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A methodological framework for geospatial modelling of hydrogen demand in cities

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Abstract

Urban energy system planning is vital for cities shifting towards a more sustainable and integrated energy system. Hydrogen is considered one of the most promising solutions in future energy systems. Previous work on hydrogen energy systems predominantly analysed hydrogen models on a national level or only parts of the mobility sector. This indicates a research gap for geospatial models that include multiple sectors in which hydrogen can be used. These models can be used to support decision-making processes around the hydrogen economy in cities. This study presents a holistic model addressing the geospatial modelling of hydrogen demand in urban areas. It proposes a method that integrates a variety of open source data, including geodata, earth observation data and energy data to estimate hydrogen demand top down for the industrial feedstock (steel, ammonia, organic chemistry), process heating, and mobility (buses, trucks, trains, airplanes, ships) sectors. The proposed method can also be extended to different sectors. The method is validated by modelling the hydrogen demand in all German cities and benchmarking it with national studies. This study's results are within the same range as the results of national studies. For this paper, the method is applied for two case studies in Freiburg im Breisgau and Frankfurt am Main. Applying this method in urban areas shows potential hydrogen demand hotspots in these areas. The model's results help policymakers and industry stakeholders make informed decisions about the development of hydrogen infrastructure and facilitate the adoption of hydrogen as a low-carbon energy carrier. Future research could explore the temporal aspects of hydrogen demand and the spatial influence of hydrogen demand on future hydrogen production facilities such as electrolysers.

Keywords: Hydrogen, Geospatial, Hydrogen demand, Hydrogen energy system

Introduction

Decarbonisation and the transition towards renewable energies to combat climate change are centrepieces of global environmental policies. The Paris Climate Agreement aims to limit the temperature increase to 1.5°C above pre-industrial temperature levels and reduce net greenhouse gas (GHG) emissions to zero by 2050 (United Nations 2015). GHG emissions reductions are needed across all sectors and industries to achieve this goal (United Nations 2015; Bundesministerium für Umwelt 2019). Among many alternatives, sustainably produced hydrogen (H_2) is viewed as an attractive solution to phase away from the current fossil fuel-based energy system to a renewable, integrated energy system (Ogden 1999; Blanchette 2008) while considering the above mentioned challenges. Especially in hard-to-decarbonise sectors, where direct electrification is not feasible, such as the industrial sector and different types of heavy mobility, sustainably produced H_2 and its secondary products are the primary zero carbon alternatives (IEA 2019). H_2 can be used as feedstock for industrial processes or in fuel cells and internal combustion engines (ICEs) in the mobility sector. As energy carrier, H_2 can enable sector coupling in an integrated energy system in which the electricity, heat, industry, and mobility sectors are increasingly interconnected (IRENA 2018; Robinius et al. 2017). Here, it can serve as energy storage: H_2 can be produced during times of peak power generation, using surplus renewable energy that would have been curtailed and lost otherwise. It can then be used in other sectors or as seasonal storage (IEA 2019). When the electricity demand is high, and the electricity production from variable renewable energy sources is low, gas turbines using H_2 can relieve the electricity grid's load (Nagasawa et al. 2019). Moreover, H_2 can indirectly electrify the transport sector, as well as the heating sector for buildings (IEA 2019), e.g., by using the waste heat from electrolysis (Deutsche Energie-Agentur 2016). More than 30 countries currently have hydrogen strategies with global projects existing across the entire value chain (Hydrogen Council and McKinsey & Company 2021; Ludwig Bölkow Systemtechnik and World Energy Council 2021; U.S. Department of Energy 2020; Bundesministerium für Wirtschaft und Energie 2020). In the National Hydrogen Strategy (Nationale Wasserstoffstrategie (NWS)), Germany has set goals for creating a hydrogen economy in which it describes how and where to use hydrogen in future energy systems to decarbonise sectors such as industry, mobility, and heating (Bundesministerium für Wirtschaft und Energie 2020). Additionally, industrial companies are starting to invest in technologies to develop the hydrogen economy further (Hydrogen Council and McKinsey & Company 2021). Barriers to a hydrogen economy remain. Legal and economic challenges regarding large-scale electrolysers, electricity pricing, existing natural gas infrastructure usage, hydrogen transport, and building hydrogen infrastructure exist (Dolci et al. 2019; Deutsche Energie-Agentur 2018). According to the NWS, in Germany, sustainable hydrogen shall be produced locally first. An in depth analysis of potential hydrogen sinks and sources is needed to explore the benefit of hydrogen in future energy systems and support decision-making surrounding the hydrogen economy. Consequently, for cities and municipalities, it is vital to know if they are suited to build up a hydrogen economy and where to invest in it. Hence, they need to know the geospatial demand of hydrogen.

Related work

Due to the complexity of hydrogen energy systems, optimisation models are typically used to analyse the future hydrogen demand and potential of hydrogen in a country or region. Hydrogen energy system models can be classified into three different categories (1) national models, (2) regional models, and (3) local models (Agnolucci and McDowall 2013).

National models are based on energy system models and match the supply and demand of hydrogen at the lowest cost for an entire country on a timeline. These models are bottom-up energy system models that endogenously optimise the hydrogen demand: Hydrogen technologies (e.g., fuel cell electric vehicles) compete in these models with other technologies (e.g., battery electric vehicles) to meet the total demand in the country (e.g., demand for car transport). These models only look at the system without addressing spatial issues. Only a few models include spatial geographic information system (GIS) data into national models (Strachan et al. 2009). Several national-scale hydrogen energy system models exist for Germany (Deutsche Energie-Agentur 2017; Hebling et al. 2019). Some models have spatial information, though they typically only focus on the transport sector (Welder et al. 2018; Reuß et al. 2019).

