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What is the design of a potential HDV HRS network in Germany in 2050?

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Short abstract

Long-distance road-freight transport emits a large share of Germany's greenhouse gas (GHG) emissions. Hence, in February 2019, the European Union agreed on the introduction of GHG emission standards following Canada, China, Japan and the United States. A potential solution for reducing GHG emissions in this sector is the use of hydrogen in heavy-duty fuel cell electric vehicles (FC-HDV). Due to the non-return-to-base nature of long-haul HDV, a large public hydrogen refuelling station (HRS) network would be required. Most installed and planned public HRS are designed for passenger cars, but the refuelling process of passenger HRS is not suitable for FC-HDVs due to its hydrogen output quantity. Thus, in this study, we determine a potential HDV HRS network regarding spatial distribution and capacity for Germany by 2050 using German traffic demand data for heavy-duty trucks and a refuelling station design model. Designing the network, we aim on determining the potential German HDV hydrogen demand, optimal HRS locations and a station size portfolio. In result, we find the hydrogen demand through national FC-HDV traffic at about 3,500t of hydrogen per day (circa 29TWh per year). Moreover, an optimal HRS network for FC-HDV on German highways in 2050 amounts to 125 stations in accordance with German legislation (capacity limit at 30t). Without capacity restrictions, the minimum viable HRS network is at 90 stations. Third, a suitable HRS portfolio depends on the capacity limit, but mainly consists of bigger sizes, such as XL and XXL, and almost no smaller sizes (S, M and L stations). Smaller station sizes, however, may be relevant for market introduction or non-highway applications.

Keywords: FCEV, FC-HDV, Hydrogen Refuelling Stations, modelling, optimization, capacitated FRLM

1 Introduction

The abatement of greenhouse gas emissions (GHG) from the transport sector is focus of several global regulations [1]. Due to high mileage and weight, long-distance road-freight transport is mainly carried out by heavy-duty vehicles (HDV) [1], representing up to 20% GHG emissions of the transport sector [2]. Hence, it could be a major lever for reductions. The design of fuel efficiency regulation for newly registered trucks in the EU is currently under discussion [3]. On the other hand, the long-distance road-freight market is very competitive and thus focused on optimal operation of its HDV at low cost.

The use of hydrogen-based fuel cell electric HDV (FC-HDV) is a potential solution for reducing GHG emissions in long-distance road-freight transport and keeping an optimal HDV availability for logistic purposes. The use of hydrogen refuelling stations (HRS) for HDV in commercial long-distance operations comes with challenges, as most installed and planned HRS are designed for much smaller passenger cars (with 700bar refuelling pressure for max. 10kg hydrogen per refuel). However, according to the current state of international standards and guidelines, the individual refuelling process on passenger HRS is not suitable for FC-HDVs with large on-board tanks (cf. Figure 1). Elgowainy and Reddi (2017) developed a model to determine HDV-HRS design and cost to understand their impact on FC-HDV fleets [4]. However, this tool has not been used on a national level for public infrastructure and a FC-HDV fleet yet.

		Passenger Cars & Light Duty Vehicles		**Heavy & Medium Duty Vehicles**	
Criteria	**Unit**	**350 bar**	**700 bar**	**350 bar**	**700 bar**
Standard	-	SAE TIR J2601	SAE TIR J2601	No Standard available *(only Guideline for Busses SAE TIR J2601-2)*	No Standard available
Max. Allowed Tank Capacity	kg H2	6	10	n.a. (user require approx. 60)	n.a. (user require approx. 60)
Hydrogen volume (@300K)	m³ H2	0,24	0,25	2,6	1,6
Charging Time (A-type dispenser)	kg per min	6	2	6	2

Figure 1: Hydrogen tank systems (350bar, 700bar) for different vehicle segments, their corresponding International Refuelling Standards specifying maximum capacity for on-board hydrogen storages, resulting hydrogen volume and charging times

In this study, we design a national HDV-HRS network from a capacitated flow refuelling location model (capacitated FRLM). The optimization model FRLM has been widely used in previous studies to develop infrastructure for alternative fuel stations [5–11]. However, an FRLM extension considering limited station capacity remains unsolved as the capacity restriction was implemented as additional step after the location optimization and resulted in an heuristic [7, 11]. Our model will fill this gap including the station capacity restriction as additional constraint into the optimization algorithm of the FRLM.

