*	*[25]*

Table 2: Overview of HDV infrastructure literature

While little work has been done on FC-HDV infrastructure, the research provides insights for passenger vehicle refueling networks. Alazemi and Andrews review the current state of all existing HRS in 2013, which mainly serve passenger cars and LDVs but also buses [27]. Of those 224 HRS, 109 stations have on-site hydrogen production, and 59 obtain hydrogen from a central production facility via trailer delivery (the production method for 56 stations cannot be identified). Most HRS are installed in the US (62), Japan (23) and Germany (22). The largest HRS has a daily capacity of 600kg and is able to dispense max. 30kg at a time. None of the stations is designed for HDV applications. Seydel developed a model for the build-up of hydrogen refueling infrastructure for the German national transport sector [28]. He estimates about 10% of the traffic to refuel at highway stations. Besides analyzing refueling stations, Seydel also considers hydrogen production and distribution, and determines investments accordingly. He projects the HRS network in Germany using a set covering approach and determines an infrastructure investment of 21 billion euros for 7.5 million passenger cars and light-duty vehicles (LDV). Other studies show similar results for a relative share of HRS per vehicle [29]. For passenger FCEVs, recent studies already focus on optimal HRS sizing to decrease on-site hydrogen production costs, finding that HRS oversizing for future applications does not increase the costs significantly [30]. On the other hand, they also focus on optimizing the hydrogen production and delivery process, finding that hydrogen delivery in a liquid state is neither cost-effective nor feasible with the current technology due to high liquefaction costs [31]. The first to conduct research explicitly on FC-HDV infrastructure are Elgowainy and Reddi, who focused on the design of HDV-HRS [32]. They underline the difference between LDV and HDV hydrogen refueling, develop a refueling model for HDVs, and evaluate the impact of key parameters on the refueling cost of FC-HDV.

3 Approach

The infrastructure design and cost of a HDV-HRS network for German highways in 2050 is projected using a two-step approach: determining the optimal station locations and calculating the total costs required to build and operate all the HRS in Germany in 2050. The two-step approach was taken due to our main objective to identify the optimal HRS network configuration based on customer satisfaction rather than to optimize the total cost required to build the infrastructure itself. In addition, two different scenarios are applied: a decentralized scenario, where hydrogen is produced on-site and thus each of the HRS is equipped with a certain size of electrolyzer, and a centralized scenario, where hydrogen gas is supplied through pipelines from several centralized electrolyzer sites. The two-step approach permits that the optimal HRS network configuration can remain the same for both scenarios, the only difference lies in hydrogen production and distribution costs.

First, the optimal HRS locations are defined using the NC-FRLM model from our previous study [23], which is based on one of the most comprehensive surveys of domestic road traffic in Germany [38]. A total of 4,103 trips are completed by HDVs (the same trailer and tractor truck weight categories as in [36]), the focus of this work. Compared to our previous study [23], we additionally synthesize transit and border traffic flow (= international traffic) in this paper by subtracting the domestic traffic flows of data set [38] from the total HDV traffic of the data set [36]. These transit routes represent a significant share of about 40% of the HDV traffic on German highways, most likely due to Germany's central location in the European Union. As the market diffusion of alternative power train for trucks could reach 100% in 2050 [5], it is assumed that all long-haul trucks will be FC-HDVS (thus 100% penetration scenario) in this study. Further details of the NC-FRLM is described in section 3.1.

The total cost of the HDV-HRS network consists of total capital expenditures (CAPEX), e.g. low-pressure hydrogen storages or compressors, total fixed operational expenditures

(OPEX), e.g. maintenance, and the total fuel/electricity cost to generate hydrogen from the electrolyzer. Further details on the calculation of HDV-HRS is explained in section 3.2.

Overall, this work differs from our previous study in [23] in terms of the traffic data used, the HRS network cost estimation and the additional scenario analysis with two scenarios for hydrogen supply - centralized plus pipeline and onsite at the refueling stations.

3.1 Node-capacitated FRLM (NC-FRLM)

The node-capacitated flow refueling location model (NC-FRLM) was developed in our previous study [23], and is used to identify the optimal HDV-HRS locations on German highways [23]. It is a flow-based, demand-driven model that considers hydrogen demand from HDVs on a regional scale. The concept of flow-based demand closely resembles the behavior of heavy-duty long-haul freight trucking operations, since truckers mostly refuel in stop locations en route to their destination [76]. The traffic flows are defined in the form of OD (Origin – Destination) paths, which will be further described in section 4.1. Hydrogen demand is determined based on HDV traffic data, FC-HDV powertrain efficiency, and FC-HDV market diffusion that are used as input to forecast the local hydrogen demand on a NUTS3[2] level. Further, we estimated the refueling demand using data from section 4.1, while the data from section 4.2 characterize the vehicle and facility type.

The formulation of the model can be seen in the following

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

Subject to:

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[2] 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).

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

$$\sum_{q\epsilon Q}[f_q \cdot y_q \cdot r_{iq} \cdot p \cdot g_{iq} \cdot x_{iq}] \leq c\, z_i, i \in N \tag{3}$$

$$\sum_{i\epsilon K^q_{jk}} x_{iq} = y_q, \forall q \in Q, a_{j,k} \in A_q \tag{4}$$

$$\sum_{i\in N} \sum_{q\epsilon Q} x_{iq} = y_q . l_q \tag{5}$$

$$x_{iq} \leq z_{i,}, i \in N, q \in Q \tag{6}$$

$$0 \leq x_{iq} \leq 1 \tag{7}$$

$$z_i \in \{0,1\}, \forall q \in Q, i \in N \tag{8}$$

Nomenclature

Sets and Indices

A_q	Set of directional arcs on the shortest path *q*, sorted from the origin to the destination
$K^q_{j,k}$	Set of all potential HRS 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[3]
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}	Potential station location indicator
$\mathbf{y_q}$	Proportion of vehicles refueled on path q

Decision variables

x_{iq}	Proportion of vehicles on *path q* that refuel at node i
z_i	= 1 if an AFS is built at node i. $z_i = 0$ if otherwise

Equation (1) represents the objective of the model, which is to minimize the number of HRS built in the network. Equation (2) is a constraint that ensures a station z_i should at least be opened/constructed at one of the potential station locations $K_{j,k}^{q}$ that lies in path q to allow y_q trucks to refuel. In this case, y_q is set to 1 as our main aim is to identify the minimum number

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[3] In this case, S = 100% (all flows will be refueled at least once per trip).

of refueling stations required to serve the total demand in Germany. Equations (3) – (5) are constraints that limit the potential station's capacity in the model based on the amount of energy consumed. Constraint (3) says that a station built at node *i* can only serve a total demand below the capacity limit. The total demand served is equal to the total truck flow f_q multiplied by the fuel consumption *p* and the amount of refueling at node *i* (r_i). Parameter g_{iq} acts as the potential station location indicator, which will be equal to 1 if node *i* is a potential station location in path *q* and 0 if otherwise. x_{iq} is a variable that defines the proportion of vehicles in path *q* that can refuel at node *i* in order to keep the demand at node *i* below the capacity limit. Constraint (4) ensures that all vehicles in path *q* refuel at one of the potential station locations along the path. Constraint (5) defines how many refueling occasions should take place along path *q*, depending on the path's total distance. Here, l_q defines the number of refueling occasions on path *q*, which is calculated by dividing the total OD trip *q* distance by the maximum driving distance that can be reached with a single refueling and then rounded up. Equation (6) is a constraint, which defines a station should be open at node *i* in *path q* if a vehicle in that path refuels at that particular node. Equation (7) defines that x_{iq} is a fraction between 0 and 1, while Equation (8) represents the nature of binary variable z_i.

