Assessing regional potentials for green hydrogen infrastructure planning in Germany

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Abstract
Green hydrogen offers significant advantages in terms of sector coupling and electrification of energy systems. To ensure a reliable hydrogen supply chain in regions, there is a growing need for hydrogen infrastructure planning. Strategies need to take into account spatial characteristics of supply and demand as well as existing regional potentials. The aim of this study is to develop a holistic approach to assess regional potentials in the context of green hydrogen infrastructure planning by considering both technical and socio-economic factors. A principal component analysis was carried out in NUTS-3 regions throughout Germany. We identified four indices representing regional hydrogen and location potential. A cluster analysis was used to identify region-specific needs and requirements. This will benefit the planning process for developing regional hydrogen strategies.

Keywords
Green Hydrogen; Regional Planning; Planning Methods; Energy Infrastructure; Assessment Concept

1. Introduction

In the process of global sustainable energy transition, green hydrogen is often referred to as a game changing technology. As a carbon-free energy carrier, green hydrogen provides options for storing and delivering volatile renewable energy and is an integral part of sector coupling. However, the role of green hydrogen in future energy systems remains controversial, due to uncertainties about supply, demand and cost of system integration during the rollout phase (Ren et al., 2023). This poses major challenges to the development of hydrogen infrastructure, which relies on a stable and long-term framework for initial investments.

In recent years, the European Union and several European countries have published strategies to increase green hydrogen production capacities. For example, the European hydrogen strategy for a climate-neutral Europe (EHS) increases their target for green hydrogen production capacity significantly to 40 gigawatts by the year 2030 (European Commission, 2020). With the expected increase in green hydrogen production and imports, a need for a reliable infrastructure to transport hydrogen from areas with high renewable potential to demand centres and hydrogen storages is emerging (Baufumé et al., 2013).

In this context, different planning approaches for the development of green hydrogen infrastructure can be observed in hydrogen strategies of the European Union and Germany. The development and implementation of the suitable strategic approach for hydrogen infrastructure planning is highly dependent on the spatial context (Mai et al. 2023). In this way, the assessment of regional location potentials is seen as an essential component. While the EHS refers to a wider range of location potentials such as spatial connectivity and socio-economic factors, the current focus of assessments is still on technical potentials such as green hydrogen supply and demand. However, as a basis for planning and decision-making, it is important to examine and assess all relevant potentials in detail.

This raises the question of how to develop an assessment of regional potentials for green hydrogen infrastructure planning in order to derive context-specific planning strategies. The

study aims to develop a holistic concept for the assessment of regional potentials related to the planning of green hydrogen infrastructure. During the study we examine regional hydrogen supply and demand potential, as well as a selected range of location potentials. Using spatial clustering methods, we explore region-specific requirements in the process of green hydrogen infrastructure planning.

The concept is intended to support the planning and decision-making process by exploring suitable strategies for hydrogen infrastructure planning. By saving valuable time and resources, the concept accelerates the planning and decision-making process at the regional level. In particular, regional planners benefit from the systematic assessment in order to adapt hydrogen strategies with location-specific actions and measures.

2. Theoretical Framework

The deployment of green hydrogen depends mainly on future supply, demand and cost developments that accumulate along the hydrogen supply chain (HSC). The HSC refers to the entire process from the production of hydrogen gas to its use by the final consumer. It includes hydrogen infrastructure for production, transportation, storage and utilisation (Changjong et al., 2022). However, the process of green hydrogen infrastructure planning is challenged by uncertainties such achieving competitive costs and mass market acceptance (Mai et al. 2023). In this section, we focus on green infrastructure elements across the HSC and on planning strategies to implement these infrastructures. The EHS will be considered in this context, as well as the role of assessing regional potentials for green hydrogen infrastructure planning.

2.1 Green hydrogen infrastructure

Hydrogen can be produced through various pathways using fossil fuels, nuclear energy or renewable energy. For the generation of carbon-free or green hydrogen, only renewable energy sources (RES) are utilised to dissociate water into hydrogen and oxygen (Xu et al. 2023). This process, called water electrolysis, is widespread and uses volatile RES such as wind, solar or bioenergy. Global electrolysis capacity is expected to increase from 0.5 million tonnes in 2022 to over 21 million tonnes in 2028 (Al-Douri and Groth, 2024, p.777).

The cost of producing hydrogen from electrolytic water (between $5.78 and $23.27/kg) is currently significantly higher than the cost of producing hydrogen from gas ($2.08/kg) (Nikolaidis and Poulikkas 2023, p.621). Although costs for electrolysers are expected to halve by 2030, another challenge in this regard is meeting the increasing demand for electricity from RES. A study by Kakoulaki et al. (2020, p.9) predicts that major hydrogen production regions, especially densely populated regions, will not have enough green electricity to cover both current electricity consumption and electrolytic hydrogen production. However, given the overall surplus of electricity from RES across the European Union, this challenge could be met by interregional electricity transmission.