2 Methods and data

2.1 Optimal HDV-HRS Network Determination

In order to design a HDV-HRS network, we developed a model consisting of two parts: a hydrogen demand determination model (DDM) and a potential HRS location model (PLM). As a first step, the DDM gives us information regarding the hydrogen demand on a regional scale. It uses HDV traffic data, FC-HDV powertrain efficiency and FC-HDV market diffusion as input to forecast the regional hydrogen demand on a NUTS3 level.

The PLM model helps us to identify the optimal HDV-HRS locations on German highways based on the output from the DDM. The PLM model is built based on the FRLM from [8]. Within the FRLM, the traffic is considered as a flow of demand, which starts, ends or passes by businesses that want to serve this given demand. In this study, the flow is determined as HDVs trip from an area to another based on the available data. Generally, the concept of flow-based demand closely resembles the behaviour of heavy-duty freight trucking operations because truck drivers tend to refuel *en route* to their destination. A similar approach as the FRLM extensions developed by [9, 10] is also applied in the model.

We use a traffic intensity data from [12] and local Germany HDVs trips and routes information from [13]. We define HDV trips between the German NUTS 3 regions as "OD trips" to construct the PLM model. The [12] and [13] data will be further explained in the following section. Moreover, the coordinates of each highway section are gathered to spatially build the German highway network. Our German highway network covers a total of 2,405 nodes with each node represent a single highway entrance point. Several assumptions, which depict as closely as possible to meet real conditions, are moreover applied in the model. The following assumptions are applied to our models:

(1) A station will only be placed in one of the nodes that is in the highway network.
(2) A vehicle drives in a single OD path that is determined as the shortest path from the centre of the origin area to the centre of the destination area.
(3) The distance travelled is equal to the fuel consumption.
(4) Only trips with a distance of higher than 50 km need refuelling.
(5) The traffic volume within a single OD path is known in advance.
(6) The drivers have full knowledge about the location of refuelling stations in the path and refuel as much energy as used on their single trip.
(7) The maximum driving range per refill of each vehicle is similar.
(8) Each trip starts with a fuel to reach a predefined range, and each vehicle only refuels to the amount it needs to complete the trip finishing with a predefined range tank level. A refuelling to a maximum level only occurs if the trip is longer than the maximum driving range.
(9) All refuelling stations are capacitated.

The first assumption is made with respect to the characteristic of a highway, in which station is normally located close to the entrance / exit point. With regard to the second assumption, the shortest path from the entrance node to the exit node in the highway network is calculated by applying the Dijsktra algorithm [14] effectively to every path in the OD trip. We then measure the shortest Euclidean distance from each central point to the nearest highway entrance as an access for the HDVs to reach the highway. While HDVs are less likely to travel within a city, HDVs still need to deliver the goods to the inner city area, which makes this assumption reasonable. The third and fourth assumptions are made to increase the effectiveness of HRS deployment. The fifth assumption is made with the data availability. Using a correlation between both [12] and [13] data, which was performed by testing the significance of the slope of the regression line, we define the amount of HDVs that travel within a single route. An average of 244 HDVs for each OD trip was then identified. The sixth assumption is logical with the availability of GPS in current situation. The seventh and eight assumptions are made because in a long journey, logistics companies (HDV users) normally have short lead- and load-times of new orders. Hence, they cannot refuel at all origins or destinations but on their route and thus rely on public refuelling infrastructure. This also explains the previous assumption, which is only a single trip, and not a round-trip, is considered in this model. Assumption (7) is also made assuming a uniform model of the fuel cell HDVs, as future fuel cell HDVs model is still uncertain.

Our assumptions then result in only some of the OD trips are included in the model. These are unique trips that travel from and to different NUTS 3 regions, trips with a distance of higher than 50 km, and trips that passed at least a single highway section, which consists of a single entrance and exit highway point. Out of a total of 4,103 OD trips provided, only 1,513 trips are considered in the model.