Unless otherwise stated, we used similar assumptions as our previous study [23]. The potential station locations $K_{j,k}^{q}$ are defined in a pre-optimization process using an algorithm. In general, the algorithm calculates the (cumulative) distance from a single node to the next node in *path q,* starts from the origin point (O) and ends at the destination point (D). If the distance to the next node exceeds the maximum vehicle range, the algorithm will then check (previous) nodes that count as potential station locations and keep the nodes as a single set of potential station locations $K_{j,k}^{q}$. Complying with the assumption that all vehicles start and end with the same fuel amount, the algorithm will apply an additional "virtual distance" every time a destination node is reached. This "virtual distance" can be formulated as below

$$AD_q = TD_q + IFR - DO_q$$

Where AD_q is the virtual distance from the starting point, IFR is the initial fuel range, TD_q is the total distance of OD trip q, and DO_q is the distance from the origin point to the highway entrance. The model has already been described in detail in our previous publication [23] and we therefore advise readers to refer to [23] for further information.

3.2 Total HRS Cost Calculation

Within the second step, the total HRS cost calculation is performed for the previously defined HDV-HRS network based on the two scenarios shown in Table 3: On-site (1) and Pipeline (2). This optimal cost of HRS is determined exogenously from the NC-FRLM, meaning that we consider the NC-FRLM result along with the additional hydrogen production, distribution, and storage data from section 4 as the input for the calculation.

Scenarios	***1***	***2***
HRS network (stand alone, without H2 production)	√	√
"On-site" (= local production)	√	-
"Pipeline" (= central production)	-	√

Table 3: Scenarios 1 and 2 to determine infrastructure costs

3.2.1 On-site Production Scenario

For the on-site production scenario, the total cost is defined in our model as follows:

$$TI = \sum_{i^* \in N} \sum_{s \in S} [([FI]_s + [EL]_s + [OM]_s) + \; l_{i^* s}] \qquad (9)$$

Equation (9) defines TI as the total annualized costs (in €/yr) of building a station network. i^* is an indicator of the node at which a station will be built in network N, while s is an indicator of station size from the overall station profile S. Accordingly, the total CAPEX is equal to the sum of FI_s (annualized investment cost for size s station in €/yr) as well as El_s

(on-site electrolyzer annualized investment cost that complies with size s station in €/yr).[4] Meanwhile, the total fixed OPEX consists of the sum of variable operating and maintenance costs (OM_s in €/yr, which are 4 % of FC_s). Finally, the total fuel cost is defined as the sum of the electricity costs (l_{i^*s} in €/yr) to produce the amount of hydrogen that meets demand at a station built at i^* with size s. Apart from the annuity factor, no other cost elements are taken into account. Therefore, the total cost to build a single HRS typically follows the average cost curve, in which the total cost of HRS/kg hydrogen decreases as the capacity limit increases. For this reason, in the on-site hydrogen production scenario, the only optimization conducted is within the first model stage (NC-FRLM).

3.2.2 Centralized Hydrogen Production Scenario

The centralized production scenario includes four large electrolyzers (of equal size; close to the northern shorelines) and hydrogen pipelines to transport the hydrogen from the production site to the stations. This section describes the methodology used to model the hydrogen pipeline in the network and the total cost calculation for this scenario. Further explanation about the input data for the model (e.g. electrolyzer sites, techno-economic parameters of the hydrogen pipeline) is described in section 4.2.2 and section 4.2.3.

To determine the total cost of HRS built up in the centralized hydrogen production scenario, the previous cost formula (Equation 9) is adjusted as shown:

$$TI^P = \sum_{p\in N}\left((FI_p + El_p + OM_p\right) + \sum_{p\in N}\sum_{i^*\in N}\left(FI_{pi^*} + OM_{pi^*}\right) + \sum_{i^*\in N}\sum_{s\in S}((FI_s + OM_s) + l_{i^*s}) \quad (10)$$

Equation (10) determines total annualized costs for the pipeline scenario in €/yr TI^P from the total annualized costs for hydrogen production facilities, a hydrogen pipeline system as well

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[4] For the CAPEX within this analysis, the annuity factor concept has been applied to the asset investments to represent the cost per year of owning an asset over its entire lifespan [34]. For all technologies, a universal discount rate of 7% is assumed.

as the total annualized station costs. Here, p is an indicator of a node in network N in which a hydrogen production facility is built. The total cost to build the hydrogen production facilities is then equal to the total sum of annualized investment to build centralized hydrogen production site at node p in €/a FI_p , variable operating and maintenance costs of centralized hydrogen production site at node p in €/yr OM_p, and annualized investment cost of electrolyzers that comply with centralized hydrogen production site at node p and total demand, in €/yr El_p. The total annualized costs for a hydrogen pipeline system include annualized investment cost of pipeline from production site p to station site built at i^* in €/yr FI_{pi} and variable operating and maintenance cost of pipeline from production site p to station site built at i^* in €/yr OM_{pi}. Finally, the total annualized station costs cover annualized investment cost of building station with size s in €/yr FI_s, variable operating and maintenance cost of s in €/yr OM_s, and the total annual electricity costs electricity costs to produce the hydrogen that meets demand at node i in size s station in €/yr l_{i^*s}.

In the centralized scenario, a second stage of optimization is performed to determine the annualized investment of the hydrogen pipeline. Here, we apply a similar methodology as in [35] to obtain the minimum cost of building a hydrogen pipeline network to satisfy the network's hydrogen demand. The model is a mixed integer linear programming (MILP) optimization model with binary variables depicting the decision to build a production facility at a single node with a certain size, or to construct a pipeline segment between two nodes and certain diameter sizes. In addition, the model includes continuous variables that represent decisions in terms of the quantity of hydrogen production at a certain node and transportation from one node to another. The model’s objective is to determine the infrastructure design with the least total annual costs of production and pipeline transmission, which also considers the surge in demand in the summer. However, we adjusted the method to suit our case by pre-defining the potential centralized electrolyzer sites and not considering the summer surge effect, leaving the cost to build the hydrogen pipelines as the only decision variable. A multi-stage optimization technique is then applied. The formula to define the minimum annualized investment cost of the hydrogen pipeline is then defined as follows:

$$Min \ \sum_{i \epsilon N^P} \sum_{j \epsilon N^P} \sum_{d \epsilon D} C_{ijd}^P w_{ijd} \qquad (11)$$

Subject to:

$$h_{ij} \leq \sum_d K_d^P \ w_{ijd} \quad \forall i, j \epsilon N^P, d \in D \qquad (12)$$

$$a_i \leq K_i^F \quad \forall i \epsilon N^F \qquad (13)$$

$$\sum_j h_{ij} + T_i = \sum_j h_{ji} + a_i \quad \forall i, j \epsilon N^P \qquad (14)$$

$$\sum_{i \in N^F} a_i = \sum_{i \in N^T} T_i \qquad (15)$$

$$\sum_d w_{ijd} \leq 1 \quad \forall i, j \epsilon N^P, d \epsilon D \qquad (16)$$

$$h_{ij} \geq 0 \quad \forall i \epsilon N^F \qquad (17)$$

$$a_i \geq 0 \quad \forall i \epsilon N^F \qquad (18)$$

$$w_{ijd} \in \{0,1\} \quad \forall i, j \epsilon N^P, d \epsilon D \qquad (19)$$

Nomenclature

Sets and indexes

N^P Set of all nodes that will form the hydrogen pipeline network, $N^P = \{1,\ldots n\}$

N^F Set of all centralized electrolyzer sites (a subset of N^P)

N^T Set of all potential hydrogen refueling station locations (a subset of N^P)

D	Set of all pipeline diameters
i,j	Indices of all nodes
d	Indices of the diameters

Parameters

T_i	The hydrogen refueling station peak demand at node i
K^P	Maximum capacity of a pipeline (tons/day)
K^F	Maximum capacity of a centralized electrolyzer site
C^P	Fixed annualized capital costs for constructing a hydrogen pipeline (MEUR/yr.)

