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The market introduction of hydrogen focusing on bus refueling

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ABSTRACT

Public transport plays a prominent role with respect to mitigating transport-related environmental effects by improving passenger transport efficiency and the quality of life in cities. Batteries and fuel cells are at the forefront of the technological shift to zero-emission powertrains. Within the scope of the German-funded project BIC H2, corresponding systems analysis research focuses on the market introduction of fuel cell–electric buses in the Rhine–Ruhr Metropolitan Region through 2035. This study presents the related methods and major outcomes of this techno-economic research, which spans spatially-resolved hydrogen demand modeling of all relevant sectors, to hydrogen refueling stations and upstream infrastructure modeling, to scenario-based analyses. The latter builds upon an empirical study supporting the development of the Hydrogen Roadmap of the State of North Rhine–Westphalia (NRW). Our results show that the demand in NRW alone is expected to account for one third of total German hydrogen use. Hydrogen bus refueling could substantially support market introduction during its early phases. In the long term, however, hydrogen demand in industry is significantly higher compared to that in the transport sector. Furthermore, spatial analysis identifies regions with pronounced hydrogen demands that could, therefore, be candidates for initial infrastructure investments. With the Cologne area showing the highest hydrogen demand levels, such regions can offer particularly high infrastructure utilization, e.g., for bus refueling. On the infrastructure side, trailers for transporting gaseous hydrogen to refueling stations are the most favorable option through 2035. Pipelines would be the preferred solution soon after 2035 due to increased hydrogen demand. If effectively deployed, converted natural gas pipelines would be the most cost-effective option even earlier.

1. Introduction

A successful transition of the transportation sector towards carbon neutrality is particularly linked to the avoidance, modal shift, and improvement of its environmental performance. Public passenger transport plays a special role in this context: in terms of modal shift, on the one hand, a significantly higher degree of transport efficiency becomes feasible. On the other hand, the change of propulsion technology towards electric drivetrains with batteries and fuel cells allows a significant improvement with regard to the environmental impact of transport by inherently avoiding local emissions and simultaneously switching to low-greenhouse gas (GHG)-emitting fuels. In this context, the concept of sector coupling is particularly noteworthy, as it entails the use of renewable electricity via the generation of hydrogen and, where appropriate, the generation of downstream products for industrial and transport application [1,2]. Against the background of intended improvements in local public transport, the BIC H2 project that was funded by the German Federal Ministry for Digital and Transport focuses on the fuel supply of bus fleets in hydrogen operation. The respective locations of the project's two hydrogen refueling stations ((HRS)) are the cities of Wermelskirchen and Meckenheim near Cologne in Germany. This study presents major outcomes of systems analysis research that has accompanied BIC H2 with regard to the market introduction of hydrogen as a fuel for fuel cell buses.

During the exercise, it became clear that the foreseeable contribution of additional demands in transport and industry, which may go far beyond hydrogen uptake for bus and car refueling, would require more detailed consideration, especially to analyze and evaluate the effect of shared infrastructures on supply costs. For this reason, an extended approach was developed and used to permit a more comprehensive analysis of hydrogen supply systems with additional sources and offtakers. A detailed overview of the methodology used is shown in Table 1. Elements of the content presented in these sections are taken from Cerniauskas (2021) [3].

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Table 1
Key elements of analyzing hydrogen market introduction with a focus on fuel cell bus refueling. HRS: Hydrogen refueling station.

Identification of relevant hydrogen utilization sectors
- Infrastructure elements: H_2 production, storage, conditioning, transport, and dispensing
- Hydrogen applications: Transport (buses, cars, trucks, and trains) and industry (chemical, steel, and industry logistics)
Model development and application (ETHOS.H2MIND)* [3]
- Demand modeling in appropriate spatial and temporal resolutions for all applications considered (see above)
- Consistent HRS modeling for buses, cars considering fueling rate, quantity, duration and profile, and mode alternatives for hydrogen delivery
- Modeling of hydrogen dispensers in industry
- Options for converting natural gas pipelines for hydrogen operation
Scenario
- Defined scenario H_2 Roadmap NRW for the years 2025, 2030, and 2035 [4]
Model parametrization (ETHOS.H2MIND)
- Results from scenario-related country-wide energy system modeling with ETHOS. NESTOR (part of IEK-3's ETHOS modeling suite) [4]
- Hydrogen supply scenarios within BIC H2 project

[*] ETHOS is the name of IEK-3's modeling suite "Energy Transformation PatHway Optimization Suite" which contains a variety of energy system models, a part of which was used in this study, i.e., ETHOS.NESTOR, ETHOS.H2MIND and ETHOS.Infrastructure. More information on ETHOS.NESTOR can be found in Kullmann et al. [5], on ETHOS.H2MIND in Cerniauskas [4] and on ETHOS. Infrastructure in Busch et al. [6].

In the following sections, the study's objectives and procedure are explained in detail and the results are presented. In the remaining Section 2, the background objectives of the project-related research is presented. The concrete procedure for model development is the subject of section 2. Section 3 then explains the scenarios developed for the analysis of the market introduction and presents the results.

1.1. Background and study objectives

The introduction of electric buses is supported by political objectives (Climate Protection Program 2030 of the German Federal Government) and legal requirements (Law on the Procurement of Clean Road Vehicles in the implementation of the Clean Vehicles Directive of the EU) [7–9]. In addition to battery–electric buses (BEBs), fuel cell–electric buses (FCEBs) are currently gaining importance worldwide. A report by the National Renewable Energy Laboratory (NREL, USA) estimates the number of FCEBs in currently planned projects globally to be around 4000 (excluding the USA) [10]. Asia accounts for 98% of these, at around 2500, and Europe for just under 1500 [10]. In the USA itself, corresponding projects are concentrated above all in the state of California. Here, it is assumed that at least 1800 FCEBs will be deployed by 2040 [10]. According to the German company NOW GmbH, the stock of zero-emission buses in Germany as of 01/05/2022 was 70 FCEBs and 1468 BEBs, according to information from the German Federal Motor Transport Authority (KBA) [11]. With regard to the project BIC H2, 52 buses out of the 70 FCEBs are operated by Regionalverkehr Köln GmbH. The acquisition of a further 108 is planned [12]. The maturity level of the vehicle technology is currently classified in the technology readiness level (TRL, [13]) schema as having a TRL of seven to eight (the highest market readiness corresponds to a TRL of nine) [10,14]. For further information regarding the current status in Germany, the report on the accompanying research program on innovative drives and vehicles is recommended [14].

In addition to functional and reliable refueling facilities, the successful nationwide deployment of hydrogen-powered FCEBs in particular face the economic challenge of a cost-efficient hydrogen supply. Thus, the following options with selected examples are being discussed and implemented today:

- Refueling at bus depots with supplied (BIC H2 project), self-produced (Wuppertal [15]), or locally-available hydrogen;
- Refueling at public or non-public external refueling stations with delivered (eFarm [16]), self-produced, or locally-available hydrogen (Hürth [17]).

Although delivered and on-site-generated hydrogen can only partially be assumed to come from renewable sources today, a complete switch to green hydrogen, with a particular focus on electrolytic generation with renewable electricity, is required in Germany in the medium to long terms.

Within the framework of the BIC H2 project, the main objective of this study is to improve the quality of simulation modeling-based hydrogen market introduction analysis. We therefore integrate an existing simulation model for market roll-out analysis findings from project activities on the hardware side of the BIC H_2 project with results from cost-optimizing energy system modeling. With respect to the project goals, we focus on hydrogen-fueled FCEBs for local transport in Germany's Rhine–Ruhr Metropolitan Region which is located in the State of North Rhine–Westphalia (NRW). Central to our simulation-based analysis are computer models that were previously developed by Reuss et al. [18–20] and Cerniauskas [4] for analyzing hydrogen infrastructures and explorative market rollout scenarios, respectively. For the purpose of this study, we furthermore integrate scenarios based on the results of the accompanying scientific study [4] for the Hydrogen Roadmap of the State of North Rhine–Westphalia (H_2 Roadmap NRW) as we consider these scenarios most relevant for the hydrogen infrastructure development in the region analyzed. More specifically, the H_2 Roadmap NRW considers – on a high level of detail – the role of hydrogen during the transition to a near-zero greenhouse gas emission economy in Germany through 2050 and provides energy-economic data relevant to the present study.

With respect to the market introduction of hydrogen as a fuel for transport or as an industrial feedstock, the demand side must also be taken into account, which in turn has an impact on the design, costs, and utilization of the infrastructure and so the fuel costs via connection capacity, demand profile, and quantity. Current global hydrogen demand amounts to some 115 million t per year and relates primarily to non-energy uses in the heavy and chemical industries [21,22], such as oil refining, as well as methanol and ammonia production [21]. Smaller applications can be found in the food processing, electronics, and glass manufacturing industries [23]. In the future, there will be significant increases in hydrogen use, especially in the steel industry, power-to-fuel processes, re-electrification in the power sector for balancing residual grid loads, and the transportation sector. Moreover, hydrogen utilization for heating appliances in the industrial and residential sectors are also under discussion at present. Based on a detailed analysis of current hydrogen and fuel cell-related projects, this study considers hydrogen demands in (i) the transport sector, i.e., local buses, non-electrified rail lines, cars, trucks, and material handling vehicles; and (ii) industry, i.e., refineries, ammonia production, methanol and steel production, and defines these as hydrogen sub-markets.