Regional models typically split countries into several regions and thus introduce spatiality into the model. The goal is to minimise the cost of the entire hydrogen supply chain (HSC) in a specific timeframe. The model of Almansoori and Shah (Almansoori and Shah 2009) is the foundation of most regional-scale models. Here, each region has different available primary energy sources and hydrogen demand. The model includes several hydrogen sources such as steam methane reforming, gasification plants and electrolysers. Other parts of the HSC that influence the costs in the model are hydrogen storage and transport from sources to sinks. The outputs of these models are the quantity of each energy source needed, the number, type, and location of production and storage facilities in each region and the amount produced, stored, and transported quantity of hydrogen, as well as the associated cost of each facility in the HSC (Almansoori and Shah 2009; Agnolucci and McDowall 2013). The hydrogen demand is calculated exogenously in a top-down manner, as explained below. Typically, these models recommend suitable regions for electrolysers and not their geospatial site in that region. Some models base the suitability of a site solely on the potential for excess renewable power (Robinus et al. 2014). Local models introduce additional spatial structure to hydrogen models. They focus on the optimal siting of hydrogen delivery points (Agnolucci and McDowall 2013). Since these models typically focus on passenger cars, they emphasise the siting of hydrogen refuelling stations (HRSs). Similarly to regional models, local models calculate the hydrogen demand exogenously and allocate it spatially in a top-down manner (Agnolucci and McDowall 2013). Local models (and to some extent also regional models) cover one (or more) of three interdependent areas: (1) the modelling of the hydrogen demand, (2) the site selection and (3) the dimensioning or operation mode of the selected site.

Hydrogen demand modelling

Regional and local models typically estimate the hydrogen demand exogenously. Equation 1 shows such an exogenous estimation exemplarily. Here, the H_2 demand is calculated via the demand for the underlying application, the market penetration of the relevant hydrogen technology and its intensity of hydrogen consumption. The market penetration refers to the share of H_2 technologies inside a market. The corresponding values result from underlying economic and technical assumptions typically reflected in various scenarios (Tlili et al. 2020; Ni et al. 2005).

$$H_2demand = sectordemand[unit] \cdot H_2penetration[\%] \cdot H_2consumption[\frac{H_2}{unit}] \quad (1)$$

For example, in the transport sector, the *sectordemand* is the transport demand in vehicle kilometres (vkms), the $H_2penetration$ is the share of fuel cell electric vehicles in the vehicle market, and the $H_2consumption$ is the fuel use of hydrogen for each driven vkm (Agnolucci and McDowall 2013). This methodology enables the identification of demand centres geographically within a larger region, as in Ni et al. (2005).

Different ways exist to estimate the parameter sector demand. Either by using real consumption data or via proxies in a top-down disaggregation. Grüger et al. (2019) classify different possible hydrogen sinks in the mobility sector and model their respective demand geospatially using data of petrol station operators, public bus operators, taxi fleets and car-sharing companies. Coleman et al. (2020) use bus operator data to estimate their hydrogen demand. Proxies used in top-down demand disaggregation are, e.g. population data and statistics of the relevant sector (Strachan et al. 2009). For example, in the transport sector, transport demand can be estimated by using population data [persons] in a region, vehicle ownership [cars/person] and car use [vkm/car] as proxies to calculate transport demand [vkm] which can then be used to estimate hydrogen demand as shown in Eq. 1 (Ni et al. 2005; Agnolucci and McDowall 2013; Kamarudin and Daud 2009).

On a temporal scale, origin–destination trip simulations or real time-series data model the demand. The results are daily time-series, typically constant for weeks, seasons or years (Grüger et al. 2019; Tlili et al. 2020; Bush et al. 2013; Chen 2010; Ko 2017). Kurtz et al. (2020) introduce a predictive demand model for passenger cars to account for the variability through a year (Kurtz et al. 2020). Statistical models introduced additional uncertainty to optimise timed demand modelling as in Kim et al. (2008).

Most research modelling hydrogen demand in the transport sector focuses on light-duty vehicles. Rose (2020) is one notable exception, focussing on heavy-duty transport by using flow data on German highways to model trips between German regions for trucks.

Research gap

Previous work has investigated various pathways to implement a hydrogen economy on several levels. National models and roadmaps estimate the overall potential and process of ramping up a hydrogen economy in a country as a whole. Regional models identify regions within a country with high potential for either hydrogen demand or production. Local models include geospatial factors to focus on optimal site selections for electrolysers or HRSs (Almansoori and Shah 2009). These local models of hydrogen energy systems concentrate primarily on the mobility sector. Previous works have modelled the hydrogen demand geospatially in the mobility sector, mainly focussing on passenger road transport (Grüger et al. 2019; Tlili et al. 2020; Ni et al. 2005; Melendez and Milbrandt 2008; Rose 2020). Other local models determine the potential for Power-to-Gas (PtG) plants on a geospatial level based on surplus renewable energy (Kopp et al. 2017).

The analysis of previous studies indicates a research gap for models that analyse the potential H_2 demand on a geospatial level of multiple sectors. Due to today's importance of developing a hydrogen economy, there is a need for research on the subject. This study aims to develop a geospatial model that includes the sectors industry as well as other forms of mobility such as aviation, shipping, and trains in a holistic model that can be applied relying only on open source data. It proposes a methodology for using open source data to geospatially model hydrogen demand for these sectors, as well as overcoming the challenges of data availability.

Contribution of this work

This work aims to model the demand side of an urban hydrogen energy system by addressing the above-mentioned challenges. The goal is to estimate the hydrogen demand for all relevant sectors on a geospatial level. Such a geospatial hydrogen demand model can be used twofold: First, to assess which cities or municipalities are suited for a local hydrogen economy, and second, to help decide where hydrogen infrastructure should be built. The main objectives of this work are:

- developing a method to model the hydrogen demand in a city or municipality for all relevant sectors,
- implementing this method to model hydrogen demand in cities or municipalities in an automated manner using open source data,
- applying this methods in cities to investigate their potential hydrogen demands.

Paper outline

To provide context of the sectors modelled in the method and case studies, "Hydrogen usage" section gives a brief introduction of the sectors in which hydrogen is expected to be used in the future. The model of the hydrogen demand estimation is introduced and explained in the "Methods" section. The method is then applied for the case studies of *Freiburg im Breisgau* and *Frankfurt am Main* are the results presented in "Results" section. The method is discussed and validated in "Discussion" section followed by a summary of core findings and an outlook for continuing research in "Conclusion" section.

Hydrogen usage

Multiple ways exist to use hydrogen. In energetic applications, it generates heat or electricity. Here it can either be combusted directly or be converted into electricity using fuel cells and subsequently used in electrical engines (Armaroli and Balzani 2011). Also, it functions as feedstock for other products, including organic chemicals, ammonia, and steel (Armaroli and Balzani 2011). Secondary products like synthetic natural gas or ammonia can then be used in ICEs for energetic applications (Armaroli and Balzani 2011).