Decision variables

h_{ij}	Units of hydrogen transported from node *i* to node *j* (tons/day)
a_i	Hydrogen produced at node *i* (tons/day)
w_{ijd}	Binary variable; 1 if a pipeline is constructed from node *i* to node *j* with diameter d, 0 if otherwise

Equation (11) states the objective of the model, which is to minimize the cost of building hydrogen pipelines that meet the demand. Equation (12) is a constraint that limits the amount of hydrogen flow from node *i* to *j*, which must not exceed the capacity of a pipeline with diameter *d.* Equation (13) is a constraint to ensure that the hydrogen produced at node *i* does not exceed the maximum daily production capacity of a centralized hydrogen production site. Equation (14) and Equation (15) represent the mass balance constraints. Equation (14) ensures that the total hydrogen flow from each node, which includes the hydrogen produced from centralized hydrogen production sites, is equal to the total hydrogen flow entering the other node that also consists of the hydrogen demand at node *i.* Equation (15) ensures that the total hydrogen produced is equal to the total hydrogen demand. Equation (16) dictates that only one pipeline size can be built to connect two nodes. Equation (17) and Equation (18) define the continuous variables and Equation (19) sets the binary variable used.

Finally, the hydrogen supply cost of each scenario – pipeline and on-site – will be compared and analyzed after describing the input data in the next section.

4 Data

In order to apply our model to a potential HDV-HRS network in Germany, we require traffic-related data as well as fuel cell and hydrogen data.

4.1 Vehicle usage data

We use two types of input to characterize German HDV traffic: highway data to determine the current network system, and individual HDV vehicle trips to understand traffic flow. In general, we used a similar but extended data set for highway road network data and HDV traffic flows as in our previous study [23]. Hence, we present both types of data only briefly here and refer to [23] for further details.

4.1.1 Highway road network in Germany and current fuel stations

We used the 2,500 traffic surveillance points (hereafter referred to as "nodes") as well as distances between adjacent nodes from the Federal Highway Research Institute (BASt) as our primary data for the highway network [36]. The nodes along with the connecting routes depict the complete German highway network of about 13,000 km and 121 highways. For further spatial analyses, the coordinates of each node were located within EPSG:4326 for geographic coordination and the distance between each node obtained from BASt. The resulting HDV traffic intensity on German highways is shown in Figure 1, which is illustrated using QGIS software. Furthermore, we added information about existing conventional fuel stations in Germany in accordance with [37] as additional nodes to the network.

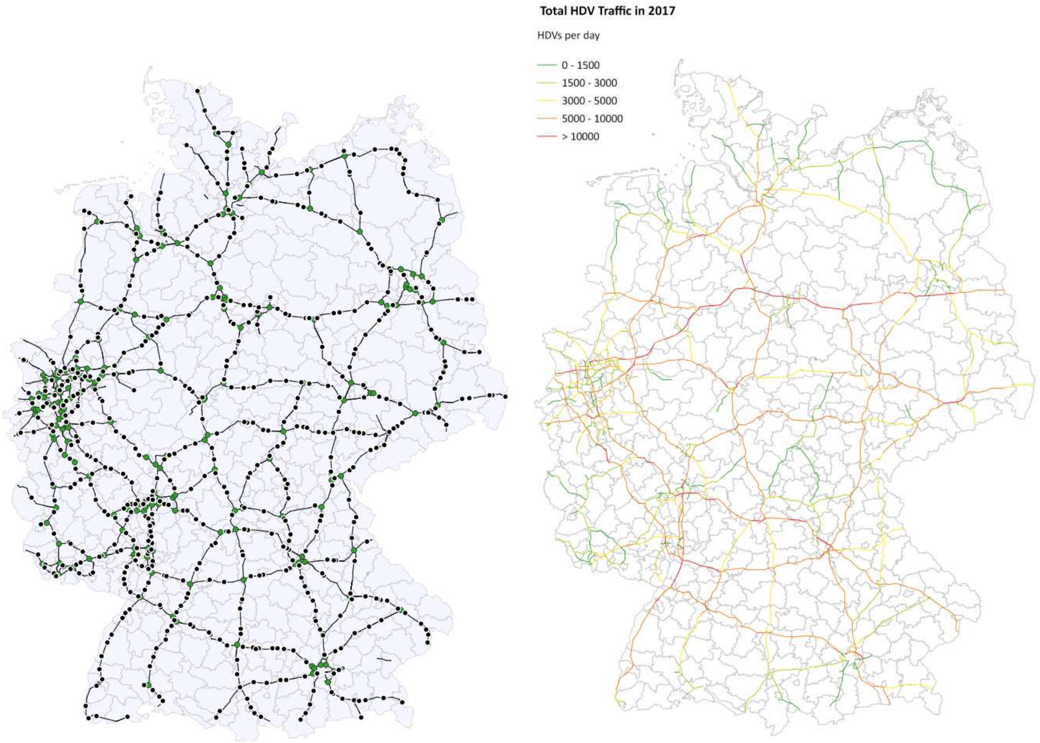

Figure 1: German NUTS3 areas; left: highway network (black lines), junctions (green dots) and other nodes (black dots); right: HDV traffic intensity on German highways in 2017 (based on [36])

4.1.2 HDV flows

The final OD path subsets and their vehicle intensity are displayed in Figure 2. 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.

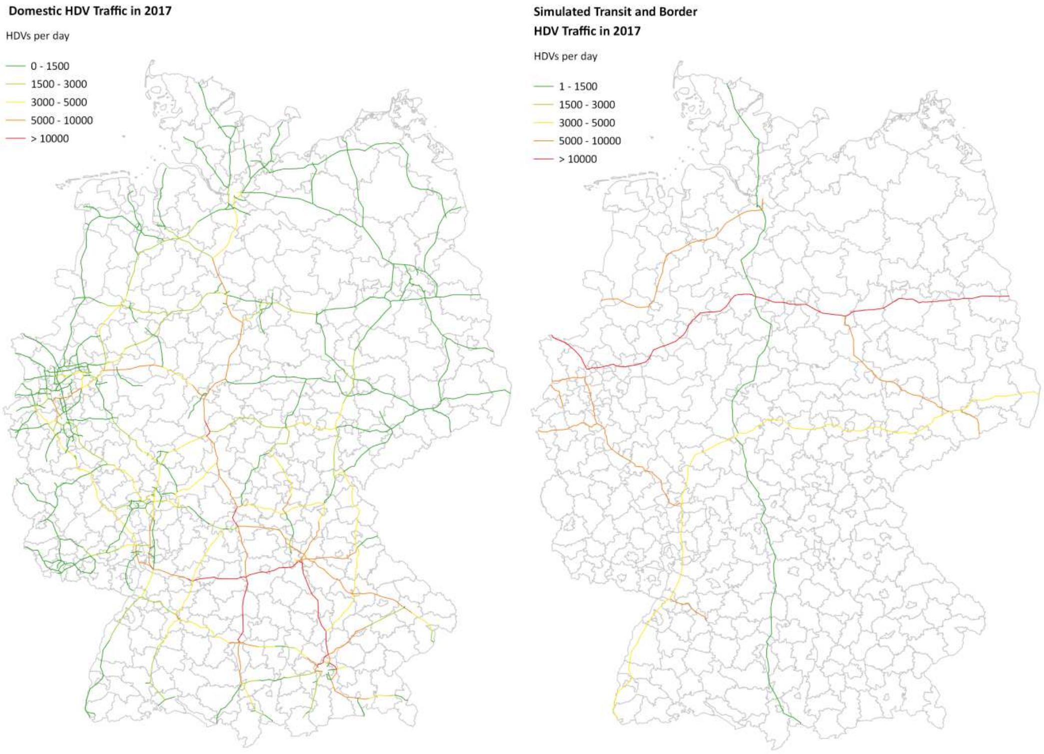

Figure 2: Traffic of OD trips used in this study including domestic HDV traffic (left, based on [38]) as well as synthesized transit and border HDV traffic (own illustration)