In this study, we also investigate the effect of capacity limit in the optimal HRS location for fuel cell HDVs. This last assumption is based on national regulations [Annex 1, Federal Immission Control Ordinance (Bundesimmissionsschutz-Verodnung BImSchV)], whereas operators storing below 30t hydrogen of HRS may use a "simplified procedure" when build the HRS compared to an extended "approval procedure with public participation" when storing above 30t hydrogen. In addition, storing above 30t hydrogen would require "extended obligation" [Incident Ordinance, BImSchV]. Hence, our stations have a capacity limit at 30t hydrogen. To analyse the capacity restricted model, we further extend the model to determine the optimal HRS location with capacity restriction.

The formulation of the PLM model, which is without the capacity limit restriction, is as follow:

$$Min \sum_{i \in N} z_i \quad (1)$$

s.t.

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

$$\sum_{q \in Q} f_q y_q \geq S \quad (3)$$

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

Nomenclature

Sets

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 refuelling station sites / nodes that can refuel the directional arc $a_{j,k}$ in A_q
N	Set of all nodes that built the highway network, N = {1,…n}
Q	Set of all OD pairs

Parameters

$a_{j,k}$	Unidirectional arc from node j to node k
f_q	Total vehicles flow per OD trip refuelled
i,j,k	Indices of potential facilities at nodes (i = potential node for HRS; j = current node; k = following node)
q	Index of OD pairs
S	Objective percentage of the traffic flow refuelled[1]

Decision Variables

y_q	$y_q = 1$ if the flow on path q is refuelled. $y_q = 0$ if otherwise
z_i	$z_i = 1$ if a refuelling station is built at node i. $z_i = 0$ if otherwise

The equation represents our objective to minimize the number of stations built (z_i) over all nodes i in the entire network N. Equation (2) is a constraint which [9] developed to replace the requirement to calculate initial feasible station combinations in most FRLM models. Constraint (2) assures that if path q is refuelled (y_q), there should be a minimum of one station that is built (z_i) in one of the nodes i that is in a set of potential stations sites $K_{j,k}^q$. Equation (3) is a constraint that ensures the total amount of flow (f_q) in every path refuelled (q) needs to be larger or equal than the minimum service coverage that wants to be observed. Equation (4) represents the nature of every indices and variables, where z_i and y_i are binary variables, q is an element of set Q, and i is an element of set N. The set $K_{j,k}^q$ is determined prior to the optimization process. We made an algorithm that used a similar approach as [10] to define the set. Generally, the algorithm operates with iterating over each node, starting from the origin point, which is also the current node j, and calculates the (cumulative) distances to the next node k. If the distance to the next node k exceeds the vehicle range, the algorithm will check the (previous) nodes that are potential locations to build 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. We excluded nodes that represent intersections in the highway network as a potential station location, as a refuelling station is rarely built in a highway intersection. The vehicles will start with an initial level of fuel that is capable to reach 300 km and end their trip in the destination with the same level of fuel. Furthermore, the maximum level of fuel in a vehicle can achieve a driving range of 800 km. General differences between our PLM model and other models (e.g. [9]) are assumption (4) and assumptions (7) to (9). Our algorithm then results in 10,374 sets of $K_{j,k}^{q}$ from all 1,513 OD trips.

Meanwhile, we expand the PLM formulation for the capacity-restricted PLM (CPLM), which adds the following additional constraints:

$$\sum_{q\in Q} f_q\left(e_{iq}+r_{iq}\right)\cdot p\cdot\ y_q\cdot g_{iq}\cdot x_{iq}\ \leq\ c\cdot z_i \quad (5)$$

$$\sum_{i\ \in K_{j,k}^{q}} x_{iq} = y_q \quad (6)$$

$$x_{iq} \leq\ z_i \quad (7)$$

$$0 \leq x_{iq} \leq 1,\ g_{iq}\ \in \{0,1\} \quad (8)$$

Additional parameters

c capacity at node i

d_q the amount of fuel required to accomplish path q

e_{iq} distance from origin point to node i in path q

r_{iq} distance from node i to destination point in path q

p fuel consumption

Additional variables

g_{iq} binary variable; 1 if node i is in path q, 0 if otherwise

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

Scenario settings

c = 30t (following legal regulations in Germany)

e_{iq} ≤ 300km

r_{iq} ≤ 800km

S = 100% (all flow will be refueled at least once per trip)