Hydrogen usage in the industrial sector

In the industrial sector, hydrogen is mainly discussed to decarbonise the steel industry, to produce basic organic chemicals and ammonia in the chemical industry and as an industrial heat source (Geres et al. 2019).

In the steel sector, an alternative steel production method is the hydrogen-based direct reduction of iron ore (DRI). DRI is the chemical removal of oxygen from iron ore in its solid form. DRI is achieved through the use of hydrocarbons or hydrogen. H_2-DRI can result in carbon-neutral steel production if green hydrogen is provided. Cavaliere (2019). Equation 2 shows the H_2-DRI process for Hematite.

$$Fe_2O_3 + 3H_2 \longrightarrow 2Fe + 3H_2O \tag{2}$$

Hydrogen serves an important role decarbonising the chemical sector (Geres et al. 2019). Here, it can be used to produce the basic chemicals methanol, ammonia, and methane synthetically. In downstream processes, methanol is then used to produce other organic chemicals like olefines such as ethylene and propylene and aromatic compounds (Geres et al. 2019). Ammonia is currently produced using the Haber-Bosch process, as shown in Eq. 3. The hydrogen used today overwhelmingly comes from unsustainable sources and can be replaced by green hydrogen. Geres et al. (2019)

$$N_2 + 3H_2 \longrightarrow 2NH_3 \tag{3}$$

Methanol from hydrogen and CO_2 is produced using electricity, as presented in Eq. 4 (Geres et al. 2019; Bazzanella 2017).

$$CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O \tag{4}$$

Hydrogen combustion creates large amounts of heat. In the low and medium temperature segments ($< 400°C$) other sustainable technologies are more cost-efficient and thus most studies to not expect the use of hydrogen in this temperature segment (including residential heating). Nonetheless, the use of synthetic fuels, including hydrogen and hydrogen-based fuels, can be cost-efficient in the high-temperature segment ($> 400°C$) (Agora Energiewende and AFRY Management Consulting 2021).

Hydrogen usage in the mobilty sector

In the mobility sector, several use cases for hydrogen exist. Depending on the application, for hydrogen adapted ICE, hydrogen fuel cells or electrofuels (e-fuels) are potential uses. These e-fuels can be produced via different power-to-x (PtX) processes. Examples are ammonia, synthetic methanol, synthetic methane, and synthetic oil products (IRENA 2019).

Especially in local passenger rail transport, the potential of using hydrogen as alternative drive train technology to non-electrified transport is high. Commercial hydrogen fuel cell trains exist already, with regional fuel cell trains expected to become cost-competitive with diesel trains (Ernst & Young GmbH et al. 2016; Pagenkopf et al. 2020). While fuel cell electric cars have been on the market since the early 2000 s, and several studies have analysed a hydrogen energy system based around private mobility (Tlili et al. 2020; Ni et al. 2005; Grüger et al. 2019; Melendez and Milbrandt 2008), hydrogen struggles to compete with the rapid developments in battery technology. Hydrogen buses are already being tested in cities worldwide (REN21 2021) and research and development of hydrogen fuel cell trucks is accelerating, especially for long-distance traffic (Deutsche Energie-Agentur 2018; Hyundai 2020). Hydrogen and hydrogen-based e-fuels in the aviation and shipping sectors are in early development phases (Airbus

2022; REN21 and FiA Foundation 2020), with concepts or pilot projects existing as the predominant sustainable alternative on long-haul flights (Air Transport Action Group 2021) and in the shipping industry (e4ships 2022; American Bureau of Shipping 2021).

Methods

This study proposes and applies a method to estimate the potential yearly hydrogen demand spatially resolved on a building level. Two main inputs are needed to calculate the *yearly H_2 demand on a building scale*: their geographic location (following called geographic *sink*) and *energy demand* for that sink. If no energy demand data is available, *proxies* that correlate with the energy demand are used instead. *Technical and chemical process data* is used for each type of sink (subsector) to calculate the hydrogen demand based on their energy demand. The *geographic disaggregation* in the method accounts for data availability issues using open source data: energy demand (or proxy) data is sometimes only available for an entire city or region. Thus, it needs to be disaggregated to the geographic sinks using different parameters.

Based on Chapter Hydrogen Usage, the two main sectors for an urban hydrogen economy are the industrial and mobility sectors. Industrial subsectors, in which hydrogen is used as feedstock such as steel, organic chemistry, fertiliser and ammonia production, and industrial process heat, are included in the methodology. In the mobility sector, hydrogen sinks included in the method are heavy-duty vehicles (trucks), buses, trains, ships, including inland and maritime vessels, and airplanes. Regarding trains, only non- or not-yet electrified trains are modelled. The ships modelled as hydrogen sinks consist of maritime and inland ships and the airplanes are medium- and large-sized airplanes. Fuel cell electric cars as well as the residential heating sector are not modelled in this study. The potential hydrogen demand is modelled geospatially resolved for each type of sink. Furthermore, the method can be expanded or reduced for different types of use cases that might emerge or disappear in the future. The overall goal is to model hydrogen demand geospatially for cities by assigning the modelled hydrogen demand to precise geographic coordinates, also called geographic sinks.

Figure 1 presents the method to model the hydrogen demand in a city for each potential sector. As a starting point, based on each sector's specific energy demand, each sink's hydrogen demand is calculated geospatially and assigned to each geographic sink (i.e. each building with a H_2 demand). Suppose no energy data is available for a sink. Then the energy demand is approximated via proxies like mileage (energy data) or production output of that sink type (georeferenced data). To calculate the hydrogen demand based on the specific energy demand or the corresponding proxies, technical or chemical data particular to each hydrogen technology is used for each type of sink. The two-step geographic disaggregation accounts for the fact that data - e.g. proxies - is often unavailable geospatially. Often it is only available on city-specific or country-specific levels. It thus needs to be disaggregated and allocated geospatially to the geographic sinks (buildings) stepwise. Therefore, zero, one or two steps of geographic disaggregation are required depending on the data availability. Figure 1 illustrates the methodology if data is available on a city-specific scope, with the solid lines. Here, only one step of geographic disaggregation is needed. It also illustrates the methodology if data is available on a country-specific scope, with the additional dotted line. Here, 2 steps of geographic