Applying the NC-FRLM algorithm and assumptions, as explained in section 3.1 , to these nodes and OD trips, the potential station locations $K_{j,k}^{q}$ results in 11,084 sets from all 1,591 OD trips. These sets are utilized in the station location optimization model.

4.2 Fuel Cell and Hydrogen data

4.2.1 FC-HDV design and market diffusion

There are currently limited FC-HDVs in commercial operation (TRL 9), such as the Hyundai XCient [77]. Subsequently, only FC-HDVs prototypes (TRL 7) with limited available technological data are present. Therefore, we develop an FC-HDV design, which is based on the regulatory framework in the EU and Germany as well as the technical feasibility of the subcomponents.

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 shafts (40t). The speed of HDVs is limited to 80km/h on highways (§18 StVO). 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.

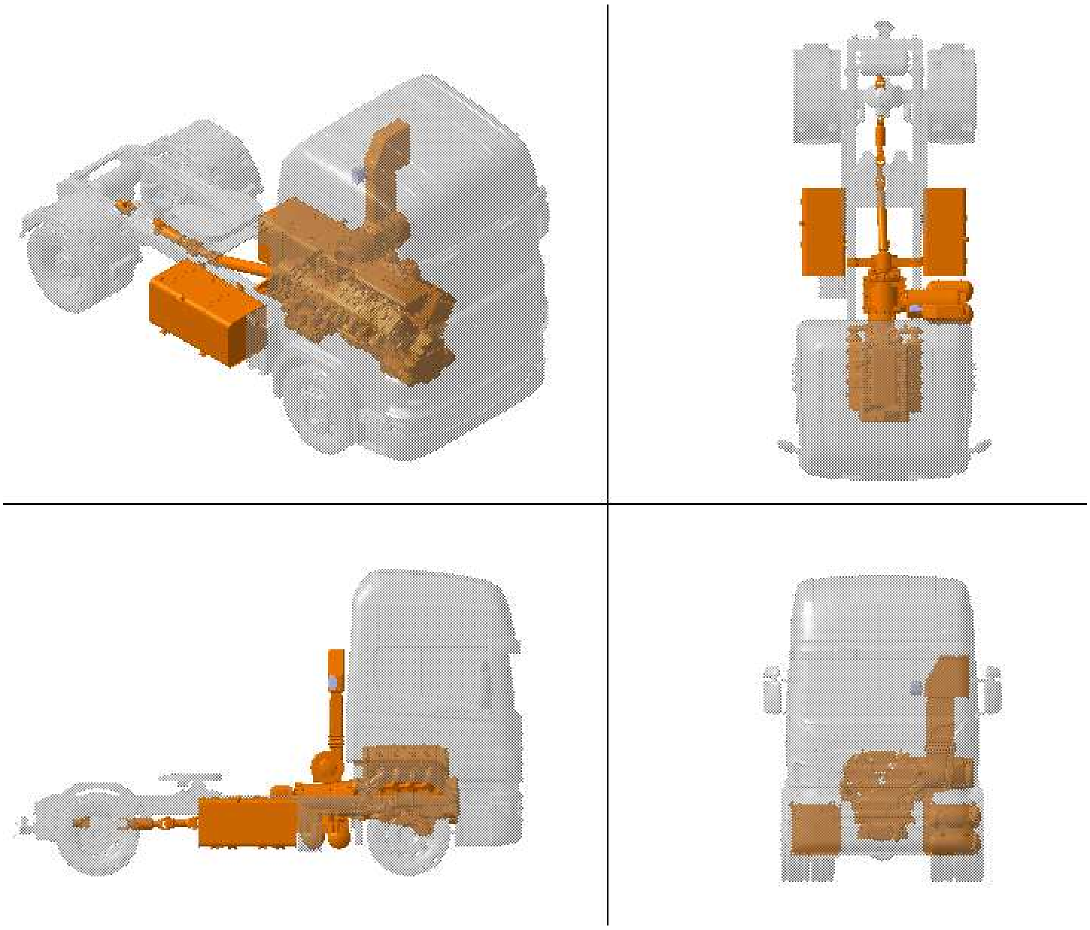

Figure 3: CAD model of current conventional HDV tractor that complies with German road traffic regulations [39]

Subsequently, parameters are defined for a FC-HDV, including components that comply with the given regulatory framework with particular attention paid to volume, length, and weight. Neglecting the fuel storage components, the size of a FC powertrain is almost the same as a conventional diesel HDV. The available space determines the hydrogen storage capability of the HDV tractor. Under EU directive 2015/719, an average HDV tractor provides about 4.3 m^3 behind the driver cabin[5]. An additional one m^3 stemming from the previous conventional fuel tank[6] can be used for battery system components. For onboard hydrogen storage, the necessary conversion of square tanks to cylindrical ones as well as storing the hydrogen in type 4 tanks [40] 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 2.15m^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) [40]. This translates into a driving range of about 550 km (350 bar) or 810 km (700 bar), assuming a tank-to-wheel (ttw) powertrain efficiency of about 51 %[7] and the energy consumption of a fully-loaded HDV (2.10 kWh/km). Given German HDV user requirements, with a required average HDV range of 800 km, only the 700 bar option seems suitable for a FC-HDV powertrain. The CAD layout of the FC-HDV, including its dimensions, can be seen below.

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[5] Space assessment behind driver cabin: x-axis (600 mm), y-axis (2,400 mm), z-axis (3,000 mm).

[6] The size of a diesel fuel tank is estimated at about 500 liter (1,400 mm x 600 mm x 600 mm) with two tanks per HDV.

[7] This efficiency is based on a component level and corresponds to most of the prototypes.