On the supply side, the hydrogen production processes of electrolysis, methane reforming, and hydrogen import are included in the analysis. Other elements of the process chains considered here are compressed and liquefied hydrogen storage vessels, salt caverns, and hydrogen conditioning and processing equipment. These include compressors, liquefaction plants, vaporizers, and temperature and pressure swing adsorption plants for hydrogen purification. Delivery options considered include trucks for pressurized and liquid hydrogen transport, as well as newly-built hydrogen pipelines or natural gas pipelines reassigned for hydrogen transport.

Finally, it is necessary to perform the market introduction analysis on a national level for Germany and with the inclusion of all relevant demand drivers, as an isolated consideration of the Rhine–Ruhr Metropolitan Region does not seem to be appropriate due to supra-regional production sites (large-scale electrolyzers) and large-scale infrastructure elements (pipelines). The inclusion of further hydrogen consumers in the transport and industrial domains significantly increases the hydrogen quantities to be transported and thus also determines the most cost-effective logistics options in each case.

The previously-mentioned aspects are decisive for the development of the methodology, which is further detailed in Section 2. At appropriate points, information from the construction and operating phases of the fueling stations will be incorporated into the considerations.

2. Methods and data

In order to implement a sound techno-economic analysis of the development of hydrogen supply systems by 2050, a five-step approach was developed within the framework of the BIC H2 project: (i) determination of market potentials in the hydrogen submarkets; (ii) derivation of market penetration scenarios in the hydrogen submarkets; (iii) regionalization of hydrogen demand for the submarkets; (iv) concretization and analysis of hydrogen supply pathways; and (v) analysis of the hydrogen supply infrastructure's development. The respective workflow is implemented in IEK-3's ETHOS.H2MIND model. For performing scenario calculations in the present study, we include results from ETHOS. NESTOR and ETHOS.Infrastructure calculations that were conducted during the preparation of an empirical study [4] supporting the Hydrogen Roadmap of North Rhine–Westphalia (H_2 Roadmap NRW). In the following, we introduce relevant, BIC H2 project-related information before presenting details of methods and data pertaining to hydrogen demand and supply, as well as infrastructure and cost modeling.

As previously noted, Germany was selected as the balance boundary, as the connection to further supply areas can be implemented in a simplified way due to the small number of coupling points, i.e., to neighboring countries and seaports. With respect to BIC H2's regional focus, results will be presented in greater detail for the Rhine-Ruhr Metropolitan Region located in the State of North Rhine-Westphalia, Germany. Furthermore, requirements were defined regarding the project-specific system design and parameters, as well as refueling station operation. These are refueling station costs and market introduction scenarios related to the prospects for a nationwide hydrogen supply. Moreover, measurement and reporting data from fueling station operation were used for parameterization (Table 2).

Table 2
Project-related information regarding the hydrogen refueling stations (HRS) in the cities of Wermelskirchen and Meckenheim, Germany.

Wermelskirchen	Meckenheim
H_2 delivery - from Marl and Dormagen (Germany), at present - at 200 (at present) or 300 bar - duration of trailer unloading 45–60 min Buses: - Fuel economy: ca. 8 kg/100 km on average (ca. 9 kg/100 km during wintertime) - use in different bus rotations - maximum mileage per rotation: 300 km (Remscheid–Köln during weekend) - internal rule: H_2 buses first in the morning for noise protection of adjacent residential areas – 10 years of operation planned with an optional extension H_2 mass storage: - at 6–45 bar using H_2 bottles High-pressure storage - Constant at 400 bar, max. 240 kg H_2 – 9 piston storage vessels Compressor: - ionic piston compressor - capacity: 4x (2 × 2) 20–25 kg/h (per compressor) at 600 bar (4 of 5 stages used); variable minimum inlet pressure - power rating: max. 75 kW per compressor + auxiliaries; 175 kW per container (2 compressors) + cooling – 5 compressor stages and up to 900 bar possible - Energy use: 3 kWh/kg_{H2} Bus refueling: - max. 15 min incl. “handling-time”; max. 10 min. refueling time - cooling of H_2 to 0 °C (cooling unit adjacent to dispenser → short distance)	H_2 delivery - from Marl and Dormagen (Germany), at present Buses: - H_2-consumption per bus and tour: ca. 16 kg - Average specific consumption: <8 kg_{H2}/100 km, slightly elevated in wintertime - use in different bus rotations – 10 years of operation planned with an optional extension Low-pressure storage: - trailer at 200 (at present), 300 bar, or 500 bar - 2 trailer spaces incl. protective wall Compressors: - H_2 relieved to 30 bar compressor inlet pressure - Two-stage compression to 500 bar: stage 1: 125 bar, stage 2: 500 bar - mass flow: 8.3 g/s High-pressure storage: – 81 × 216 L tanks → ~1000 kg H_2; of which 500 kg can be utilized Bus refueling: – 350 bar at 15 °C – 10 min refueling time - H_2 cooling to −23 °C (rated cooling power: 85 kW) - mass flow: 40 g/s

Fig. 1 shows typical real data of all refueling operations at the Wermelskirchen site in the period from 26/07/2021 to 01/08/2021. The left diagram (a) of the figure shows the refueling volume depending on the time of day. This reveals that the majority (85%) of refueling operations are carried out in the second half of the day. Only four of the 59 refueling operations recorded occurred in the morning hours between 00:30 and 10:30. These time-of-day-specific findings support the bus refueling load profile shown in Fig. 2, which is used in the system's analytical studies. The average refueling quantity in the visualized observation period is 10.7 kg, with a refueling duration of less than 6 min.

The diagram in Fig. 1(b) displays the pressure at the beginning of a refueling process as a function of the refueling quantity. The visualization of the real data points illustrates the expected negative correlation between the two variables. The larger the refueling quantity, the emptier the vehicle tank is at the beginning, which is associated with a lower pressure. On average, the tank pressure at the start of the refueling process is 207 bar.

2.1. Supply infrastructure

The modeling of the hydrogen delivery infrastructure is based on previous work, which is referenced here. This concerns the newly built hydrogen and natural gas pipelines converted to hydrogen transport [24], pipeline, and truck routing [20], as well as the HRS modeling [25]. Further information can also be found in Cerniauskas (2021) [3]. Related to pipeline and truck routing, existing models are further developed in the present work for achieving better optimization results and to simplify the analysis. The target is to better reconcile the number of regional hubs with the costs of transportation by trailer and pipeline. The basic idea of this approach is that non-linear systems can be described linearly on a sufficiently small scale. Applied to the problem of route finding for transportation by pipeline and trailer, this results in a comparison of the specific delivery costs for each edge of the network. However, as transportation by pipeline and trailer do not use the same routes, a threshold is introduced to determine the maximum allowable specific cost of a pipeline edge between two nodes. After cost optimization of the pipeline network also regarding pressure losses, all edges whose costs exceed the threshold are discarded, and hubs are established at each node with the capacity of the first edge removed. Then, distribution by trailer is optimized among the newly-configured sources and hubs to supply the sinks. It was found that a threshold value of 0.003 €/(kg/km) would be suitable and that this value is used in the present study.

In relation to the HRS model, it should be noted that this is characterized by a high versatility corresponding to its high range of applicability spanning cars, trucks, buses, trains, and industrial uses. Table 3 shows a typical assignment of the model's input parameters. The requirements of fueling stations for industry are normally lower in comparison to road vehicle fueling stations and their design is simplified because the hydrogen is often taken more continuously on a scheduled basis. The number of inputs is, therefore, reduced. Component scaling and optimization is accomplished step by step, starting with a storage tank and dispenser, followed by the cooling unit and ends with a

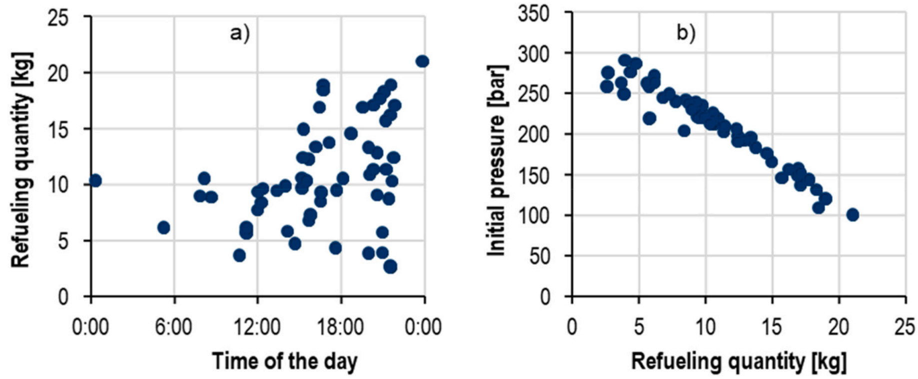

Fig. 1. Fueling quantities depending on daytime (a) and initial tank pressure depending on the refueling quantity; (b) data points are taken from the actual HRS operation in Wermelskirchen during 26/07–01/08/2021.