Hydrogen is supplied to the final consumer at hydrogen refuelling stations. Currently, hydrogen is used as a chemical feedstock and as a raw material in heavy industrial processes such as oil refining or fertiliser production. In general, these sectors are particularly difficult to decarbonise, which underlines the crucial role of hydrogen (Abdalla et al. 2023). Typically, the amount of hydrogen used in these industries is produced on-site or near the location of its use, in quantities that meet the needs of these industries (Steen, 2016).

By focusing on future decarbonisation scenarios and considering the use of power-to-gas or power-to-X technologies, the potential for hydrogen applications in other sectors is expected to increase further (Kakoulaki et al 2020). There are application potentials in the transportation sector and in the building sector as a fuel in combined heat and power systems. But hydrogen demand in the building sector is highly dependent on regional conditions such as renovation rates and the mix of heating technologies used (Wang 2021; Ge et al., 2024). The future global market for hydrogen is expected to grow significantly to between 115 and 130 million tonnes by 2030 (Dou et al., 2023; Al-Douri and Groth, 2024, p.775).

As noted by Baufumé et al. (2013) hydrogen transport and storage infrastructure should be designed to suit spatial and temporal distribution of demand and supply. If hydrogen production plants are located far from energy consumption sites, storage and transportation methods are necessary. Hydrogen can be stored in either gaseous or liquid state depending on its use in low-, medium- and high-pressure storage tanks (Mai et al., 2023). Whereas subsurface hydrogen storage in salt caverns or abandoned mines is a suitable option for large-scale and long-term storage uses (Ge et al., 2024). To connect relevant areas of supply and demand, a ubiquitous hydrogen transportation and distribution infrastructure is essential.

Hydrogen can be transported via trailors or pipelines. The former is used to transport gaseous and liquid hydrogen, while the latter is used to transport gaseous hydrogen only (Abdalla et al. 2023). The choice of transport mode depends on the delivery costs, which are influenced by the quantities transported, the delivery distances and local circumstances (Hugo et al., 2005; Ball and Weeda, 2015). Because fixed costs for initial construction of pipelines are relatively high (around 80,000 USD per 100m), this investment is only economical when transporting large quantities over longer distances (Changjong et al., 2022, p.1706). Therefore, transportation through pipelines is considered as the most cost-effective option for distances up to 3,000 kilometres, when there is high demand for hydrogen (Abdalla et al. 2023; Lipiäinen et al., 2023). For longer distances, sea transport by ship is an option.

Using the existing gas network by blending hydrogen into natural gas pipelines is expected to achieve significant savings (Jens et al. 2021, Moultak, et al. 2023). The European Union and several of its Member States are in the process of developing hydrogen transport projects, some of which are even planned to carry exclusively hydrogen (Lipiäinen et al., 2023). To reduce costs and improve infrastructure design and operation, coordinated support and strategic planning across the HSC is essential.

2.2 Strategic hydrogen infrastructure planning

According to Luise et al. (2023), the selection of an appropriate strategic concept is essential for the planning of hydrogen infrastructures across the HSC. Different planning concepts are distinguished according to their degree of centralisation and decentralisation with regard to production, storage and transport infrastructures. The EHS published in 2020 pursues both concepts simultaneously. While long-term initiatives such as the European Hydrogen Backbone (EHB) take a centralised approach in planning large interconnected transport networks, the focus lies also on the development of local hydrogen clusters.

The EHS aims to establish a hydrogen ecosystem by 2050 in close cooperation with the European Member States. The target for 2030 is to increase electrolyser capacity by 40 gigawatts by 2030 (European Commission, 2020). To achieve this, key actions are described, such as the establishment of an investment agenda for the European Union or the expansion of hydrogen supply and demand across the HSC. In this context, a suitable hydrogen infrastructure will be developed in stages, from a decentralised to an increasingly centralised system.

In the initial phase, local hydrogen valleys with on site production, closely located to consumption and distribution network systems will be developed. Afterwards, the strategy intends on progressively connecting emerging hydrogen valleys, import terminals, large-scale storage facilities and industrial clusters to an initial backbone transmission infrastructure. In this regard, eleven transmission system operators presented plans in 2021 for an integrated European hydrogen network largely based on repurposed and existing natural gas infrastructure (Jens et al., 2021). Since then, the vision of the EHB initiative has grown fast into a pan-European pipeline network of almost 53,000 kilometres to be established in 2040 (Moultak et al., 2023).

As noted by the EHS, to ensure the implementation of infrastructures across the HSC, further research and innovation efforts are required. This refers to the development of hydrogen technologies such as large scale, efficient and cost-effective electrolysers, large scale end-use applications and infrastructure to distribute, store and dispense large quantities of hydrogen (European Commission, 2020). To address these challenges, the EHS aims to coordinate and financially support European projects for research, development and demonstration of hydrogen technologies. Changjong et al. (2022) state that providing demonstration projects is a central part of the European roll-out strategy for developing hydrogen infrastructure.