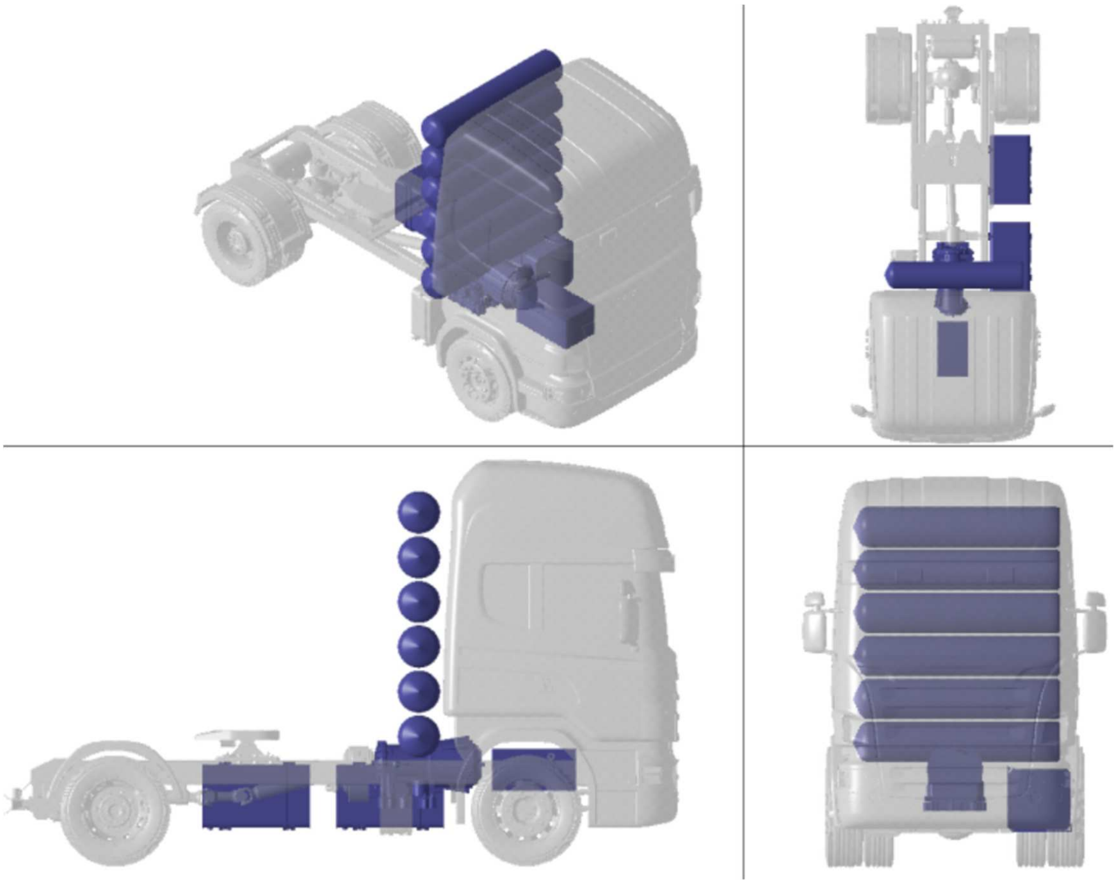

Figure 4: CAD model of potential FC-HDV tractor after replacing the diesel engine with a fuel cell powertrain, which meets HDV user requirements

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 2.4t, with 1t for the full fuel tank, 1.3t for the engine and gears, and 0.1t for the exhaust system [15]. In contrast, the FC-HDV powertrain is considered to be 2.2t. 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.

Component	Energy / Power	Volume	Efficiency	Weight	Source
Motor	350 kW	0.5 m^3	92 %	200 kg	[41]
Battery system	30 kWh	0.08 m^3	95 %	150 kg	[42]
Stack	300 kW	0.5 m^3	60 %	450 kg	[43]
Tank [8]	1,665 kWh[9]	2.65 m^3	98 %	1,400 kg	[44]
Total	-	3.73 m^3	51 %	2,200 kg	

Table 4: Techno-economic parameters: power, volume, efficiency, and weight for FC-HDV in 2050 (own assumptions based on mentioned sources)

In addition to the previously defined powertrain component parameters, vehicle energy consumption is an essential input for the analysis. In this study, the energy consumption for FC-HDV in 2050 is based on the on-wheel energy consumption [45], efficiency improvements over time due to non-powertrain enhancements [46] as well as HDV fuel cell powertrain efficiency. 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 [38] shows, about 30 % of the HDVs operate with a full load and about 30 % with zero loads. Therefore, an average load of 12.5 tons and 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.

The market diffusion of FC-HDVs into the German HDV stock by 2050 is defined as an external input. To reach global climate targets of almost zero emissions in 2050 [47], we

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[8] at 700 bar

[9] 1,665 kWh equals 50 kg hydrogen

assume a share of 100% FC-HDV in 2050 following [5] with a stock of 176,000 FC-HDV in Germany.

4.2.2 Discrete HDV-HRS portfolio

We used a similar configuration of potential HDV-HRS design portfolio as in our previous work [23]. The portfolio consists of six different HDV-HRS sizes, ranging from XS to XXL, and is defined using the Heavy-Duty Vehicle Refueling Cost models (HDRSAM) from Argonne Lab [48]. Following the German Federal Immission Control Act (Bundesimmissionsschutz-Verordnung BImSchV, Annex 1 and BImSchV, Incident Ordinance), storing more than 30 tons of hydrogen in a single hydrogen refueling station requires additional procedures which increase construction complexity. Thus, the largest station size (XXL-sized station) has a maximum capacity of 30 tons of hydrogen. Further details of the portfolio can be seen in Table 5.

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	[kg_h2]	114	228	455	900	1,821	3,642
Compressor rate	[kg_h2/h]	114	228	455	900	1,821	3,642
Footprint (station only)	[m^2]	198	198	486	1,109	2,628	6,170
Footprint (incl. Electrolyzer)	[m^2]	290	565	1,190	2,725	6,330	13,470
Dispenser	[k€]	107	214	214	428	856	1,712

Parameter	Unit	XS	S	M	L	XL	XXL
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€]	107	187	358	715	1,394	2,763

Table 5. Overview of technology and economics for all HRS types (XS to XXL) based on HDRSAM tool [32] and own assumptions for 2050

4.2.3 Hydrogen production

A promising way to produce carbon-neutral hydrogen from renewable energies – also known as “green” hydrogen – is to split water through electrolysis. The PEM electrolyzer seems most suitable to HDV-HRS applications due to its fast dynamic response, low space requirements, and independence of an (industrial) waste heat environment (cf. [50]).

Currently, multiple small- to large-scale PEM projects have been announced, as shown in Figure 5. For example, the North American company “Hydrogenics” recently started offering a new standard PEM electrolyzer with 500 kW power and an average daily production of about 200kg hydrogen. Further, “Nikola Motors” plans to open their first (small) HDV-HRS in the United States with a daily hydrogen production of 1t at a capacity of 2.2 MW. Later on, a larger HDV-HRS will produce about 30t 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, 35 tons hydrogen daily), initialized by a grid operator to support the energy transition by storing excess renewable energy as hydrogen.

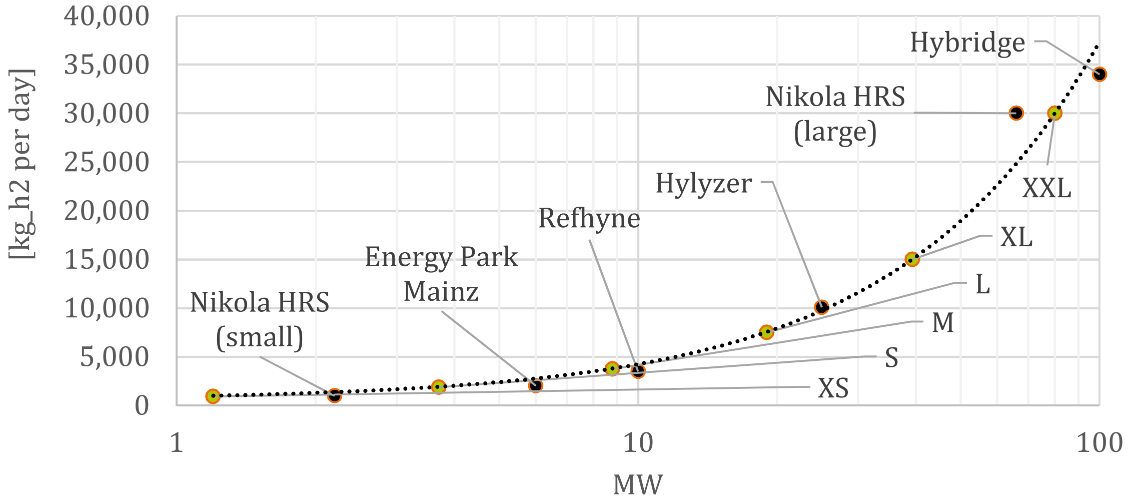

Figure 5: Exemplary PEM electrolysis projects by power (in MW) and daily hydrogen production (in kg hydrogen per day) and derived potential electrolyzer sizes for HDV-HRS portfolio (XS to XXL) (more details on these projects can be found in Table 10 in the appendix)

Techno-economic input parameters are needed to determineg both the total network cost and the optimal electrolyzer dimensions, particularly when integrating the HDV-HRS infrastructure network with the electricity system using the PyPSA tool. These include efficiencies, investment, operating and maintenance costs, production rate, lifetime, grid connection, and transformer investment. The techno-economic parameters for electrolyzers in this study are summarized in Table 6.