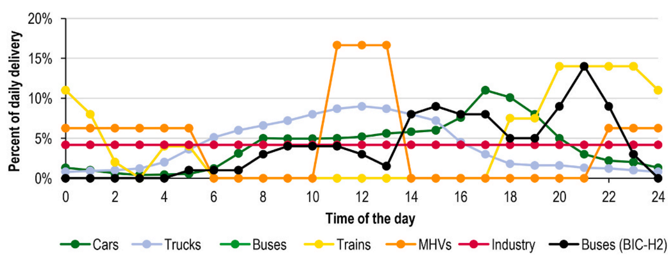

Fig. 2. Assumed time series of hydrogen refueling for different fuel cell-electric vehicle (FCEV) markets [34–37]. MHV: Material handling vehicles.

Table 3
Range of input parameters of the hydrogen refueling station model. CGH_2: Compressed gaseous hydrogen; LH_2: Liquefied hydrogen.

Category	Input parameter	Value
Delivery information	Delivery mode	CGH_2, pipeline, on-site production, LH_2
	Delivery pressure (bar)	Depending on delivery mode
Operational data	Utilization technology	Car, truck, bus, train, conveyor, industrial plant
	Daily demand (kg/d)	Depending on type of application
	Refueling concept	Cascade, booster compressor, high-pressure pipeline, cryo pump concept
	Utilization	0–100%
	Daily hours of operation (h)	Up to 24 h
User-side technical data	Nominal tank pressure (bar)	Depending on type of application
	Tank size	
	Refueling time (min)	
	Buffer time (min)	

compressor or pump and cascade system.

The hydrogen sub-markets considered in this study feature different fueling station properties depending, e.g., on the vehicle segment served. An overview is presented in Table 4.

For the present analysis, publicly available refueling profiles for cars and trucks are used. For trains, refueling is assumed to occur in the late evening or early morning before the start of daily operations to ensure maximum operational flexibility. For forklifts, on the other hand, the usual two-shift operation is assumed, resulting in a notable increase in refueling at midday, as well as more consistent refueling during the nighttime hours. Deviating from the literature values, we use the bus refueling time series according to the project. Fig. 2 presents the corresponding data.

Table 4
Sub-market-specific refueling station properties, here relating to fuel cell vehicles. MHVs: Material handling vehicles. Remark: For larger vehicles, on-board hydrogen storage is composed of a number of tank vessels.

Property	Car	Truck	Bus	Train	MHV
Nominal tank pressure [bar]	700	350	350	350	350
Onboard storage capacity [kg]	3.5	35–40	35–40	170	3.2
Tank capacity [kg]	3.5	8	8	8	3.2
Time between refueling [min]	3	5	5	30	1
Refueling time [min]	3	10	10	30	1
Source	[26, 27]	[28, 29]	[28, 29]	[30, 31]	[32, 33]

The description of details on the fueling station components is omitted here. Related information can be found in the work of Cerniauskas [3].

2.2. Cost assessment

By means of economic modeling, the specific production costs of the hydrogen to be used are calculated. We employ the annuity method to distribute all relevant expenditures associated with the investment object evenly over the years of use. For this purpose, the total investment costs are first determined. Then, the specific capital-related costs (CAPEX) and operating and throughput-independent operating costs (fixed and variable OPEX) are converted into discounted annual cash flows over the period under consideration using a specified interest rate. The levelized cost of hydrogen (TOTEX) is the sum of the CAPEX and fixed and variable OPEX:

$$TOTEX = CAPEX + fix.OPEC + var.OPEX \quad (1)$$

For calculating the refueling station CAPEX, the costs of all major components (dispenser, gas storage tank, cryo-LH_2 tank, cooling unit, compressor, booster compressor, cryo-pump, vaporizer, cascade system, control system, and electrical system) are included. The related costs are drawn from Argonne National Lab's Hydrogen Refueling Station Analysis Model (HRSAM) and Heavy-Duty Refueling Station Analysis Model (HDRSAM) [38], also including the cost update for hydrogen storage and dispenser costs, according to Pratt et al. [39]. Table 5 lists the cost functions of all of the main components. An installation factor of 1.3 is also applied to all components to account for the installation costs.

$$AN_k = I * a \quad (2)$$

$$a = \frac{i * (1+i)^n}{(1+i)^n - i} \quad (3)$$

Table 5
Breakdown of fueling station investment costs.

Component	Cost estimate	Dimension	Source
Dispenser	57,500	2015 $	[39]
Cooling unit	$14,000 * \left(\frac{28.43 * P_{ref}[KW]}{T_{max}[^{\circ}C] + 273.15}\right)^{0.8579} +$ $35000 * \left(\frac{m_{HX}[kg]}{1000}\right)^{0.9}$	2014 $	[40]
LP storage	645	2015 $/kg-$H_2$	[39]
MP storage	822	2015 $/kg-$H_2$	[39]
HP storage	1190	2015 $/kg-$H_2$	[39]
CGH_2-Trailer	660,000 (capacity of 1100 kg)	2017 € per unit	[18]
LH_2 storage	$991.89 * m_{capacity}[kg]^{0.692}$	2014 $ per unit	[41]
Compressor	$40,528 * P_{comp}[KW]^{0.4603}$ [350 bar] $40,035 * P_{comp}[KW]^{0.6038}$ [700 bar]	2014 $ per unit	[41]
Cryopump	$4250 * m_{pump}[kg/h]$ [350 bar] $7000 * m_{pump}[kg/h]$ [700 bar]	2014 $ per unit	[41]
Evaporator	$m_{evap}[kg] * 1000 + 15,000$	2014 $ per unit	[41]
Booster compressor	$6000 * P_{booster}[KW]$	2014 $ per unit	[41]
Control systems and electronics	180,000	2014 $	[41]
Installation factor	1.3 for all components		[39]

$$CAPEX = AN_k / m_{H2,a} \tag{4}$$

where AN_k: capital cost; I: investment; a: annuity factor; i discount rate (8%); n: period (10 years); $m_{H2,a}$: annual hydrogen use.

The throughput-independent operating costs fix.OPEX are comprised of maintenance costs, capacity costs, personnel costs, and costs for control investigations (e.g., emission measurements). In our model, these costs are estimated to make up 10% of the total investment costs. The variable cost var.OPEX are given with equation (5).

$$var.\ OPEX = c_{strom} * \sum w_i + c_{H2} * \sum v_i \tag{5}$$

where: c_{strom}: electricity cost [€/kWh]; c_{H2}: hydrogen cost [€/kg]; Σw_i: specific electricity use [kWh/kg$_{H2}$]; Σv_i: sum of hydrogen losses [%].

Within the model, the electricity cost is determined based on the Eurostat 2016 electricity tariff according to the level of consumption [42], with the hydrogen cost assumed to be 9.5 €/kg. The losses differ according to the refueling station concept.

2.3. Hydrogen demand

This subsection explains the hydrogen demand modeling for Germany that references the scenario assumptions and results from the empirical study accompanying the H_2 Roadmap NRW, and which was derived from calculations made with the ETHOS.NESTOR model. The ETHOS.NESTOR model enables the calculation of cost-optimal transformation pathways for Germany's energy system through 2050. More detailed information on the structure and methodology used can be found at [4]. The information is complemented by further external data sources for achieving the demanded spatial resolution with respect to potential HRSs for bus operators in NRW.

According to the H_2 Roadmap NRW and as derived from the ETHOS. NESTOR calculations, the total demand for hydrogen in Germany is expected to be about 11 million t/a in 2050. The transport and industrial sectors will account for the largest shares, at 44% and 27%, respectively. In industry, the demand for hydrogen as a feedstock will be highest in steel production through the direct reduction of iron ore, followed by ammonia and methanol production. Also relevant for 2050 are the production of high-temperature process heat (>500 °C) and electricity for the energy system, whereas synthesis gas production as a precursor for e-fuels and chemicals and the generation of space heat for buildings in Germany are expected to play a minor role. The time frame of the present analyses (2025–2035) cover the short and medium time horizons. The corresponding hydrogen demand is detailed in the Supplemental Information (S 1). For the further calculations with the ETHOS. H2MIND model, the demand for re-electrification is excluded from the analysis, as the location of the corresponding power station sites requires the integration of an electric grid model, which is, at present, not possible with ETHOS.H2MIND. The hydrogen demand considered in this study is therefore lower compared to the ETHOS.NESTOR results.

In order to ensure the consistency of the ETHOS.H2MIND model, two additional hydrogen demand sectors are included in the simulation: the demand from forklifts and refineries. Even though they only account for about 2% in total, they are considered relevant for the market introduction phase. Demand for these two sectors is calculated using a specific methodology in ETHOS.H2MIND based on an improved version of the Bass model for technology and innovation diffusion as presented in the work by Cerniauskas [3]. The total hydrogen demand as used in this study is presented in Table 9 and in the Results and discussion sections.