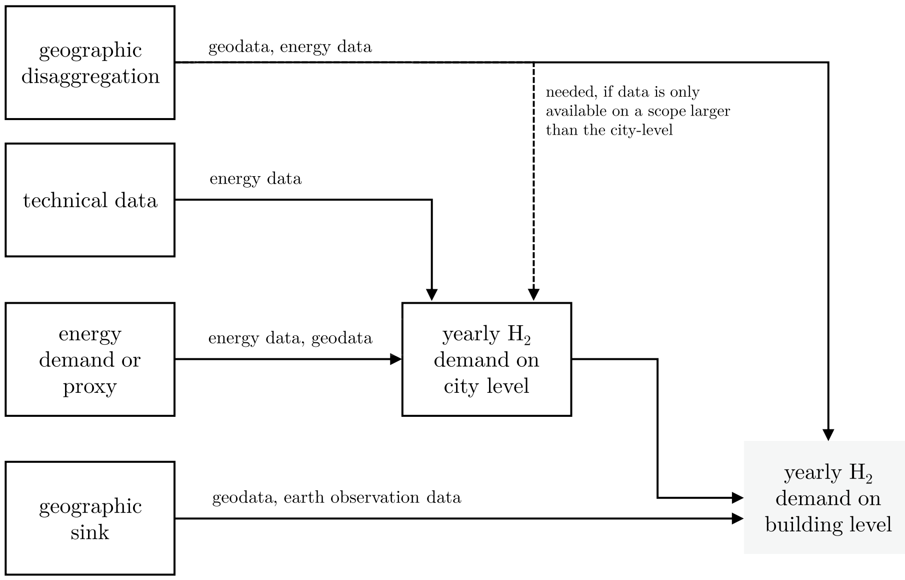

Fig. 1 Methodology

Table 1 Hydrogen sink proxy overview

Sector	Proxy hydrogen demand	Geographic disaggregation	Geographic location
Steel	Production volume	CO_2 emissions	Industrial facilities
Organic chemistry	Production volume	CO_2 emissions	Industrial facilities
Fertiliser and ammonia	Production volume	CO_2 emissions	Industrial facilities
Process heat	CO_2 emissions	NA	Industrial facilities
Buses	Driven distance	Size of bus depots	Bus depots[a]
Trucks	Driven distance	Size of logistic centres[b]	logistic centres[a]
Trains	Driven distance (non-electrified)	NA	Train petrol stations
Ships[c]	Bunker fuel	Tonnes kilometres	Ports
	Tonnes kilometres	NA	Ports
Airplanes	Passenger kilometres	NA	Airports

[a] If no data is available for the investigated area, the hydrogen demand is allocated to industrial and commercial zones. The underlying assumption being that most heavy-duty traffic as well as bus depots are situated here

[b] In a first step, the German national data for trucks is disaggregated via cargo handling data to a city-specific level using the same methodology

[c] Ship data is separated for inland and maritime ports

disaggregation are needed. Different parameters can serve as geographic disaggregation factors if given on a building or region-specific level. E.g., geodata such as the size of the sink or georeferenced energy-related data such as their CO_2 emissions.

The geographic disaggregation to the different sinks is performed as in Eq. 5:

$$demand_i = share_i(GD) \cdot demand_{total} = \frac{GD_i}{GD_{total}} \cdot demand_{total} \tag{5}$$

With $demand_i$ being the hydrogen demand at sink i, GD_i the value of the geographical disaggregation factor for sink i, and GD_{total} the total geographical disaggregation factor. $demand_{total}$ is the total hydrogen demand for the sector.

Table 1 gives an overview of the proxies for the specific energy consumption for all modelled sectors in the implementation of this method. It also presents the geographic disaggregation used to allocate the hydrogen demand on a building-specific level. Table 5 goes into more detail of the open data sources used to determine these variables and proxies.

Industry

Industrial feedstock

Since no direct data for an industrial facilities' energy demand is publicly available, proxies are used to estimate the hydrogen demand for the entire relevant industry, which is then disaggregated for each industrial facility at a geospatial scale.

First, the industrial hydrogen demand is estimated for each industrial sector. The estimation requires knowledge of the total production volumes x_p in these sectors and the amount of H_2 needed to produce a unit of each sector's product. Following, this value is referred to as specific hydrogen demand h_p for a product p. Thus, for each sector, the total hydrogen demand results from Eq. 6.

$$demand_{total} = h_p \cdot x_p \tag{6}$$

The steel sector and the fertiliser/nitrogen compound sector mainly produce steel and ammonia, respectively. The specific hydrogen demand is known for H_2-DRI and ammonia is calculated stoichiometrically based on Eq. 2 and Eq. 3, respectively. Their total production values x_p are publicly available. Table 2 shows the specific hydrogen demands in each sector and its respective specific hydrogen demand. The organic chemistry sector does not consist of mainly one product. It produces several products which must be accounted for. In Germany, three groups of products make up the largest share in the sector: methanol (MeOH), olefins (mainly ethylene and propylene) and aromatic compounds (mainly benzol, toluol and xylol) (VCI 2022). Based on chapter Hydrogen Usage in the Industrial Sector, it is assumed that all these organic chemicals are produced using MeOH via clean hydrogen and CO_2. Thus, the specific hydrogen demand of MeOH is used as a proxy for the sector. It is calculated stoichiometrically using Eq. 4. Similarly, the total MeOH production volume thus results from the primary MeOH production volume $x_{MeOH|primary}$, and the MeOH needed to produce olefins and

Table 2 Hydrogen demand per product of each industrial sector, rounded

Industrial sector	Product	Specific hydrogen demand [t H_2 /t product]	Source
Steel	Steel	0.05	Vogl et al. (2018)
Organic chemistry	MeOH	0.19	Geres et al. (2019), own calculations
Fertilizer and ammonia	NH_3	0.18	Geres et al. (2019), own calculations

aromatic compounds, as shown in Eq. 7. These values are denoted as $x_{MeOH|olefins}$ and $x_{MeOH|aromats}$, respectively.

$$x_{MeOH_{total}} = x_{MeOH|primary} + x_{MeOH|olefins} + x_{MeOH|aromats} \tag{7}$$

Analogously to the specific hydrogen demand, the number of units of MeOH needed to produce a unit of olefins/aromatic compounds is called specific MeOH demand. The MeOH needed for the production of olefins and aromatic compounds is the product of their respective specific methanol demands ($m_{olefins}$ and $m_{aromats}$), and production values (in the German industry), as shown in Eq. 8.

$$x_{MeOH_{total}} = x_{MeOH|primary} + \underbrace{x_{olefins}\, m_{olefins}}_{x_{MeOH|olefins}} + \underbrace{x_{aromats}\, m_{aromats}}_{x_{MeOH|aromats}} \tag{8}$$

The specific MeOH demands are calculated stoichiometrically based on Geres et al. (2019).