Parameter	Unit	Value	Source
Electrolyzer efficiency	[%]	68	[51]
Electrolyzer investment	[€/kW]	510	[52]

Parameter	Unit	Value	Source
Electrolyzer operating & maintenance costs	[%/a]	4	[53]
Electrolyzer production rate	[Nm^3/h/MW]	200	[51]
Electrolyzer lifetime	[a]	20	[51]
Connection investment	[EUR/MW/m]	11	[54]
Transformer investment	[EUR/MW]	27,000	[54]

Table 6: Techno-economic parameters for electrolyzers in 2050

We calculate the CAPEX, fixed OPEX and energy costs to determine the cost of each scenario. Regarding CAPEX, the capacity of the electrolyzers is demand-driven in both scenarios (centralized and on-site). It adds up to about 11 GW, assuming a capacity factor of 90% based on [55] and 68% efficiency based on [51]. In our first scenario, the size of the on-site electrolyzer, and therefore the size of each HRS, is based on local demand. On-site electrolyzer dimensions for the HDV-HRS portfolio are defined by assuming a linear trend line between the exemplary projects and considering the mentioned capacity. Based on daily demand at each station, as defined in section 0, the on-site electrolyzer of the stations would range from 1.2 MW for a station size XS, through 3.7 MW (size S), 8.8 MW (size M), 19 MW (size L), 39.3 MW (size XL) to 80 MW for an XXL station (cf. Figure 5). The second scenario features four large, centralized electrolyzers at Germany's northern coastline in the cities of Rostock, Cuxhaven, Wilhelmshaven, and Emden based on [56]. These electrolyzers are each allocated about 25% of production, which is in line with current literature (cf. Table 7). Finally, we assume full exploitation of economies-of-scale due to the large electrolyzer sizes even for small HDV-HRS for both scenarios leading to 510€/kW in 2050 based on [52].

Source	Total GW	Full-load hours	TWh (year)	Northern Sea	Baltic Sea
[56]	28	3,958	111	90%	10%
[55]	15	4,604	69	65%	35%
Own assumptions	11	4,000	42	75%	25%

Table 7: Overview of German offshore-wind capacity available for centralized electrolysis in 2050 and own assumptions

Regarding fixed OPEX, we assume maintenance of the stations and electrolyzers at 4% per annum [55] for both scenarios.

For the energy cost, both scenarios assume the locational marginal price of electricity shown in Figure 6 for the electrolyzers in 2050, which are based on the European electricity system model "PyPSA" [57]. These locational marginal price of electricity cover the cost of electricity generation as well as its distribution.

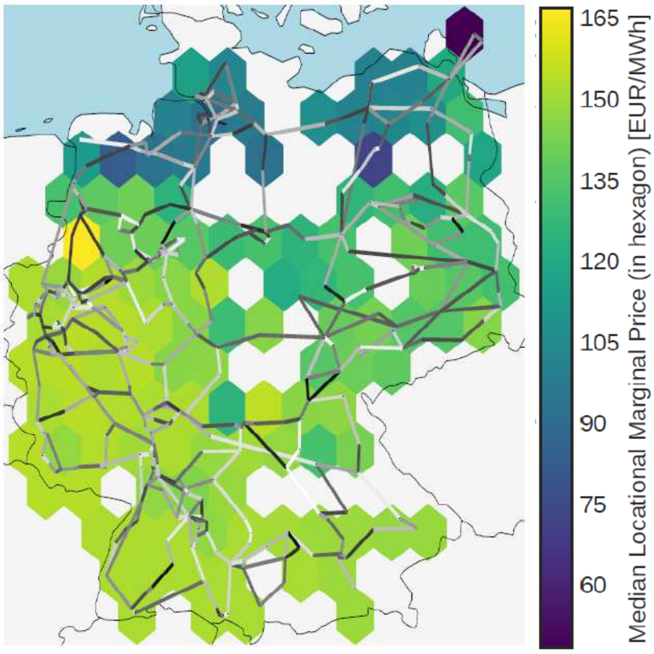

Figure 6: Overview of locational marginal electricity price in Germany in 2050 based on PyPSA (cf. [57])

4.2.4 Hydrogen distribution

Hydrogen can be provided at the HDV-HRS either on-site at the station (using a local electrolyzer) or through a hydrogen delivery service to the station from centralized electrolysis at a place with low electricity cost. On-site hydrogen production needs almost no additional hydrogen distribution effort[10]. In contrast, centralized hydrogen production involves additional expenditure from using either trucks or a dedicated pipeline network to deliver the hydrogen to the stations [59]. None of the truck delivery options seem suitable for a HDV-HRS network in Germany (cf. [60–64]) and are thus excluded from further analysis. Hydrogen pipelines are well established throughout the world, with about 4,500 km of installed assets, 390 km of which are in Germany. The most common application for hydrogen pipelines is currently in the chemical industry [58]. Accordingly, pipelines seem a good option for transporting large amounts of hydrogen overland without significant energy losses, primarily to supply HRS on a national scale [28, 56]. Moreover, German highways are inalienable federal property. Theoretically, therefore there is the chance of a shorter installation time here(most other German street types are state or private property, which would have to be bought or confiscated to install pipelines) [65]. Thus, in addition to on-site hydrogen production, a hydrogen pipeline network seems a feasible option to distribute hydrogen from a centralized electrolyzer to a national HDV-HRS network.

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[10] 79 of today's 303 active HRS have on-site hydrogen production. At 171 HRS, the source of hydrogen is "unknown" (cf. [58]).

To analyze whether a pipeline network is competitive with on-site production, we define techno-economic parameters for the hydrogen pipelines based on [66]. We determine the required pipeline diameter based on the given mass flow between a specific HDV-HRS location (i.e. its daily hydrogen consumption) and the centralized electrolysis facility (cf. [66]). In the case of parallel pipelines, e.g. if two HRS are relatively close to each other, the diameters of each station are added to result in a single pipeline. The author of [66] defines 100mm as the minimum and 600mm as the maximum diameter for hydrogen pipelines. Hence, in this work, similar to the distinct HRS sizes, we apply distinct pipeline diameters in steps of 100mm (i.e. 100mm, 200mm, 300mm, 400mm, 500mm, and 600mm) to take standardization benefits into account. This results in a specific pipeline cost per diameter based on hydrogen mass flow rates, as shown in Table 8 below. For on-site production of hydrogen, we consider the HDV-HRS and the electrolyzer asset cost but no additional distribution asset cost.