2.4. Spatial distribution of hydrogen demand

The spatial distribution of future hydrogen demand is one of the critical aspects for determining infrastructure costs. It is conducted in two steps: first, in a nationwide approach on the NUTS3 (county) level and subsequently in relation to specific sinks within each NUTS3 region (NUTS: Nomenclature of Territorial Units for Statistics). The criteria chosen for allocating hydrogen demand to the submarkets considered in this study are displayed in Table 6. For fuel cell bus operation, we chose population and median disposable income in combination with fleet size, existing pilot projects, and associated federal funding for low-emission transportation. For trains, the allocation of fuel cell trains is determined by weighting the German states (NUTS1 level) with the length of non-electrified train lines, federal funding for regional development, and train mileages. Then, each NUTS3 region is weighted by the number of existing refueling stations for diesel trains. As with passenger cars, Robinius' approach [2] is used to allocate fuel cell vehicle demand according to population, population density, income, and total car ownership within the NUTS3 regions. The number of registered vehicles and registered freight intensities are used to determine the distribution of truck miles, with freight intensity estimated based on the mass loaded and unloaded in the NUTS3 region. For the allocation of forklifts, the freight intensity data are extended by the area of logistics sites, so that a correlation between the size of the forklift fleet and that of the logistics area is assumed. The selected weights for the relative spatial distribution of hydrogen demand is presented in Table 6. A more detailed description of the data sources can be found in Cerniauskas et al. [43].

The approach chosen for allocating hydrogen demand to individual

Table 6
Criteria for the spatial allocation of hydrogen demand at the NUTS3 level [4].

Buses	Trains	Cars	Industry	Trucks	Forklifts
Population	Non-electrified train lines	Population	Plant capacities	Mass loaded	Mass loaded
Income	Federal funding	Population density		Mass unloaded	Mass unloaded
Fleet size (NRW)	Train milage	Income		Fleet size	Area of logistics sites
	Diesel refueling stations	Fleet size			

sinks within each NUTS3 region distinguishes between public and non-public infrastructure, with the latter referring to commercial vehicle fleets and industry. In the case of public refueling infrastructure, a mixed-integer optimization (MILP) is performed for each region to determine the optimal number of refueling stations to meet demand. The model is only limited to the construction of small refueling stations (S: 212 kg/day) if a certain percentage of existing refueling stations within the NUTS3 region are not yet equipped with hydrogen dispensers. This assumption is based on other literature that examines the minimum size of the refueling station network necessary to provide sufficient geographic coverage during the deployment phase [44–46]. According to the strategy proposed by a joint venture to build HRSs in Germany [47], refueling stations will be built first on highways and then on main and rural roads. The construction of captive refueling stations is also limited to the appropriate existing infrastructure, such as industrial parks and warehouses. Due to the variability of daily refueling behavior and the associated uncertainty, the utilization rate of a public refueling station is set at 70% [25]. In contrast, non-public refueling stations can be geared to the needs of the company's own fleet of vehicles, allowing a utilization rate close to 100%. However, in order to achieve a more realistic deployment of non-public infrastructure, a minimum fleet size is required before it is deployed and an associated non-public refueling station site can be created. In cases where the minimum fleet size is not met, vehicles are allocated to regions that meet this criterion. This simplified approach allows for a better distinction between the main characteristics of public and non-public infrastructures, as it permits a higher concentration of vehicles at a single refueling station. In the future, this approach could be extended by allowing the refueling of smaller fleets of cars, trucks, and buses at public refueling stations, considering the initial testing phase of the vehicles by the fleet operators. Table 7 provides an overview of the data and methods used for the capacity allocation based on information provided in Cerniauskas et al. (2019) [43].

The nearly 100 fueling stations currently extant in Germany can be neglected in comparison to the total data points due to their small total number. Therefore, the present work does not consider them explicitly. Regarding the spatial allocation of hydrogen demand, a more advanced methodology is applied in the present analyses, especially with respect to the hydrogen demand of buses in NRW.

First, the existing bus depots in NRW are recorded, based on the list of bus companies in NRW's individual regions as presented in VDV 2020 [48]. The focus here is on municipal companies for public transport in NRW. This data collection aims to determine: (i) the GIS coordinates of the existing bus depots; and (ii) the size of the respective fleets for each depot. It is assumed that buses return to the respective depot for refueling at the end of each workday. Consequently, the installation of HRSs for buses at existing bus depot locations would be appropriate. The ETHOS.H2MIND input data of potential hydrogen bus refueling stations will be supplemented by the identified locations to improve the spatial description of bus refueling stations in NRW.

2.5. Hydrogen provision

The expected hydrogen supply to meet the demand described above is shown in Fig. 3, derived from ETHOS.NESTOR calculations [4]. Until

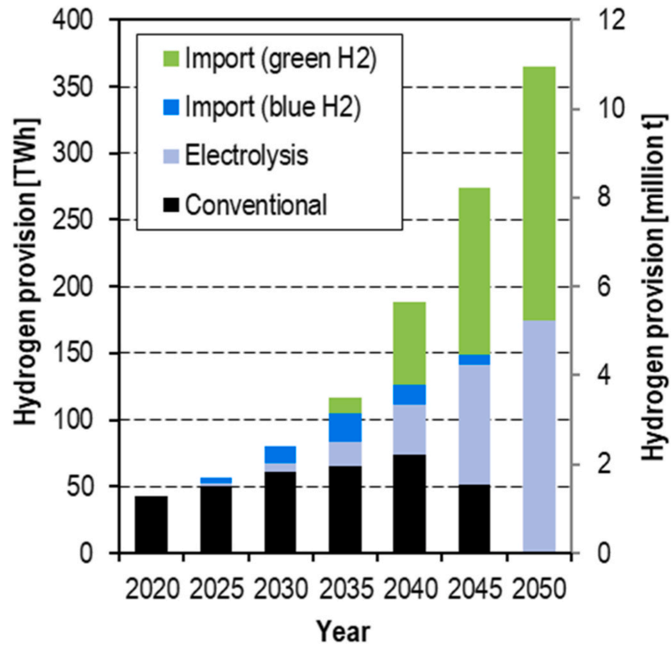

Fig. 3. Hydrogen source by production type and import for the country of Germany [4].

2030, conventional systems (gray hydrogen) will primarily be used. It will then be possible to increase domestic production through a significant expansion of electrolysis capacity, so that in 2040 and 2050, an overall share of approximately 33% and 48%, respectively, of the total supply should be achieved. The optimization results make it clear that the total amount of hydrogen needed in Germany in 2050 cannot be produced exclusively domestically. Imports will already play an important role in the hydrogen supply in 2030. The import of blue hydrogen into Germany in the years 2030–2040 represents an important bridging technology to provide the necessary import quantities in the medium term. By 2050, however, blue hydrogen will have been almost completely replaced by green. After 2040, the import of green hydrogen will play an increasingly important role, so that in 2050 more than half (approximately 52%) of hydrogen will be imported into Germany. For NRW, it is expected that the imported hydrogen will be transported to the region either in gaseous form via pipeline from the Netherlands or through the North German ports as liquefied product.

The desired spatial allocation of hydrogen production will be achieved by using results from the ETHOS.Infrastructure calculations, which are based on 80 clusters (Voronoi regions) around high-voltage nodes of the German power grid. These Voronoi centers will be augmented by the hydrogen production sites already present in ETHOS. H2MIND. As a guide to the spatial distribution of hydrogen production for the years 2025, 2030, and 2035, this analysis uses the ETHOS. Infrastructure spatial arrangement profile for conventional fossil processes, electrolysis, and import for the year 2030. In order to determine the share of each source site, hydrogen production and import for each of the 80 Voronoi regions is fixed to the areas of highest consumption or,

Table 7
Criteria for spatial allocation of refueling station capacity at the NUTS3 level. FS: Fleet size: S: "small" hydrogen refueling station (212 kg/d) [43].

Type	Public		Non-public					
Application	Cars	Trucks	Buses	Trains	Industry	Forklifts	Cars	Trucks
Max. number of sinks	9800	8000	402	170	90	10,000	7150	2340
Inner-region capacity distribution	Optimized		Evenly between sinks		Maximum capacity	Logistics space	Commercial area	Commercial area
Constraints	S, if <10% of existing fueling stations*		FS > 25	FS > 5	–	FS > 70	FS > 50	FS > 20

* Small refueling stations built if less than 10% of existing stations in the region contain hydrogen refueling equipment.

if possible, distributed among the sites in proportion to the initial maximum capacity defined in ETHOS.H2MIND. The total amount of hydrogen sourced by electrolysis, steam reforming, or import is also reduced to account only for hydrogen demand in the context of this work. The locations used in this analysis for the spatial distribution of hydrogen sources are presented in the Supplemental Information (S 2). The map also shows the subdivision of German territory into the 80 Voronoi regions within the ETHOS.Infrastructure model.