The total hydrogen demand for each industry is now be allocated to industrial facilities. It is assumed that the production of each organic chemical is equally distributed among all industrial facilities producing organic chemicals. In line with the European Union's Planheat project, a facility's CO_2 emissions are a proxy for its energy demand (Planheat 2019). Hence, the CO_2 emissions disaggregate the total hydrogen demand geographically and assign it to specific facilities. European industrial facilities have yearly emission allowances and report their CO_2 emissions annually to the European Union. The emissions are documented in the European Pollutant Release and Transfer Register (E-PRTR), containing additional datasets with their economic activity sector and coordinates.

Process heat

The hydrogen demand of a facility's process heat is calculated via its heat demand. As proposed in Planheat (2019), the heat demand of each facility is estimated as presented in Eq. 9.

$$heat\ demand = E_{CO_2} \cdot \frac{1}{EF_{fuel}} \tag{9}$$

E_{CO_2} are the facility's CO_2-emissions and EF_{fuel} is the CO_2 emission factor of the fuel used in that facility. Table 3 summarises the CO_2 emission factors for natural gas, oil, and coal. They are based on IPCC estimates (Planheat 2019). Industrial facilities belonging

Table 3 CO_2Emission factors of fuel types and their typical sectors

Fuel	CO_2Emissions factor [tCO_2/kWh]	Economic sector/product
Natural gas	0.202	All remaining economic sectors
Oil	0.281	Oil refining
Coal	0.346	Metals, minerals, coke manufacturing, mining

to a specific economic sector typically use the same types of fuels (Planheat 2019). These are presented in Table 3.

The heat demand is estimated for all facilities that do not belong to the sectors covered in chapter Hydrogen Usage in the Industrial Sector, oil refining, waste-to-energy, and electricity production. This avoids double modelling of sinks and accounts for a sustainable industry. Waste-to-energy and electricity production plants are not modelled since their heat results from burning waste and fossil fuels.

Mobility

The hydrogen demand in the mobility sector is modelled for the sectors covered in chapter Hydrogen Usage in the Mobilty Sector according to the proposed method. Table 4 includes the technical specifications for the hydrogen estimations in the mobility sector. If available, real data is used for the specific hydrogen demand of each type of vehicle. Since there are no large-scale proven hydrogen-based ships and airplanes, similar engine efficiencies to current propulsion engines are assumed.

Table 4 Technical specifications for hydrogen demand estimation

Vehicle	Specific hydrogen consumption [kgH_2 / km]	Specific energy consumption	Source
Bus	0.09	–	Skiker et al. (2018)
Truck	0.0775	–	Hyundai (2020)
Train	0.3	–	Ernst & Young GmbH et al. (2016)
Airplane	–	1.45 MJ/pkm	Air BP Ltd. (2000); Deutsche Lufthansa AG (2020)
Inland ship	–	0.4 MJ/tkm	Umweltbundesamt (2021)

Table 5 Data Source Overview

Data source	Variables
OSM and overpass API	Geolocation of bus depots, logistic centres, industrial and commercial areas
Google Maps and Google Places API	Bus depots, logistics centres
Wikidata	Geolocation of airports and ports
E-PRTR	CO_2 emissions of industrial facilities, geolocation of industrial facilities and economic activity (NACE) code of industrial facilities
DB Energie	Train petrol stations
Eurostat	Truck cargo handling (loading and unloading) data
Federal Statistical Office of Germany	Bus mileage (driven distance), tonnes kilometres shipping, passenger kilometres at airports, production volume of steel industry
Verband der Chemischen Industrie e.V. VCI (2022)	Production volumes of chemical industry
Federal Motor Transport Authority of Germany	Truck mileage (driven distance)
Bundesverband SchienenNahverkehr	Non-electrified train mileage (driven distance)
AG Energiebilanzen	Bunker fuel consumption

Data used

The implementation of the method was carried out using a Python model, exclusively relying on open source data sources. The model effectively retrieves and processes relevant geodata from a variety of sources, including OpenStreetMaps, Earth Observation data in conjunction with computer vision algorithms, Wikidata, the E-PRTR database, and open data from the European Union and the German Government to ensure its applicability within Germany. All the data sources utilized in the implementation are summarized, along with their respective merits, in Table 5.

Results

The model was implemented in a generalised way and is applicable for all of Germany using the open source data described in the section above and in Table 5. For this study, the developed model is run for two different case studies.

Case study Freiburg

The case study *Freiburg im Breisgau* assumes the usage of the full hydrogen potential in all modelled sectors. These are the industrial feedstock sector (steel, ammonia, organic chemistry), industrial processing and the mobility sector (buses, trucks, trains, airplanes, and ships).

Figure 2 illustrates the estimated hydrogen demand for each sink in Freiburg and clustered for each neighbourhood on a satellite map. Figure 5 (a) summarises the total values of yearly hydrogen demand in the area. Most of the hydrogen demand comes from trucks, with minor shares of 5% each resulting from trains and buses.