Here, we add constraint (5) – (7) to limit capacity per potential station the model. The constraint (5) represents that if the total demand served in node *i* is less than the capacity limit, then a station can be built there. The total demand that is served in node *i* from a path *q* is equal to the total flow of trucks (f_q) multiplied by their fuel consumption (*p*) and the amount of fuel required to reach node *i*. This is represented by the fuel used to reach node *i* (e_i) plus the remaining fuel needed to reach the destination / maximum range (r_i). The fuel consumption of each vehicle is similar, amounting 0.048 kg H_2 / km in 2050. g_{iq} is a binary variable that works as an indicator of potential station location. x_{iq} is a variable that determine whether vehicles in path *q* should refuel in node *i* so that the sum of vehicles refuel in node *i* should not exceed the capacity limit. The sixth constraint defines that if path *q* is refuelled, all vehicles in path *q* can refuel in any open stations along the path, as long as all vehicles do a refuelling and the seventh constraint represents that if a vehicle in path *q* refuel in node *i*, then a station should be open.

2.2 HDV Traffic and Technology Data

Traffic data

To characterize German HDV traffic, we use two types of input: highway road data to determine the current network system as well as individual HDV vehicle trips to understand the traffic flow.

The German Federal Highway Research Institute [12] regularly publishes traffic data for German highways. We use their 2500 traffic surveillance points (hereafter referred to as "nodes") including distances between adjacent nodes. These nodes and their connecting routes represent the complete German network of about

13,000 km and 121 highways, respectively. We enriched those nodes and routes with the most recent HDV road traffic census (2017) and added spatial data (geographic coordinates and NUTS3 areas). The available HDV data includes trailer and tractor trucks (26 to 40 tons) with traffic of about 62 million vehicle kilometres per day.

To apply a method addressing the flow refuelling location problem, individual vehicle flows are essential. We used data from [13], which is one of the most comprehensive surveys on vehicle traffic in Germany. This data contains 44,393 individual vehicle trips from about 35,200 vehicle IDs covering the origin NUTS3 area as well as the destination NUTS3 area. Thereof, 4,103 trips are completed by HDVs i.e. trailer and tractor trucks ranging from 26 to 40 tons; being congruent with the categories of the previous mentioned road traffic census

We are using Germany as a case study. The total demand of hydrogen is determined based on both the current and expected HDV traffic demand as well as on the national climate goals. The current HDV traffic data is recorded and available online by [12]. The institute collects the data on a yearly basis containing the number of passenger cars on all German highway sections (about 2,500 sections in total) as well as the share of HDV per section at an average working day. This current demand is extrapolated with [1], both on a highway and nationwide level. The market diffusion of FC-HDVs into the German HDV stock is given as an external input from the ALADIN model (www.aladin-model.eu). For a further explanation of this tool, we refer to [15, 16] and current work with the tool on HDVs [17]. Applying previously defined FC-HDV design parameter to a scenario with only FC-HDVs as an alternative powertrain, we see growing market penetration from 2030 onwards with about 40% FC-HDVs in stock in 2040 and 88% in 2050 with a stock of 176,000 FC-HDV in Germany by then.

Technology

We define a portfolio of potential HDV-HRS sizes. Initially, we use customer requirements that were collected from qualitative interviews with logistics companies to define FC-HDV parameters. These requirements result a range of 800km range with a 60kg on-board hydrogen storage. These parameters serve as input for the HDRSAM model (Heavy Duty Refuelling Station Analysis Model [18] defining six main HRS size types, which we use in this analysis: from size XS (0,9t hydrogen equalling 15 vehicles per day) to XXL (30t hydrogen equalling about 500 vehicles). All types operate with 700 bar, a cascade compressor and offer a maximal dispensed amount of hydrogen per vehicle of 60 kilograms from an on-site hydrogen production. Figure 2 shows main technical parameters of these HRS types.

Parameter	Unit	XS	S	M	L	XL	XXL
Vehicles	[HDV/d]	15	31	61	123	246	492
Hydrogen Demand	[kg/d]	938	1,875	3,750	7,500	15,000	30,000
Low pressure storage	[kg]	938	1,875	3,750	7,500	15,000	30,000
High pressure storage	[kg]	113	225	450	900	1,800	1,800
Electrolyser	[MW]	2	5	9	19	37	74

Figure 2: Overview HRS types (S, M, L, XL and XXL) based on [18]

3 Results

3.1 Hydrogen demand and the optimal HRS locations

As a result, we present the total hydrogen demand by FC-HDVs in 2050 and the optimal locations for HRS on German highways based on a capacitated optimization model.