2.6. Evaluation framework

The scenario analyzed in this work is applied to the ETHOS.H2MIND model by using an evaluation framework. A first level of evaluation concerns the spatial distribution of the hydrogen demand according to the Hydrogen Roadmap NRW across the 402 German counties. This type of analysis helps to identify market sectors subject to early market penetration and potential synergies at the local level to be considered in the course of hydrogen infrastructure planning. The comparison of spatial distribution for the years 2025, 2030, and 2035 also provides information on demand trends, both at the national and local levels.

The second level of result evaluation is based on the weighted average TOTEX (€/kg_{H2}). In accordance with the conclusions of Cerniauskas [3], four combinations were selected for the study that are the most interesting for the design of a national hydrogen infrastructure in Germany from a techno-economic point of view (Table 8). In general, these combinations contain the same components for the supply of hydrogen (centralized electrolysis, steam reforming and import via ship and pipeline) and in all of them the supply chain ends at HRS and industry consumption points. The difference here is in the design of the transmission and distribution of hydrogen. In two pathways, transport from source to sink is exclusively by hydrogen trailers, which can be used to transport either gaseous or liquefied hydrogen. In the other two, transmission is through pipeline networks and distribution for gaseous hydrogen is by trailers.

The four hydrogen supply pathways are compared on the basis of their weighted average TOTEX, starting from a total cost perspective. A cost breakdown is then provided to identify specific aspects of hydrogen provision cost.

3. Results and discussion

In this section, we present results from our scenario analysis using the ETHOS.H2MIND model within the context of the H_2 Roadmap NRW. We thereby first look at hydrogen refueling station (HRS) costs before analyzing the effects of market rollout on the spatial distribution of hydrogen demand and the weighted average cost of hydrogen.

3.1. Refueling station cost

In this section, we first compare the different fueling station concepts based on the specific conditions of the project before presenting the market roll-out scenario results.

Fig. 4 shows the investment cost of the HRS design considered in the project as a function of refueling station capacity. In addition, the case shown in the graph on the right (500 kg/day) corresponds to the

Table 8
Hydrogen supply chains considered within ETHOS.H2MIND simulations.

Nr.	Path name	Description
1	GH_2 truck	Compressed hydrogen transport by trailer
2	LH_2 truck	Liquefied hydrogen transport by trailer
3	New pipelines	Transmission via newly-built hydrogen pipelines and distribution by GH_2 trailer
4	Natural gas pipelines converted to hydrogen transport	Transmission via switched natural gas pipelines and distribution by GH_2 trailer

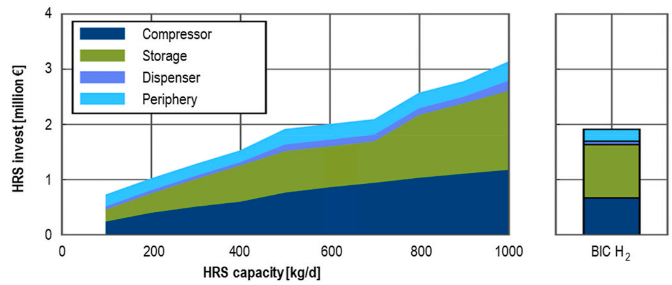

Fig. 4. Capacity-dependent refueling station investment. The BIC H_2 project-related station capacity is 500 kg/d. HRS: Hydrogen refueling station.

refueling station capacity available in the project. As with all of the other refueling station capacities considered, the major share of the investment cost corresponds to the compressor and storage tank. The investment costs of the dispenser and periphery, on the other hand, correspond to a small share. The costs presented here were discussed with the other project partners and approximate their empirical values.

Fig. 5(a) presents the investment costs of various HRS designs based on gaseous hydrogen delivery or onsite production combined with a cascade storage system and liquefied hydrogen with a gas compressor or cryo-pump. The costs are derived from applying the component-based HRS model (see the Supply Infrastructure section). The smallest refueling stations, supplying 5–10 buses, can be built for approximately €1 million, whereas large stations with a refueling capacity of 90 buses would cost €3–5 million. These cost estimates are based on literature-based component cost as of 2019. Overall, the HRS investment costs are lower for the LH_2 case than those of the other delivery options. This is in line with literature estimates that conclude that LH_2-based HRSs are 30–50% cheaper than GH_2 refueling stations [41,49,50]. However, some estimates assume more conservative LH_2 refueling station costs that are similar to those of GH_2 facilities [51].

Moreover, the results show that the design incorporating a cryogenic pump has the lowest investment costs for smaller refueling stations. If the fleet to be supplied grows beyond 30 vehicles, the compressor concept has an advantage in terms of investment costs. Notwithstanding some differences in the estimated values in the literature, it can be concluded that the choice of hydrogen supply option and the underlying refueling station design can have a significant impact on the required investment costs. This is especially important during the market introduction phase, which is associated with high uncertainty and low infrastructure utilization.

In order to quantify the scaling effects of hydrogen refueling, Fig. 5 (b) shows the specific hydrogen costs of the HRSs as a function of increasing fleet size. Consistent with previous results for bus refueling stations, specific costs can be reduced by more than 50% when the fleet size increases from 5 to more than 30 vehicles. These results are consistent with recent estimates of economies of scale for HRSs in California, which suggest a potential cost reduction of 30% (from 250 to 1000 kg/d) [50]. The results reveal that the LH_2 refueling station concept with cryo-pump is less expensive than the other concepts. However, the impact on the cost of large-scale refueling stations varies by application (not shown here). Car and truck refueling stations, which are amongst the most expensive, benefit the most from a switch to the LH_2 option, whereas the costs of bus and forklift refueling stations are less affected.

These results also indicate a significant cost reduction potential for larger vehicle fleets, as even non-public refueling stations covering a daily demand of 1000 kg_{H2} can be operated at a cost ranging from 0.7 to 1.2 €/kg_{H2}.

3.2. Market rollout

In the following, data and results related to the market ramp-up are

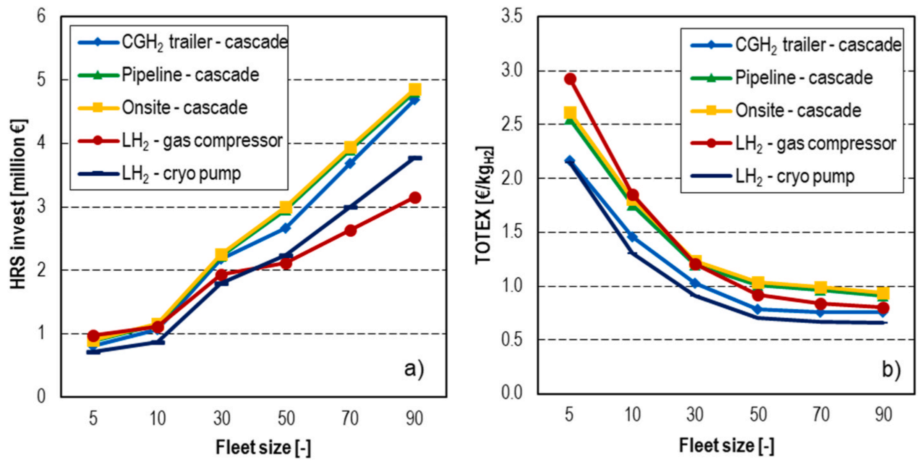

Fig. 5. Refueling station investment (a) and specific hydrogen cost of HRSs (b) for bus refueling with different delivery concepts. HRS: Hydrogen refueling station.

presented according to the H_2 roadmap of the state of NRW. In a first step, the hydrogen demand on the national (Germany) and regional (NRW) levels are analyzed. The second step includes the economic consequences, which will be presented here in the form of a cost comparison. Therefore, concrete considerations of hydrogen buses and their role in the development of a hydrogen infrastructure in Germany and NRW are presented in the last part of this sub-section.

Table 9 shows the annual hydrogen demand dataset that was used for the simulation in the present analyses. The differentiation by demand into “private/public” and “commercial,” which is not present in the ETHOS.NESTOR calculations, is derived from the market penetration coefficients available in ETHOS.H2MIND. The total demand increases by a factor of 4.1 over the time period considered. The strongest relative increase is found for transportation, with a factor of 8.6, compared to a factor of 1.9 for industry. Moreover, the largest subtotal belongs to transportation, with 1300 kt/a in 2035 compared to 562 kt/a for industry. A pronounced increase in industrial demand can be expected for the time after 2035.

Table 10 shows the final distribution of hydrogen sources after rescaling the actual hydrogen demand in the present study. These values demonstrate that the most significantly increased hydrogen sources are electrolysis and imports by a factor of 12.4 and 6.8, respectively. Hydrogen from natural gas reforming, however, exhibits the largest share throughout the time interval considered.

Looking at the spatial distribution of demand within Germany, the combination of the ETHOS.NESTOR values with the allocation factors from the ETHOS.H2MIND model results in the structure shown in Fig. 6.

Table 9
Annual hydrogen demand in Germany by application for the years 2025, 2030, and 2035 (ETHOS.H2MIND aggregation based on Cerniaskas et al. [4], not considering re-electrification, cf. Hydrogen Demand section).