While industrial facilities exist in Freiburg, their CO_2 emissions are not large enough to be documented in the E-PRTR. Hence, there is no modelled industrial Hydrogen

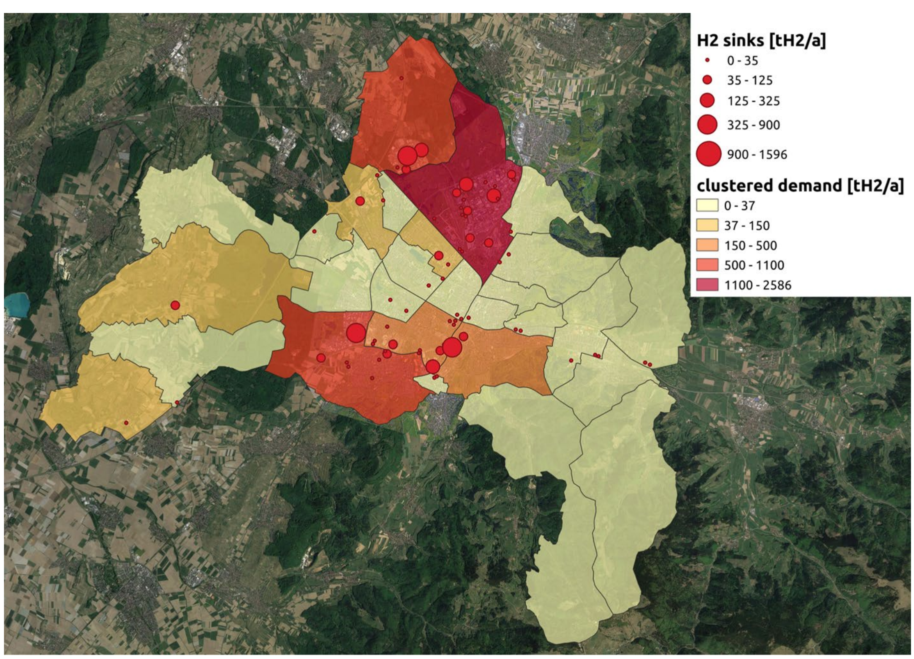

Fig. 2 Hydrogen demand map Freiburg

demand. Additionally, Freiburg does not have any ports. Though Freiburg has an airfield, it only handles small-sized aircraft and helicopters and, therefore, is not considered as a hydrogen sink, as explained in chapter Hydrogen Usage. Consequently, the hydrogen demand of ships and airplanes is estimated to be zero.

The highest hydrogen demand is in industrial zones, especially in the north and south of Freiburg since most truck sinks are located here. A subcluster exists in central-southern Freiburg where a train petrol station and several commercial areas that serve as truck sinks are located. Low demand areas are in the east and west which are mainly residential areas, agricultural areas, mountains, and forests.

Case study Frankfurt

To compare, the method is applied in *Frankfurt am Main*. In a first step, a base scenario, similarly to the case study Freiburg, is modelled assuming full usage of the hydrogen potential. The base scenario is then modelled for a restricted hydrogen demand. Instead of using the full potential, a ramp-up phase is modelled. Here, only the sectors that are technologically feasible today are modelled. These sectors are the train, bus, truck, and industrial sectors. The excluded sectors are the shipping and aviation sectors since no hydrogen-based propulsion systems exist today. Both scenarios are summarised in Table 6.

Table 6 Modelled scenarios Frankfurt

Scenario number	Scenario name	Modelled sinks [100%]	Excluded sinks
1	Base scenario	All	None
2	Ramp-Up scenario	Industrial feedstock & heat, trains, trucks, buses	Aviation, shipping