As of today, the total German HDV traffic mainly occurs on corridors from east to west and north to south including highway sections up to 15,000 HDV per day. Hotspot areas are the cities of Cologne, Hannover, Karlsruhe and Oberhausen. Focusing the national HDV traffic, excluding traffic from foreign HDVs and HDVs starting or ending a trip outside Germany, the corridors are more limited to a few highways. Here, hotspot areas are Mannheim, Munich, Nuremberg and still Oberhausen with up to 12,000 HDV per day as shown in Figure 3. Overall, the national HDV traffic accounts for about 45% of the national HDV traffic in Germany. Assuming , 250 driving days per vehicle per year, a geographically even diffusion of FC-HDV and a HDV traffic growth of 2.5% p.a. [1], we reach an average daily HDV traffic per node of 700 HDV by 2050 (some peak nodes up to 25,000 HDVs). From all FC HDVs in 2050, the total daily hydrogen demand sums up to 2,200 tons, which is equal to 18 TWh annually and about 6 GW electrolyser capacity. The hydrogen demand per node is allocated to the OD paths to determine optimal HRS layout.

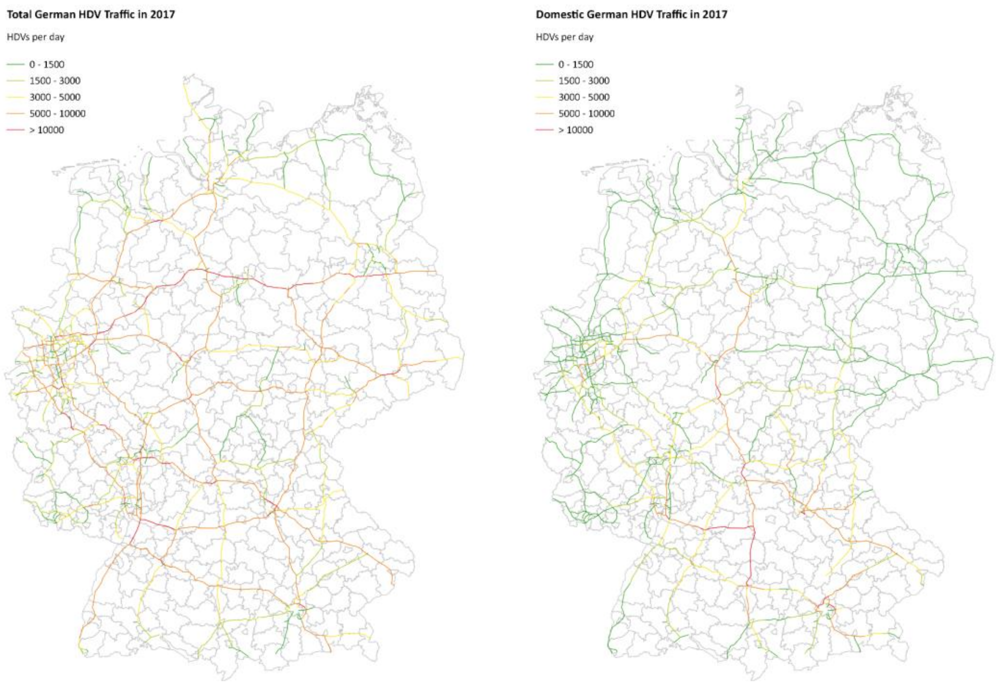

Figure 3: Total HDV traffic intensity on German highway in 2017 (left); national HDV traffic intensity on German highway in 2017 (right)

Presently, there are about 360 conventional refuelling stations located along the German highway network. These stations serve different types of vehicles (passenger cars, light- and heavy-duty vehicles) and also more concentrated in some areas, such as Frankfurt and Bavaria.