Diameter [mm]	**Hydrogen flow** [tons per day]	**Cost**[11] [€ per meter]
600	2,185	1,200
500	1,517	970
400	971	780
300	546	590
200	243	420
100	61	300

Table 8: Resulting hydrogen flow rate (in tons per day) and cost (in € per meter) based on [66]

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[11] These costs include the pipeline material, booster compressors and valves (cf. [66]).

5 Results

In this section, we present the results of the investigation. First, we show the resulting potential HDV-HRS network in Germany and its electricity demand. Second, we present our result in modelling the potential hydrogen pipeline network that is used in the centralized scenario. Lastly, we compare the resulting hydrogen supply options (local vs. central production) as well as the total potential cost to build the HRS network.

5.1 Potential HDV-HRS network

Applying the case study to our NC-FRLM model without the capacity restriction, results in an optimal solution shown in Figure 7 (left). It can be seen that about 100 hydrogen refueling stations are required to satisfy FC-HDV demand in Germany in 2050. These stations are evenly distributed across Germany, with fewer HRS in the northeast (around Berlin).

The result of the NC-FRLM with a capacity limit of 30 tons indicates an optimum of 137 stations to serve all vehicles in all OD trips shown in Figure 7 (right). Of these 137 stations, 96 stations reach the maximum capacity of 30 tons, and the average size 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).

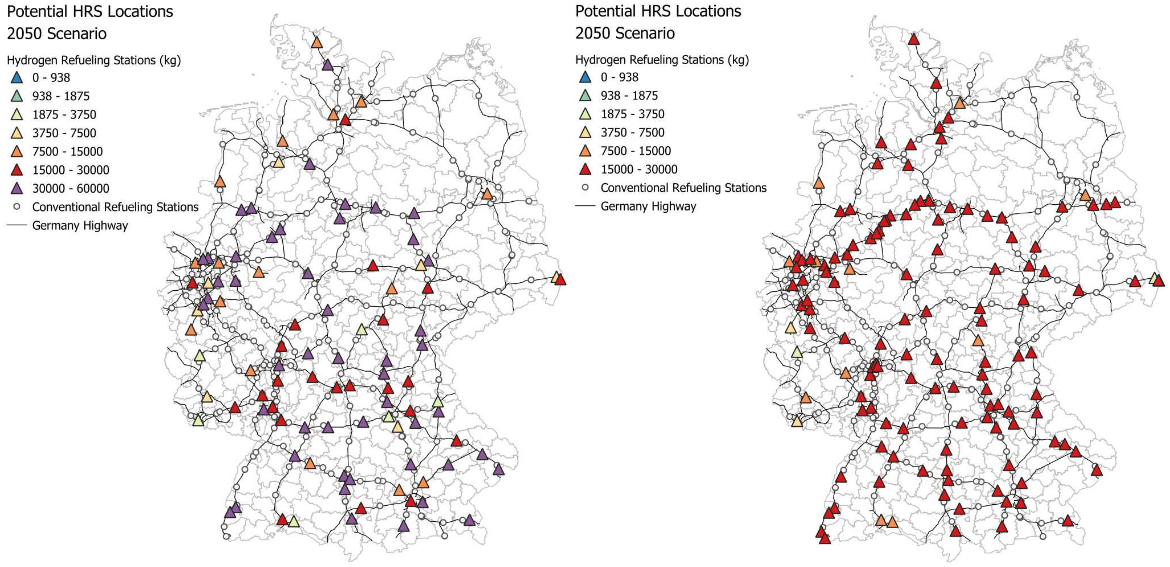

Figure 7: The existing fuel stations (white points) and 100 potential HRS locations (triangles) based on non-capacity-constrained FRLM (left); the existing fuel stations (white points) and 137 potential HRS locations (triangles) based on capacity-constrained FRLM with 30t limit (right)

The resulting electricity demand in the domestic traffic network sums up to 38 TWh per annum and to 65 TWh per annum in the total traffic scenario.

In regards to the station footprints, the footprints of each HRS station size on both scenarios as well as the footprint of conventional stations in Germany highways can be seen in Table 9.

Table 9. Station footprints for each HRS station size in centralized and on-site scenarios as well as the conventional fuel stations in Germany highways

Station Size	Unit	Centralized scenario	On-site scenario
XS	m^2	198.19	290.00
S	m^2	198.19	565.00
M	m^2	486.34	1,185.00
L	m^2	1,108.98	2,725.00
XL	m^2	2,628.45	6,330.00
XXL	m^2	6,170.48	13,470.00
Conventional stations	m^2	4,000-6,000	

It can be seen that there is a large gaps in the station footprints between the two scenarios due to the need of space for electrolyzer in the on-site scenario, which contributes for about 50% of the total area required. In the centralized scenario, the largest station would equal about the size of a conventional fuel station, while a station containing an on-site electrolyzer has about twice the size. The total area required to build the all of the stations in the network is thus is 1.68 km2 for the on-site scenario, whereas for the centralized scenario is 0.77 km2 (which equals about 140 football fields).

5.2 Potential hydrogen pipeline network

This section describes the additional pipeline network required to distribute hydrogen from centralized production sites to the HRS stations. As mentioned, four main electrolyzers are assumed; three at the North Sea coast (near Bremerhaven, Cuxhaven, and Wilhelmshaven) and one at the Baltic Sea (near Rostock). A hydrogen pipeline system along highways is then modeled to reach each HRS of the network.[12] While the highway network is used as the basis, the hydrogen pipeline network candidate is determined by applying the Dijkstra algorithm [67] only between nodes that represent the central electrolyzer sites, intersections, and potential HRS locations based on the result of the NC-FRLM model. The resulting pipeline is shown in Figure 8. This 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 [56], a full HRS network for passenger cars would require 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 nearly three million tons of hydrogen per year.[13]

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[12] 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. [28, 56]).

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

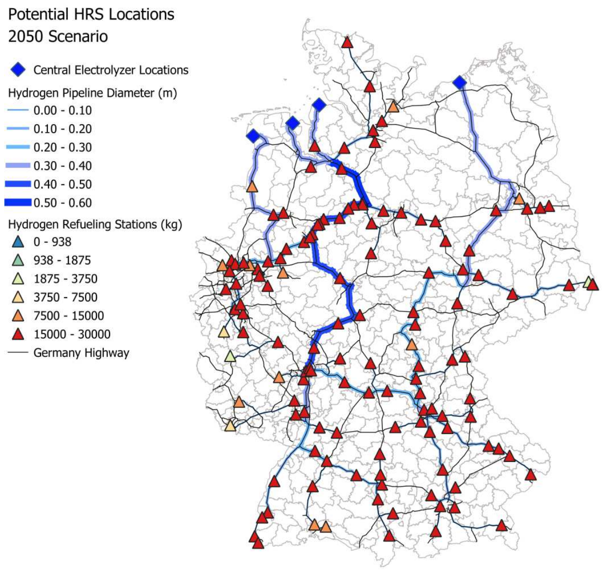

Figure 8: Pipeline network to supply the HDV-HRS network in the reference scenario with hydrogen

5.3 Total Cost of HRS Infrastructure

This section presents the results of the model-based HDV-HRS network for the reference scenario to illustrate the economic implications such as total annualized network costs and cost shares of the different components. The pipeline scenario is also 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 were applied to appraise and compare the cost of producing and supplying hydrogen via a HDV-HRS network: the total annualized costs of the network, the levelized cost of hydrogen (LCOH) per kilogram hydrogen, and the relative network cost per HDV kilometer[14]. The annualized network costs comprise the full network life-cycle costs expressed as consistent periodic payments over the lifespan (Wöhe and Döring (2010)),

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[14] These costs were analyzed from a macro-economic perspective, i.e. without levies, taxes, or other surcharges.

which include CAPEX[15] and fixed OPEX for the stations and electrolyzers as well as for 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 annualized cost of hydrogen production divided by total hydrogen generation, which can be calculated at station 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 [3]. In our study, the relative network costs show the infrastructure costs per driven distance within the network, based on the annual HDV traffic on German highways.