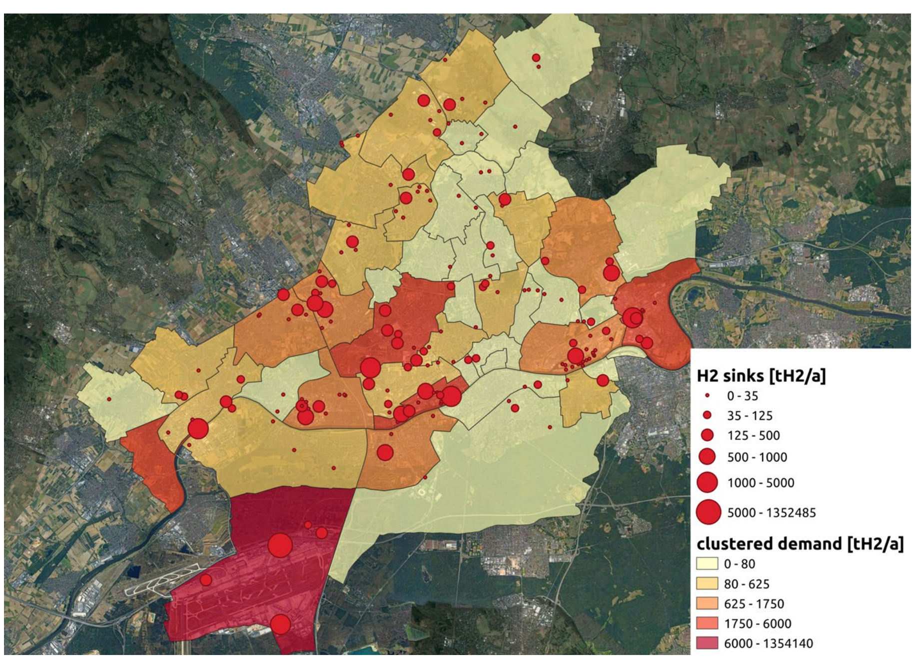

Fig. 3 Hydrogen demand map Frankfurt, base scenario

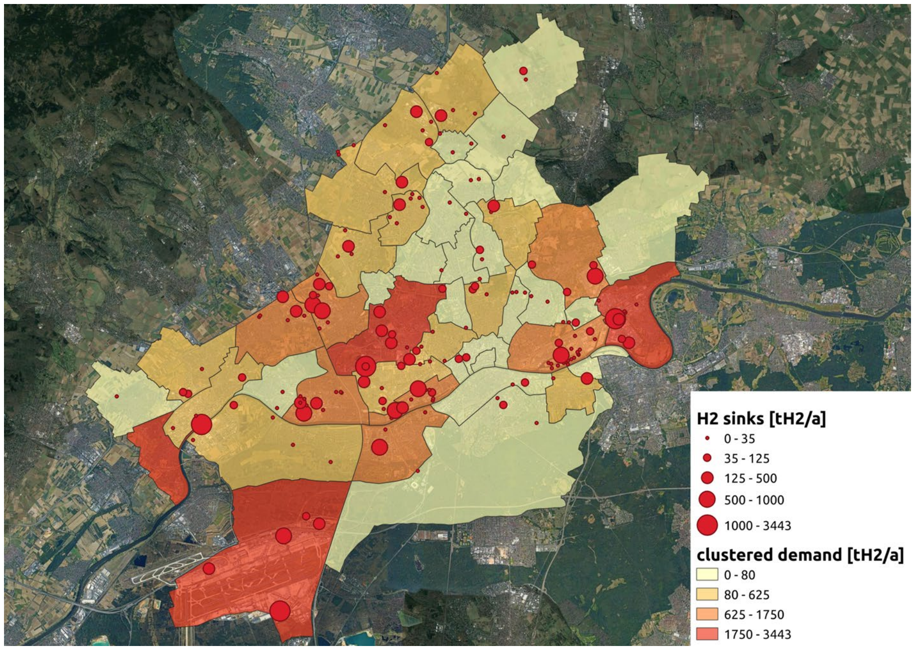

Fig. 4 Hydrogen demand map Frankfurt, ramp-up scenario

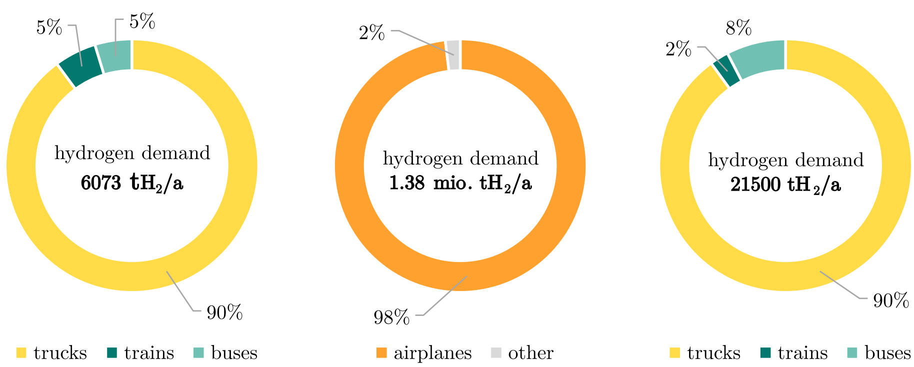

Fig. 5 Yearly hydrogen demand by type of sink for **a** Freiburg, **b** Frankfurt, base scenario, **c** Frankfurt, ramp-up scenario

For Freiburg, no difference is observable between these two scenarios since Freiburg does not have any airplane and ship sinks. Thus, Frankfurt is used as case study to differentiate between these two scenarios and to apply the method on a larger city. Figure 3 illustrates the results of the hydrogen demand estimation and Fig. 5 (b) shows the total annual hydrogen demand by type of sink for the base scenario. Large demand clusters are in industrial areas and around the airport which is in the south-west. Especially the airport makes up most of the hydrogen demand.

This hydrogen demand would require electrolysers with a total capacity of at least 8.87 GW (assuming 8760 full load hours, and an efficiency of 70% based on the calorific value) to supply the city's demand.

Figure 4 shows the results of the hydrogen demand estimation and Fig. 5 (c) shows the total annual hydrogen demand by type of sink for the ramp-up scenario. The largest sinks are around the industrial areas in eastern and western Frankfurt. Likewise, the airport area is still a significant sink due to the large amount of logistics centres located around it.

Discussion

Validation

Since no hydrogen economy has been developed on a city-wide level in Germany yet, no data exists to validate the methodology quantitatively. However, several national models estimate the potential future hydrogen demand for Germany. This work's results are thus validated by benchmarking it with those of the national models' considering each other's underlying assumptions. National hydrogen models are models that estimate the hydrogen demand on a national scale, as explained in "Hydrogen demand modelling" section. Several of these models exist for Germany.

The total estimated hydrogen demand when applying this method to all of Germany is 22.7 million tH_2/a. Based on hydrogen's energy density, this corresponds to 580 TWh of hydrogen per year. Figure 6 shows the estimated hydrogen demand broken down by sectors if every sector switches by 100% to hydrogen-based technologies. The largest sectors are industrial feedstock and process heat. Buses and trains only account for 1.0% and 0.3%, respectively.

In a meta-analysis, Wietschel et al. (2021) compare different studies that estimate the potential hydrogen demand in Germany. This meta-analysis serves as a basis to benchmark the results of this study. Every study has different underlying assumptions and scenarios with other GHG reduction goals. While this study does not directly include GHG emissions reductions, the assumption is that hydrogen is produced only from electrolysers. Like most other studies, hydrogen produced from other technologies is not modelled. The assumption corresponds to a 100% GHG reduction assuming that the electricity sector is decarbonised separately, similarly to most studies analysed by Wietschel et al. (2021), which have GHG reduction goals that are > 95%.