As result from our PLM model without capacity restriction, we achieve an optimal solution shown in Figure 4 (left). In sum, 90 HRS are required to satisfy FC HDV demand in Germany in 2050. The geographic locations of these stations are evenly distributed across Germany, with less HRS available in the northeast region (around Berlin). The highest number of vehicles passes by a HRS is around 65,600 HDV per day being located Ellwangen, Baden-Württemberg. Meanwhile, another HRS built in Donaueschingen, Baden-Württemberg serves the least vehicles with only 1,120 HDVs cross the particular area.

In the capacitated PLM with a capacity limit of 30 tons, the result indicates an optimum of 125 stations to serve all vehicles in all OD trips shown in Figure 4 (right). Out of those 125 stations, 121 stations reach the maximum capacity of 30 tons, and the average capacity of all stations built is around 28 tons. The lowest capacity of a station is around 10 tons, which is located in around Tremsbüttel in the northern part of Germany. Around 85% of the stations are located in western and southern Germany, which is a result of the high traffic demand and number of OD trips starting and travelling in those regions.

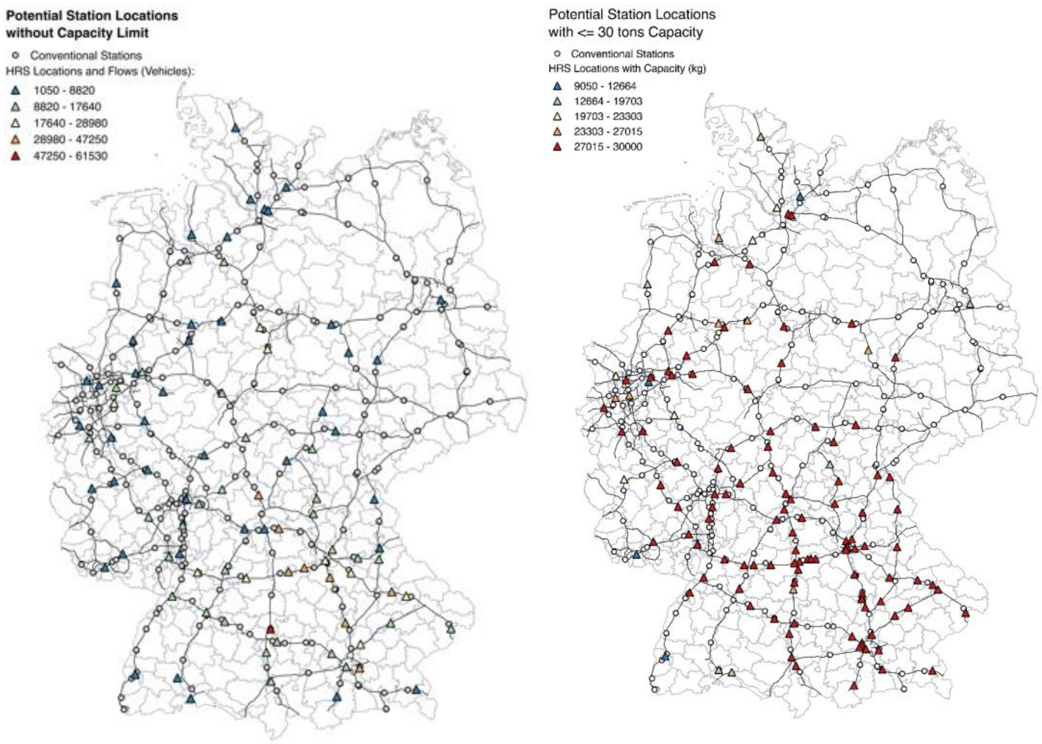

Figure 4: Regional distribution of existing 360 fuel stations (white points) and potential 90 HRS locations (triangles) based on uncapacitated PLM (left); existing fuel stations (white points) and potential 125 HRS locations (triangles) based on capacitated PLM with 30t limit (right)

3.2 Sensitivities

We added different capacity restrictions to further analyse the sensitivity of the station locations applying the following capacity limits: 7.5t, 15t, 30t and 60t. We choose the first two options to avoid the option for XXL stations, which represent the highest cost per station and thus may have the highest investment barrier. The last option will provide information about impact of doubling the regulatory limit on the minimal number of HRS.