Our results show that the economics of a potential HDV-HRS network depends strongly on the supply scenario. The on-site scenario with a network of 137 stations results in annualized costs of about 8.39 billion euro. Less than 20 % of these costs are non-electricity related, indicating the minor impact of station costs on the final costs. Correspondingly, 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.

The pipeline scenario with centralized hydrogen production instead of on-site electrolysis decreases costs significantly by more than one billion euro per year, resulting in a total investment of 7.25 billion euro and LCOH of 5.59 €/kg, which is equal to 0.35 € per HDV kilometer. The main cost advantage of the pipeline versus the on-site scenario is the availability of lower-priced electricity in Northern Germany, which outweighs the additional pipeline costs. These results are summarized in Table 9.

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[15] CAPEX are defined as annuitized investments in this work.

	Scenario	On-Site (Reference)	Pipeline	Unit
Input	Station capacity limit	30	30	t_{H2}/d
	Total hydrogen refueling demand	3,557	3,557	t_{H2}/d
	Total hydrogen refueling demand	64.88	64.88	TWh_{el}/a
	HDV range	800	800	km
	Electrolyzer location	Local	Central	-
	Electricity cost	100	80	€/MWh
	HRS electrolyzers capacity factors	90.00	90.00	%
Design results	Stations	137	137	#
	- XXL	*122*	*122*	#
	- XL	*11*	*11*	#
	- M	*2*	*2*	#
	- S	*2*	*2*	#
	- XS	-	-	#
	Utilization	96.5	96.5	%
	HRS electrolyzers	12.62	12.62	GW
Economic results	Network cost	8.38	7.25	bn€/yr
	- HRS	*0.62*	*0.62*	bn€/yr
	- Electrolyzer	*0.57*	*0.57*	bn€/yr
	- Distribution	-	*0.31*	bn€/yr
	- Electricity	*7.19*	*5.75*	bn€/yr
	LCOH	6.47	5.59	€/kg_{H2}
	Relative HDV cost	0.40	0.35	€/km

Table 10: Summary of the network design and economic results for the reference scenario as well as the pipeline scenario

5.3.1 Sensitivity Analysis

We also performed a sensitivity analysis to see the significancy of the HRS infrastructure network cost elements to the total cost. The analysis is performed in the centralized scenario in order to depict all of the cost elements, that is the station cost, electrolyzer cost, pipeline cost, and electricity cost. Here, the cost of each elements are varied by -10%, -5%, +5%, and +10%, and the result can be seen in Figure 9.

In overall, the cost of electricity causes the most significant impact to the total cost, which corresponds with the results. Varying the electricity cost by -/+5% causes the total infrastructure cost to change for about 3.97% (6.97/7.54 bn €/year) and by -/+ 10% changes the total infrastructure cost to about 7.93% (6.68/7.83 bn €/year). Meanwhile, the rest of the elements only shift the total infrastructure cost by less than 1% even in the -/+ 10% cost variance, with the parameters in descending order of impact are as follows: station cost, electrolyzer cost, and pipeline cost.

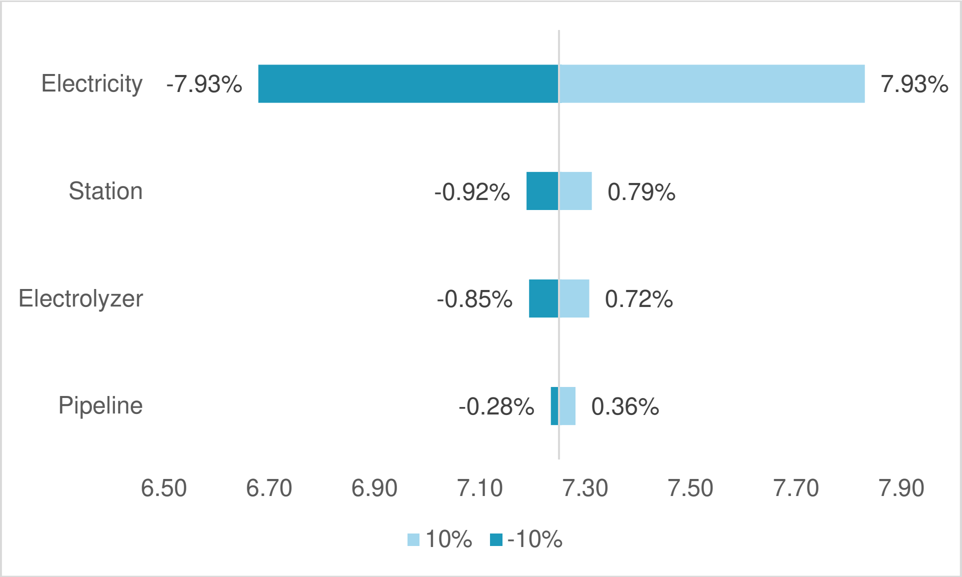

Figure 9. Sensitivity analysis of total HRS infrastructure network cost based on electricity, electrolyzer, and station cost in the centralized scenario

6 Conclusions and recommendations

In this study, we developed a method to derive infrastructure costs and applied it to a case study of an optimal set-covering infrastructure with node capacity restrictions. Our approach extended a previously presented NC-FRLM and introduced new constraints to assess hydrogen supply options. This approach was used to determine a hydrogen refueling infrastructure and its related costs for the HDV sector on a national level for both a central and a local hydrogen supply scenario.

The resulting HDV-HRS network in Germany in 2050 to service 72 million HDV kilometers per day has about 140 stations. Considering virtually zero-emission truck traffic in 2050 (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 1.5 of the size of the current passenger car HRS network in Germany (which can be further decreased in the future), 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 complement the existing passenger car HRS network, as the latter is located primarily in metropolitan areas.

A potential HDV-HRS network in Germany in 2050 would have total costs of about eight billion euros per year. 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, of which about one €/kg is 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 one billion euros per year, reducing the average LCOH to about 5.60 €/kg, but only if the locational marginal electricity cost (LMC) for centralized hydrogen production were at least 20 €/MWh cheaper than on-site production. Producing hydrogen at centralized locations and distributing it to the stations via pipeline is a favorable scenario for a high market diffusion of FC-HDVs. This assumes local marginal costs are low and reliable and does not consider the interaction of the HDV-HRS network with the electricity system.

Based on the results of our model extension and the case study, four recommendations for further research are:

1. Analyze the interplay of AFS networks with the energy system: Installing large-scale AFS networks may have – depending on the application – a massive impact on both local and national electricity demand.
2. Collect more OD data for HDVs: While we applied the most suitable available data for our case study, we still found some flaws in the representativeness of the OD data for the HDV sector.

3. Conduct more case studies using different technology options: Other technologies such as battery-electric or catenary HDVs might be interesting options for decarbonizing the HDV sector.
4. Investigating the HRS design network that is applicable for other type of vehicles: As fuel-cell application for other type of vehicles, e.g. LDVs, is also emerging, it might be interesting to see the HRS design network that is not only for long-haul HDVs but also for LDVs application.
5. Investigate the potential HRS network for FC-HDVs considering an import option for the hydrogen supply as well as the implementation of liquified hydrogen in the supply-chain.

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8 Appendix

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 12: Exemplary projects of PEM electrolyzers