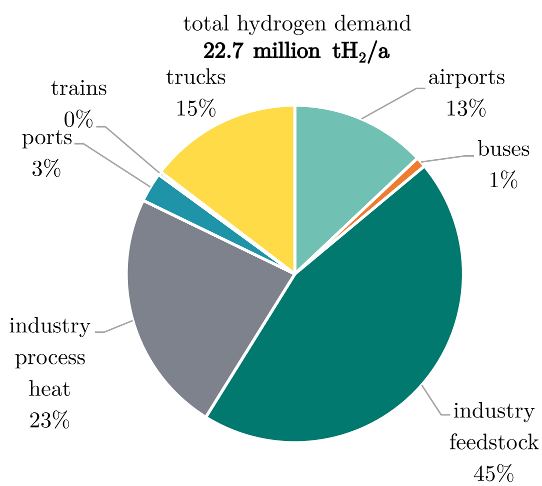

Fig. 6 Total estimated hydrogen demand, Germany

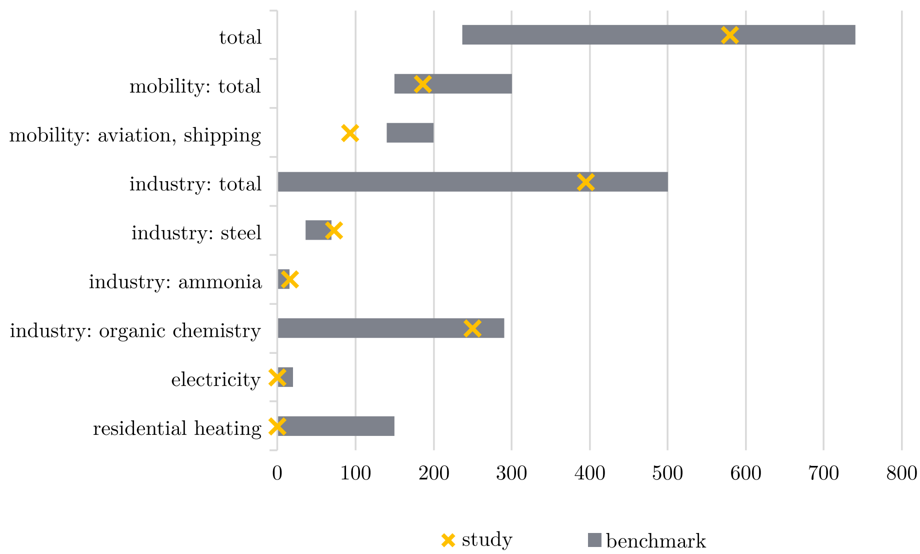

Fig. 7 Validation of the hydrogen demand estimation

Figure 7 validates this study's results by comparing them with those of the analysed studies.

The total hydrogen demand in the analysed studies ranges between 234 and 740 TWh for hydrogen, synthesis products (hydrogen-based products) and biomass (Wietschel et al. 2021). The total estimated hydrogen demand of this study (580 TWh) is within the range of the analysed studies.

The demand for hydrogen, synthesis, or biomass products in the aviation and shipping sectors ranges between 140 and 200 TWh, higher than the estimated 93 TWh in this study. This discrepancy results from the decision not to model short-haul aircraft as hydrogen sinks and the conversion of producing e-fuels. The effects of modelling the aviation sector hydrogen-fuelled also causes the discrepancy presented in the total demand for pure hydrogen.

The mobility sector's hydrogen (and synthesis products and biomass) demand ranges between 150 and 300 TWh compared to the 186 TWh of this study. Consistent with this study, the industrial sector has the most significant hydrogen demand. This study estimates the potential hydrogen demand to be 395 TWh, compared to $<$ 500 TWh in the analysed studies. In both cases, hydrogen usage for industrial feedstock is highly significant - almost all studies, including this work, model steel, ammonia, and organic chemistry. In all industrial feedstock subsectors, the results are within the same range (Wietschel et al. 2021).

This study does not model hydrogen-based heating in the building sector, hydrogen's role in the electricity sector and fuel cell electric cars. This is coherent with most other studies. Some see low potentials in the residential sector (with some outliers). In the electricity sector, some studies see possibilities of up to 20 TWh until 2030. Older studies focus more on fuel cell cars, while newer studies do not model them (Wietschel et al. 2021).

Hydrogen demand allocation

In the hydrogen demand estimation, several assumptions were made concerning the spatial distribution of hydrogen sinks. Most of these simplifications result from uncertainty of how certain sectors will develop in the future, and thus assume today's locations and demand centres. The assumptions are summarised in this section.

In the proposed method, the hydrogen demand is allocated to existing sinks. This assumes that the hydrogen demand will be at the same geographic location in the future as the fossil fuel-based demand is today. This neglect future changes of demand centres. While some sectors are likely not to change their sinks, e.g., logistic centres and airports, others might, e.g., hydrogen bus depots and train petrol stations. Furthermore, it is unclear if a hydrogen-based industry will occur at the same locations as today or maybe even shift to locations where hydrogen is cheaper. In the literature, this is also referred to as renewables pull.

Aviation and shipping sinks are modelled as airports and ports. Using e-fuels instead of hydrogen would mean that these e-fuels are produced at those sinks, another simplification made in this study.

Furthermore, demand can only be allocated to sinks in databases used in the model. Hence, if the underlying datasets do not contain all relevant geographic sinks, neither will the model allocate hydrogen to these sinks.

Conclusion

Summary

Urban energy system planning is vital for cities shifting towards a more sustainable and integrated energy system. Hydrogen is an energy carrier in integrated energy systems, and it is essential to plan cities' future energy infrastructures accordingly. For this purpose, urban energy system planners need to understand where potential hydrogen demand is geospatially located within their cities and how to supply hydrogen locally in a climate-friendly manner. Previous work on hydrogen energy systems has predominantly analysed hydrogen models nationally. Local models that analyse hydrogen energy systems geospatially mainly only focus on passenger road transport mobility. In the context of integrated future energy systems, cities need a holistic model including all relevant sectors on a geospatial level to support decision-making surrounding the hydrogen economy. This study presents a geospatial hydrogen demand estimation method for such a holistic model. The scope of this study is the mobility and industrial sector. The industrial sector includes feedstock (steel, ammonia, and organic chemicals production) and process heating. Bus, trucks, trains, airplanes, and ships are modelled in the mobility sector. A method is developed to estimate the hydrogen demand geospatially by using the specific energy demand for each sector and the geographic locations of hydrogen sinks while relying on exclusively open source data. The method accounts for various available data sources by combining a variety of data sources and geographically disaggregating the hydrogen demand in a top-down manner if needed. This allows the method to be applied even when available open source data is scarce. This method can be expanded or reduced for other unaccounted sectors. While the method is implemented for Germany in this study using open source data available in Germany, its generalisability allows it to be applied in different countries where alternative data is available.

The model is validated by benchmarking this study's total estimated hydrogen demand with comparable studies for Germany. The results show that the estimated hydrogen demand is within the same range as those calculated by other studies. One drawback of the proposed geospatial hydrogen demand allocation is the assumption that future hydrogen sinks will be located at current sinks. The method is applied in two case studies: *Freiburg im Breisgau* and *Frankfurt am Main*. Within cities, the results of the hydrogen demand estimation indicate large hydrogen sink clusters in industrial and commercial areas. The ramp-up scenario is used to model the potential hydrogen demand for cities while neglecting sectors where no market-ready solutions exist.

Outlook

The current model can be improved in several ways. The hydrogen demand estimation only focuses on the geospatial distribution of the hydrogen demand and assumes a constant demand throughout the year of the sinks. Further research could explore the temporal characteristics by including hydrogen demand profiles for each sink. It also does not include the electricity sector. Future research could investigate the influence of hydrogen-fuelled power plants and the temporal aspects of hydrogen demand.

Author contributions
SB: design of the method and development of the model, generating results and writing of this manuscript. DF: discussed method, reviewing and commenting of this manuscript. All authors read and approved the final manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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