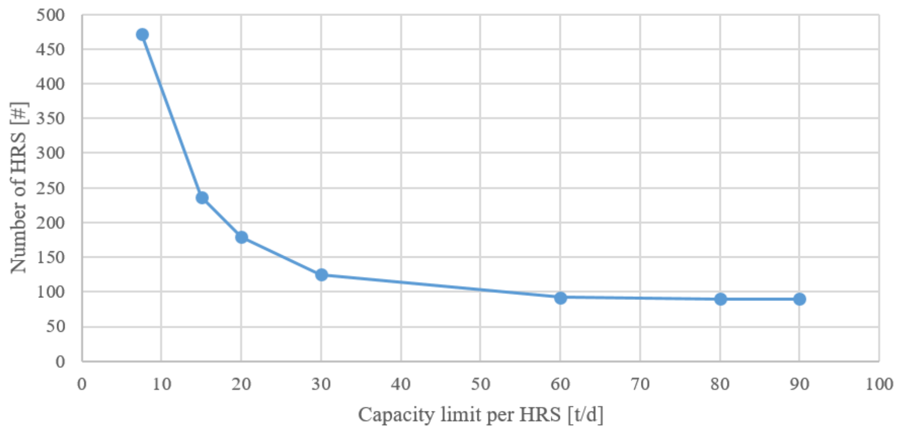

Figure 5: Number of optimal HRS locations dependent on the capacity limit per station [tons per day]

The results shown in Figure 5 indicate a saturation of HRS amount at a capacity limit of about 50t with below 100 HRS. Further, lowering the capacity limit per HRS exponential increases the number of stations with about 237 stations at 15t limit and 472 stations at 7.5t limit.

Capacity limit	XS	S	M	L	XL	XXL	[none]
[tons]	0.94	1.88	3.75	7.5	15	30	-
#HRS without limit	**-**	**-**	**-**	**-**	**-**	**-**	**90**
# HRS with 60t limit	-	-	-	7	12	73	-
# HRS with 30t limit	-	-	-	-	4	121	-
# HRS with 15t limit	-		-	-	237	-	-
# HRS with 7.5t limit	-	--	-	472	-	-	-

Table 1: Overview on number of station sizes (from given station portfolio) depending on capacity limit

Looking at the structure of station sizes within each capacity limit scenario, we find that the capacitated FRLM meets the HDV hydrogen demand mostly at the largest possible station configuration. As shown in Table 1, only 3,3% (four out of 125) of all stations in the network are smaller than the largest station from the given portfolio XS to XXL. Further, the 15t and 7,5t capacity limits only contain one single type of HRS (XL and L, respectively). In sum, only a small portfolio of station sizes is necessary to serve the full FC-HDV fleet demand on German highways.