Hydrogen demand [kt/a]	2025	2030	2035
Transportation			
Buses	6.8 (1%)	46.9 (4%)	92.5 (5%)
Trains	15.7 (3%)	67.1 (6%)	136 (7%)
Private cars	45.3 (10%)	306 (25%)	465 (25%)
Commercial cars	10.4 (2%)	70.3 (7%)	107 (6%)
Light and heavy trucks (Public services)	47.0 (10%)	123 (12%)	296 (16%)
Light and heavy trucks (commercial)	20. (4%)	61.4 (6%)	175 (9%)
Forklifts	5,7 (1%)	15.0 (1%)	29.3 (2%)
Industry			
Steel	0.01 (0%)	0.04 (0%)	102 (5%)
Methanol	0.56 (0%)	6.8 (1%)	31.3 (2%)
Ammonia	33.2 (7%)	101 (9%)	208 (11%)
Chemicals	263 (59%)	264 (25%)	200 (11%)
Refineries	2.4 (1%)	7.5 (1%)	21.2 (1%)
Total	451	1069	1862

Table 10
Hydrogen provision in Germany by supply option for the years 2025, 2030, and 2035 (ETHOS.H2MIND adaptation). LS: large-scale; SS: small-scale.

H_2 production [kt/a]	2025	2030	2035
Electrolysis	6%	12%	18%
Reformer (LS and SS)	72%	63%	46%
Imports	21%	25%	35%

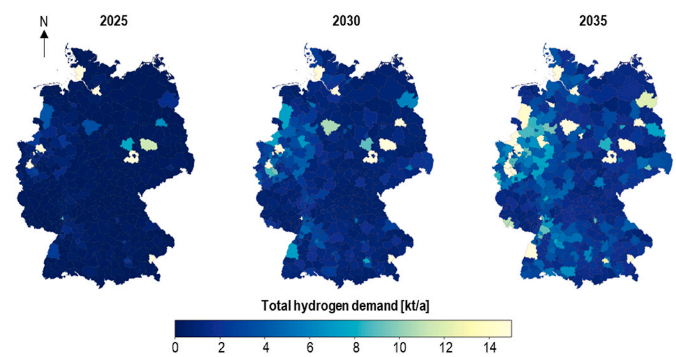

Fig. 6. Spatial allocations of Germany’s hydrogen demand for the years 2025, 2030 and 2035.

In 2025, the expected average hydrogen demand for almost all of Germany’s 402 counties is very low (average 0.341 kt/a), with the exception of a few areas where high demand is expected to be concentrated. Five of the 15 counties with the highest demand in Germany are located in NRW. These include the county of Oberhausen, with the strongest demand (67.75 kt/a), followed by the counties of Rheinkreis Neuss (52.06 kt/a) and Recklinghausen (15.81 kt/a). Other counties with increased demand are found in Saxony-Anhalt, with Saalekreis at the top (64.24 kt/a), followed by Wittenberg (11.46 kt/a). The main reason for this distribution is that relevant industrial sites are located in the mentioned counties, as can be seen from the distribution of hydrogen demand for industry. Over the next ten years, hydrogen demand is expected to develop around areas with the highest initial demand levels. NRW and southern Lower Saxony will experience the highest demand in this respect: 686 kt/a in the two regions combined, corresponding to 37% of total domestic demand. By 2035, the southwest – i.e., Baden-Württemberg – will become another area with increased hydrogen demand (182 kt/a; equivalent to 10% of total German demand).

The spatial distribution of national hydrogen demand differs by application. In terms of mobility, the penetration of buses and private cars appears to be relatively homogeneous across Germany – although there is high demand in the most populous areas of Germany (Berlin, Munich, Hamburg, Hannover, Frankfurt, and NRW, with Cologne and Düsseldorf leading the way). This can be explained by population distribution – in this case, the main driver for hydrogen demand in the road transport sector. To some extent, diffusion seems to be similar in the case of medium-duty commercial vehicles: Here, spatial distribution is directly related to the extent of logistics across the regions, suggesting that the most densely-populated areas of the country also have the highest share of logistical services. On the other hand, it is also clear that demand for trains, commercial vehicles, and heavy-duty trucks will tend to be concentrated in the northwestern part of the country over time (i.e., NRW and southern Lower Saxony, near the border with the Netherlands). With respect to trains, the reason for this is the combination of driving factors for spatial distribution: NRW, in particular, features the highest mileage of all German states and receives the most funding for regional development, suggesting heavy use of diesel train routes and state government support for their expansion. For commercial trucks and public/commercial heavy vehicles, it is primarily the expansion of commercial areas that drives the demand distribution. On this basis, northwestern Germany, i.e., the counties in NRW, will play the largest role. This is due to the fact that NRW (based on its gross domestic product) has the highest economic output of all German states.

Table 11 displays a breakdown of NRW's demand by sector for the years 2025, 2030, and 2035. Over the ten-year period, the amount of hydrogen demand triples. The dominance of the industrial sector is gradually replaced by the hydrogen transport sector (cars, trucks, and light commercial vehicles). A comparison with Table 9 indicates that the trend and magnitude are consistent with the picture at the federal level. Nevertheless, some slight differences can be discerned. In terms of the development of hydrogen demand over time, industry plays a greater role for NRW than for the whole of Germany (with an 8% higher share on average). Within the transportation sector in NRW, buses and trains have a smaller share of demand over time than in Germany as a whole. Passenger cars, trucks, and light commercial vehicles play the main role, in accordance with the expected national trend, but the shares for passenger cars are lower on average. Demand for trucks and light commercial vehicles is lower at the beginning, but subsequently is higher than for Germany as a whole. Moreover, trucks and light commercial vehicles ultimately contribute the most to hydrogen demand in the transport sector – in contrast to the national trend, where passenger cars account for the largest share.

The regional hydrogen demand for NRW and its distribution among the districts is shown below.

At the beginning of the period analyzed (2025), 76% of the hydrogen demand in the entire region is concentrated in three counties: Oberhausen (67.7 kt/a), Rhein-Kreis Neuss (52.1 kt/a), and Recklinghausen (15.8 kt/a). In these counties, the industrial sector is the driving force, with Oberhausen, Marl and Dormagen being production sites for ammonia and chemicals. It is foreseeable that hydrogen demand in the region will increase in a north–south direction. In addition to Rhein-Kreis Neuss (65.8 kt/a), Oberhausen (56.3 kt/a) and Recklinghausen (20.0 kt/a), as well as Duisburg (35.7 kt/a), Gelsenkirchen (30.4 kt/a), the county of Rhein-Erft-Kreis (21.7 kt/a), Cologne (16.9 kt/a), Borken (15.9 kt/a), and Bochum (13.1 kt/a) show significant hydrogen demand levels. Steel and methanol production – with plants in Duisburg (steel) and Gelsenkirchen and Wesseling (methanol) – are growing in importance. Gütersloh (14.3 kt/a) in the northeastern part of the region should also be considered in terms of transportation: the demand for hydrogen for commercial truck fleets and light commercial vehicles seems to play an important role there. On average, demand in the remaining counties increases from 0.8 to 5.3 kt/a over ten years (Fig. 7).

Table 11
NRW's state-wide hydrogen demand by application for the years 2025, 2030, and 2035 (ETHOS.H2MIND aggregation).

Hydrogen demand [kt/a]	2025	2030	2035
Buses	1.21 (1%)	8.4 (3%)	16.6 (3%)
Trains	3.55 (2%)	23.3 (7%)	38.8 (7%)
Cars (private)	8.65 (5%)	58.5 (18%)	88.8 (17%)
Cars (commercial)	6.36 (4%)	29.1 (9%)	35.8 (7%)
Light and heavy trucks (public services)	10.38 (6%)	27.2 (8%)	65.4 (13%)
Light and heavy trucks (commercial)	10.35 (6%)	29.0 (9%)	82.8 (16%)
Forklifts	1.36 (1%)	3.48 (1%)	5.87 (1%)
Industry	136 (76%)	153 (46%)	185 (36%)
NRW total	178	332	519

The resulting distribution of hydrogen demand in NRW is differentiated by application. In general, it can be stated that regardless of the respective hydrogen-based technology considered, the demand peaks typically occur in the districts of the Rhine–Ruhr Metropolitan Region (MRR). Recurring districts in this context are Cologne, Bochum, Oberhausen, and the county of Rheinkreis Neuss. An explanation for this could be that the Rhine–Ruhr Metropolitan Region is a very densely populated area, with about 55% of the total population of North Rhine–Westphalia alone (1478 inhabitants per km^2 in the Rhine–Ruhr Metropolitan Region compared to 526 inhabitants per km^2 in NRW) [52], and where population size is a key factor for hydrogen demand for cars and public transport (bus and train). Aachen and Borken, although located outside the Rhine–Ruhr Metropolitan Region, are also very significant in terms of demand for buses and commercial heavy/light duty vehicles (see Table 12). Aachen has the largest bus fleet and bus depot in NRW (fleet operator ASEAG: 498 vehicles in total; 300 vehicles in the bus depot [53,54]), resulting in the highest level of hydrogen demand for buses in this region. The largest industrial park in North Rhine–Westphalia is located in Borken.