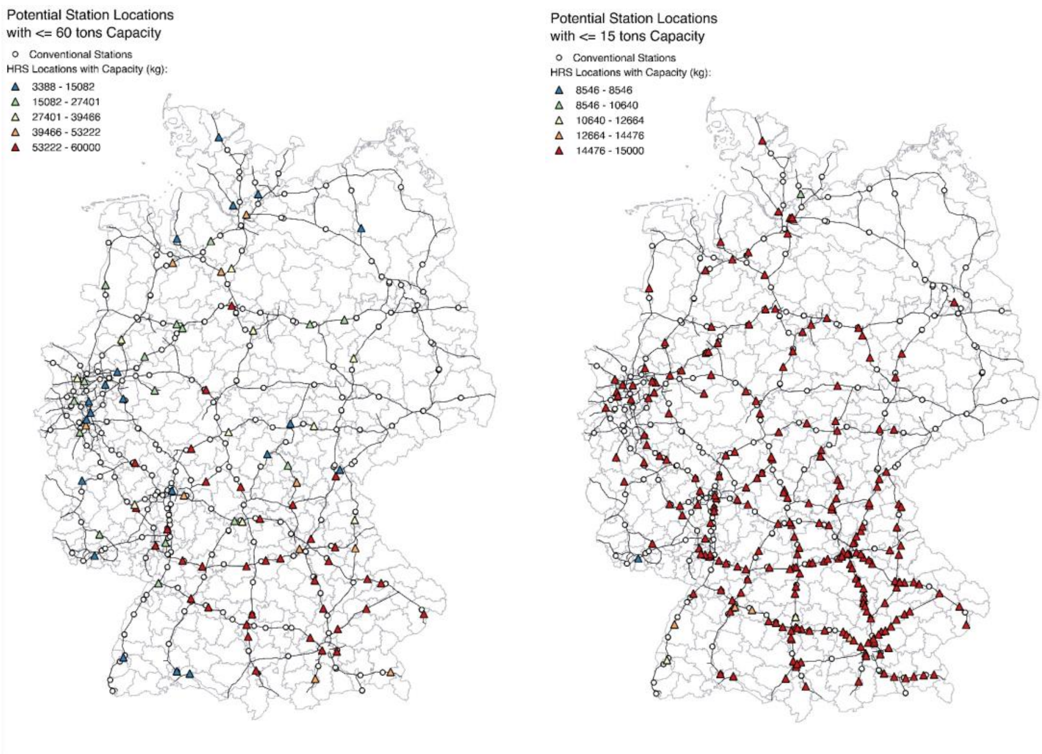

Figure 6: Regional distribution of existing 360 fuel stations (white points) and potential 92 HRS locations (triangles) based on the capacitated PLM with 60t limit (left); existing fuel stations (white points) and potential 237 HRS locations (triangles) based on capacitated PLM with 15t limit (right)

Lowering the capacity limit of the capacitated PLM, the regional imbalance of stations reinforces (cf. Figure 6). At a limit of 15t, the state of Bavaria already possesses about 25% of all HRS in the network. On one hand, this trend emphasizes the regional HDV traffic demand. On the other hand, it may also be caused by the large number of OD trips in that region.

4 Discussion, Conclusion and Outlook

In summary, we take three main findings from our analysis. First, the total hydrogen demand through national FC-HDV traffic within our scenario is about 3,500t of hydrogen per day (880,000t per year). Second, an optimal HRS network for FC-HDV on German highways in 2050 is at 125 stations in accordance with German legislation (capacity limit at 30t). Without capacity restrictions, the minimum viable HRS network is at 90 stations. Third, a suitable HRS portfolio depends on the capacity limit, but mainly consists of bigger sizes, such as XL and XXL, and almost no smaller sizes (S, M and L stations).

Compared with the existing conventional fuel station network in Germany, we conclude that the station network for HDV-HRS looks different in terms of geographic spread. The total number of optimal HRS locations is about 60% smaller following current regulations. However, with a very low HRS capacity limit of about 10t hydrogen, the number of optimal HRS would almost equal the amount of conventional stations. This is also the case if HRS want to ensure hydrogen availability for multiple days without new hydrogen supply to through the electrolyser. The regional spread of conventional versus HRS network is similar in central and west Germany. However, HRS density is lower in the northern and eastern regions, which might be caused by our focus that only include national HDV traffic in this analysis. The higher HRS density in Bavaria is likely to be caused by the large amount of OD trips in that area.

Regarding an optimal HRS portfolio, we conclude our larger HRS sizes to be most relevant to a mature HDV-HRS network in 2050. Assuming on-site hydrogen production, those stations would require electrolyser power larger than 30MW per station. These power requirements are at the upper range of current electrolysis projects and would require an extra-high voltage power supply. Smaller station sizes, however, may be relevant for market introduction or non-highway applications.

As our approach is limited, we suggest further research regarding method and data. The CPLM may be added with a HRS cost module (station and hydrogen production), so that the system cost for all stations may be optimized. Developing the method even further, the addition of a temporal analysis e.g. 2030, 2040 and 2050 to define network built-up strategy seems interesting to gain understanding of the optimal network built-up strategy. In addition, an interplay of station optimization along the highway network with the energy grid (proximity to the grid, grid bottlenecks, and demand response) seems beneficial. As our data only considers FC technology, an addition of potential alternatives for long distance HDV such as catenary trucks or Power-to-Gas may be of interest to better understand the market diffusion of FC-HDV. Further, we only consider national (domestic) traffic. Being a transit country within Europe, Germany is exposed to relevant more than national traffic; hence, the additional demand may also be considered in future analysis. Finally, our traffic data only covers domestic traffic with traffic flows from about a decade ago. More current data for national and international HDV traffic flows may also add to our results.

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