3.3. Hydrogen provision chains

As previously described, four hydrogen supply paths are selected for the study, which are the most promising for the creation of a national hydrogen infrastructure in Germany from a techno-economic point of view. They differ by the respective design of the transport segment, in accordance with the conclusions of Cerniauskas [3]. A comparison of the weighted average hydrogen cost (TOTEX, €/kg_{H2}) and its development in the period from 2025 to 2035 (calculated on a national level) can be found in Fig. 8.

During the creation and expansion of the hydrogen infrastructure, trailers represent the most economical solution for the entire transport segment in the analysis period. Trailers for transporting gaseous hydrogen show costs ranging from 6.0 to 6.5 €/kg, whereas liquefied hydrogen leads to TOTEX of 7.5–7.4 €/kg. Pipeline-based infrastructure options show decreasing TOTEX over time, namely 16.4–8.5 €/kg for new hydrogen pipelines and 11.6–7.3 €/kg for converted natural gas pipelines, respectively. Nevertheless, within the period considered, only converted natural gas pipelines compete with trailer transport variants.

To better understand the resulting cost trends, it is necessary to examine the breakdown of the weighted average TOTEX across the different sections of the hydrogen supply pathway. Fig. 9 shows the cost breakdown for the four pathways studied and their evolution over time. For the "GH_2 trailer" pathway, hydrogen supply accounts for nearly half of the costs. Electrolysis, steam reforming and imports account for 49%–53% between 2025 and 2035. This relevance of the hydrogen supply is primarily responsible for the upward trend in the weighted average TOTEX of the GH_2 trailer supply pathway because the share of lower-cost reformer hydrogen decreases in favor of electrolysis and imported hydrogen. Another relevant cost factor is hydrogen transport, which is slightly decreasing due to better trailer fleet utilization, although this does not offset the overall cost increase. Refueling also seems to play an important role, with costs increasing over time from 0.76 to 1.06 €/kg. As far as refueling is concerned, it is expected that the average size of the components of the installed HRSs will increase in order to take advantage of economies of scale. Nevertheless, this effect is not sufficient to

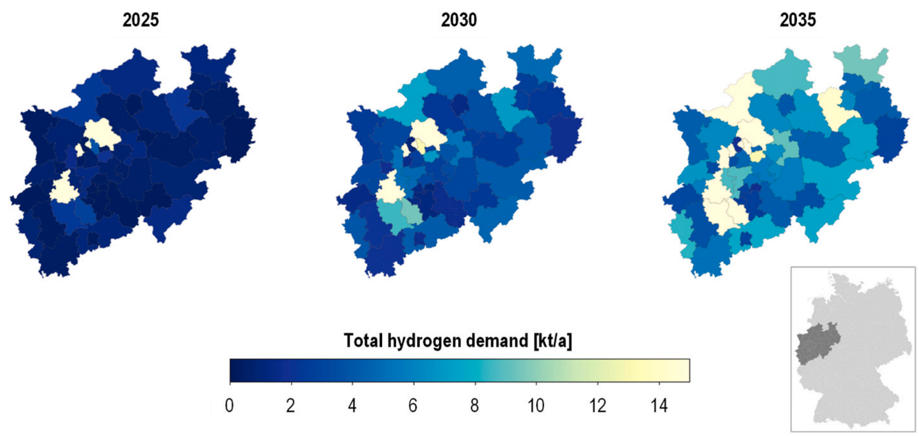

Fig. 7. Spatial allocation of NRW's state-wide hydrogen demand for the years 2025, 2030, and 2035.

Table 12
Maximum hydrogen demand by application and by county in NRW for the years 2025 und 2035. MRR: Rhein–Ruhr Metropolitan Area.

	2025		2035	
Total demand [kt/a]	Oberhausen	67.7	County of Rhein-Kreis Neuss	65.8
Buses	Aachen (not MRR)	0.09	Aachen (not MRR)	1.2
Trains	Cologne	1.18	Cologne	4.0
Cars (private)	Cologne	0.36	Cologne	3.0
Cars (commercial)	Bochum	0.8	Bochum	0.8
Trucks (public services)	Cologne	0.6	Cologne	3.6
Trucks (commercial)	Borken (not MRR)	1.3	Borken (not MRR)	9.9
Forklifts	Cologne	0.2	Köln	0.4
Industry	Oberhausen	66.7	County of Rhein-Kreis Neuss	55.3

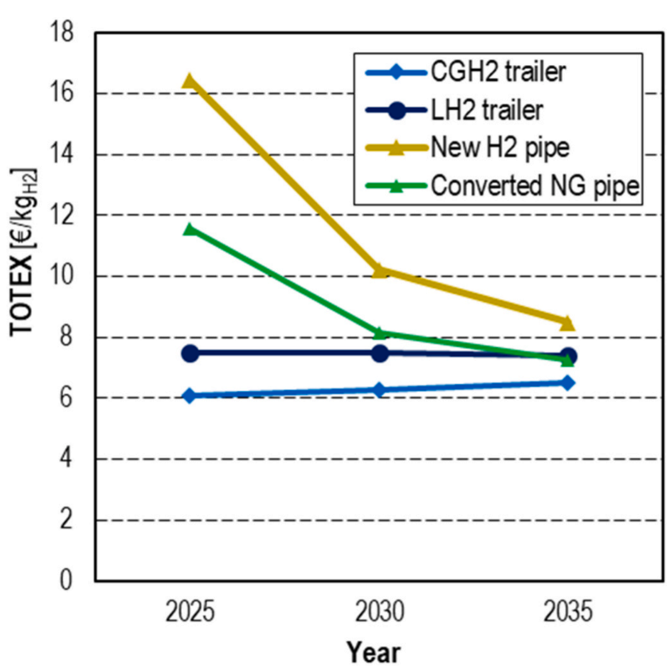

Fig. 8. Weighted average hydrogen cost (TOTEX) of the four hydrogen provision chains considered in this study for the years 2025, 2030, and 2035.

compensate for the overall increase in TOTEX due to the larger number of new refueling stations to be installed.

Similar trends can be seen for LH_2 trailers, with an upward trend in procurement and refueling combined with a downward trend in transportation. In this case, however, the liquefaction stage ("connector") is particularly relevant to the cost determination. It shows a dramatic downward trend over time (from 2.62 to 1.56 €/kg), which relates to improved plant utilization.

Apart from the trends regarding hydrogen production and refueling similar to the trailer concepts, pipeline-based hydrogen supply experiences a sharp drop from an initially high cost to a level that is competitive to the trailer supply at the end of the period considered. The pipeline network is here expected to achieve a higher utilization rate, which brings about the significant cost decrease. In this context, converting existing natural gas pipelines will result in lower transportation costs than building new hydrogen pipelines – on average, costs are 42% lower from 2025 to 2035.

3.4. Hydrogen bus refueling

It was shown before that hydrogen buses do not account for a very significant share of hydrogen demand in the time period studied, at slightly more than 5% of total demand in Germany and 3% in NRW in 2035. Therefore, the impact on the determination of the total supply chain costs could be expected to be very small. The difference between the weighted average TOTEX for cases (a) with hydrogen buses and (b) without buses are calculated (see Table 15 in the Supplemental Information S3). In terms of absolute values and percentage of cost (a), such a difference over time for the supply paths based entirely on trailers (GH_2 and LH_2 trucks) turns out to be no higher than 0.7%. For the pathways based on pipelines (new and converted), the difference is higher but remains very small, at less than 2.3%. Nevertheless, hydrogen buses work as a driver for the creation of future hydrogen infrastructure. Due to the service offered (local public transport) and the fixed structure of their schedules (routes and travel times), buses achieve high utilization rates of 70% or more if they can be refueled at the end of the working day in the bus depots.

The resulting bus refueling station sizes are determined for the simulated cases. HRSs are divided into five capacity-based categories: small (S), medium (M), large (L), extra large (XL), and extra extra large (XXL) (see Table 13). For comparison, the maximum annual hydrogen demand (kt/a) of each category is used as a reference (assuming 70% utilization). The ranges of the daily capacity (t/d) of each category are presented in Table 13.

Figs. 10 and 11 show the results regarding capacity distribution and spatial allocation for NRW; the respective figure for Germany is presented in the Supplemental Information (S 4). It can be seen that HRSs

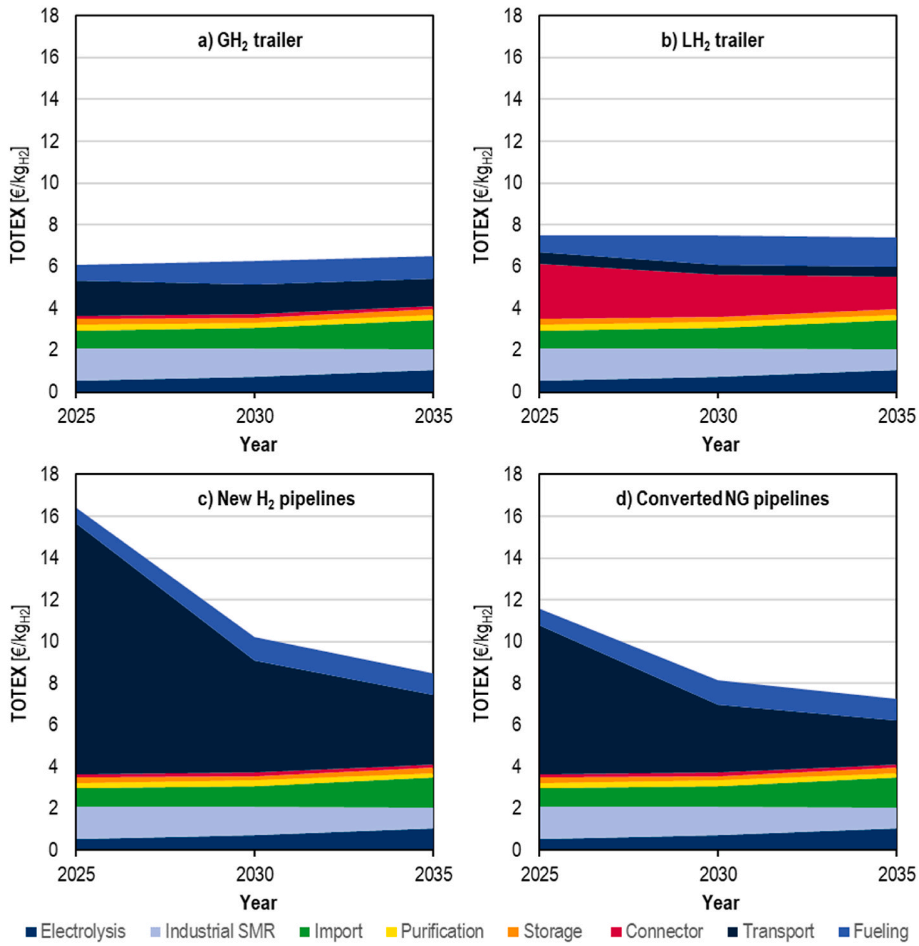

Fig. 9. Component-specific TOTEX of the four hydrogen provision chains considered in this study for the years 2025, 2030, and 2035. NG: Natural gas.

Table 13
Hydrogen refueling station classification by capacity within the ETHOS. H2MIND model.

Category	Refueling station capacity [t/d]	
	Min	Max
S	0	0.212
M	0.212	0.42
L	0.42	1
XL	1	1.5
XXL	1.5	3
XXL+	3	–

for buses of all sizes will be built in the region, with the majority of refueling stations being size L (62% of the sites considered) and a considerable proportion of even larger refueling stations from size XL (21%) being assumed for 2035.

In the last category, the majority of service stations in Aachen and Cologne will exceed the XXL size. Mönchengladbach and Wuppertal will be in the XXL size category. In Bielefeld, Hagen, Heinsberg, Borken, Coesfeld, Steinfurt, Warendorf, Oberhausen, Bottrop, Recklinghausen, Essen, and Münster, the majority of service stations will be XL.

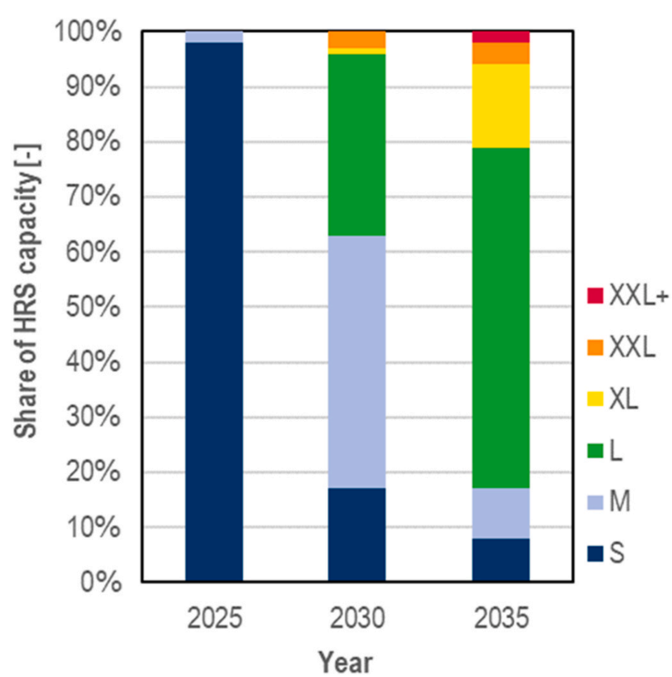

Fig. 10. Distribution of refueling stations by their capacity in NRW for the years 2025, 2030, and 2035. HRS: Hydrogen refueling station.

4. Conclusions

Against the background of the results presented in the previous section, some considerations can be made regarding the possible strategies for hydrogen infrastructure development in Germany and, in particular, for the realization of the targets in the state of North

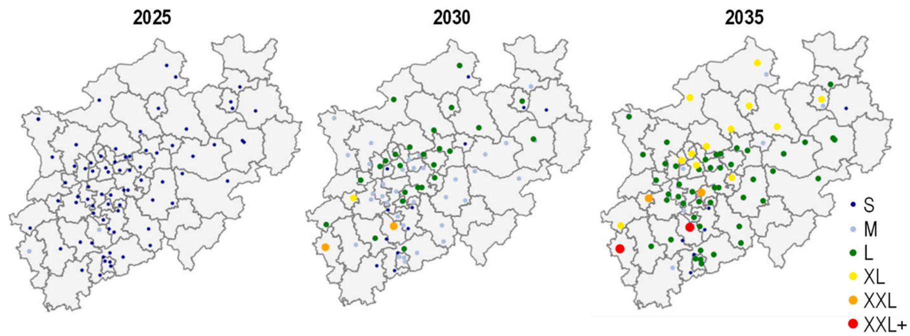

Fig. 11. Spatial allocation of bus refueling stations in NRW, also including refueling station capacity in the years 2025, 2030, and 2035.

Rhine–Westphalia (NRW) until 2025 and 2030.

For the period from 2025 to 2035, investments should focus on counties with high hydrogen demand. The analysis of the distribution of hydrogen demand highlights regions where hydrogen demand is expected to be particularly high. In order to reduce the risk associated with investments in infrastructure components, it is recommended to focus financial support and measures on these regions during the start-up phase, as they can offer a higher utilization rate of infrastructure facilities, e.g., new hydrogen refueling stations. NRW alone is expected to account for about one third of the total German hydrogen demand. Within NRW, the relevance of a district depends on which hydrogen-consuming sector is being studied. In terms of mobility and public transport, Cologne is the area with the highest demand in many transport sectors – based on the allocation factors used in this study – and could be considered a priority region for transport development initiatives. Depending on the type of transport, other counties may also be considered relevant. In the bus sector, Aachen, Wuppertal, and Düsseldorf (along with Cologne) are the three frontrunners.

For the period from 2025 to 2035, trailers for transporting gaseous hydrogen are the most favorable option in terms of the techno-economic performance of the entire provision pathway. Pipelines will play a key role in the long-term hydrogen infrastructure. Looking at the weighted average TOTEX of the four pathways studied, our results indicate that the cost curves will intersect after 2035 due to increased hydrogen demand and higher utilization of pipelines. In particular, the cost curve for converted natural gas pipelines will most likely reach the intersection point earlier than the curve for newly-built hydrogen pipelines, as the former solution is much more cost-effective, with up to 80% lower cost than new hydrogen pipeline construction. Nevertheless, our results show that trailers for transporting gaseous hydrogen are the best option for the start-up phase of infrastructure development in Germany and NRW. They also offer higher flexibility, which is especially helpful at the beginning of the market ramp-up process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of abbreviations

BEB	*Battery-electric bus*
CAPEX	*Specific capital-related costs*
CGH_2	*Compressed gaseous hydrogen*
FCEBs	*Fuel cell–electric buses*
FCEV	*Fuel cell-electric vehicle*
GHG	*Greenhouse gas emissions*
HDRSAM	*Argonne National Lab's Heavy-Duty Refueling Station Analysis Model*
HRS	*Hydrogen refueling station*
HRSAM	*Argonne National Lab's Hydrogen Refueling Station Analysis Model*
KBA	*Federal Motor Transport Authority (Kraftfahrtbundesamt)*
LH_2	*Liquefied hydrogen*
LS	*Large-scale*
MHV	*Material handling vehicle*
MILP	*Mixed-integer optimization problem, Mixed-integer optimization programming*
MRR	*Rhein–Ruhr Metropolitan Area*
NG	*Natural gas*
NRW	*German State of North Rhine-Westphalia*
NUTS	*Nomenclature of Territorial Units for Statistics*
OPEX	*Operating cost*
SS	*Small-scale*
TOTEX	*Levelized cost of hydrogen*
TRL	*Technology readiness level*

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2023.12.071.

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