Several European countries have published their own national hydrogen strategies to support the deployment of green hydrogen. It has been criticised, that these strategies often focus on policy making rather than concrete actions and local measures (World Energy Council 2020; BMWK, 2023). However, as noted by Mai et al. (2023), the development and implementation of strategic concepts or planned projects is highly dependent on the spatial context. In this regard, analysing the availability of RES or the expected demand for hydrogen is already considered as an essential part for the implementation of hydrogen strategies.

While hydrogen demand and supply potentials are assessed comprehensively at the national scale, e.g. for the planning of the EHB, the regional perspective is rarely taken into account (Moultak et al., 2023). Nevertheless, regional assessments offer a higher spatial resolution and are therefore able to detect regional impacts at a smaller scale, an advantage that has already been recognised and applied in the field of national grid planning for volatile renewable energy sources across Europe (Ebner et al. 2019).

Although several studies focus on the assessment of regional potentials, they usually solely consider the technical potentials for green hydrogen production such as RES potential, electricity demand or current hydrogen production (Kakoulaki et al., 2022; Okunlola et al., 2022). While Okunlola explores the impact of spatial distance to gas pipelines and population clusters for green hydrogen production, neither study considers socio-economic factors to contribute to the implementation of the EHS.

3. Methodology

In order to provide a reliable basis for the planning of green hydrogen infrastructure we developed a holistic concept for assessing regional potentials across the HSC. In addition to the consideration of demand and supply potential, this concept has been extended to include other location factors relevant to the implementation of the EHS. In this regard, we focused on socio-economic location factors related to research and development and energy infrastructure.

3.1 The case of Germany

In this study, we use Germany as a test case to assess regional hydrogen and location potentials for green hydrogen infrastructure planning. In the context of the EHS, the German national hydrogen strategy was released in 2020. The target for domestic electrolysis capacity in 2030 will be doubled from five gigawatts to at least ten gigawatts (BMWK, 2023, p.1). Efforts are currently focused on implementing power-to-gas technology and model regions with hydrogen-related concepts across the country (Changjong et al. 2022; BMWK, 2023).

The German industrial sector has a great need for decarbonisation, especially in high-temperature applications such as the primary steel production and in the chemical industry. The forecast for hydrogen demand in the German industry is between 290 and 440 terawatt hours by 2045. (BMWK, 2023, p.20). Although the share of RES in the electricity sector is increasing, the potential for domestic production of green hydrogen is limited. Therefore, in the long term, most of the demand will have to be met by imports (BMWK, 2023; UBA 2024).

At first, import of hydrogen and its derivatives is planned to be largely ship-based, with the possibility of pipeline expansion to European countries. As Lipiäinen et al., (2023, p.31322) note, Denmark is already planning a pipeline of 350 to 450 kilometres to export green hydrogen to Germany. Germany has ambitious plans to build a hydrogen network that consists of repurposed and newly constructed hydrogen pipelines. An initial core network of hydrogen transmission pipelines with more than 9,700 kilometres is expected to be completed by 2032 (FNB 2023). In addition, two hydrogen pipeline networks are currently in operation located in the Rhine-Ruhr area (220 km) and at the outskirts of Leuna and Bitterfeld (100 km) in eastern Germany (Baufumé et al., 2013).

3.2 Data and methods

Following the Nomenclature of Territorial Units for Statistics (NUTS) level three[1], a total of 400 cities and counties were considered as research units. NUTS is a geocode standard for referencing spatial units for statistical purposes. We used a variety of official and open databases to collect measurable indicators for the empirical examination. Relevant geospatial data was pre-processed using GIS software. Through a theory-based analysis of relevant aspects of the HSC, the EHS and the German hydrogen strategy, we compiled a dataset from an initial set of 65 variables, selecting proxy variables related to the socio-economic situation, municipal finance, public funding, renewable energy production and the hydrogen production chain. Table 1 provides an overview of the dataset used in the further research process, including 20 relevant indicators and their data sources.

[1] With the exception of the city of Eisenach, which was merged with Wartburg County in 2021. To ensure data consistency, only Wartburg County was included in the analysis.

Table 1. Used dataset

Source	Indicator / Variable	Year
Global Wind Atlas	Average wind power density at 150m height (in W/m^2)	2023
Leibniz Institute of Ecological Urban and Regional Development	Area % of windfarms out of total area	2021
Federal Ministry of Transport and Digital Service	Minimal distance to seaports (in km)	2022
Federal Office of Cartography and Geodesy	Area % of 2km-corridores around electricity transmission lines out of total area	2022
Federal Institute for Research on Building, Urban Affairs and Spatial Development	Average age of population (in years)	2022
	% of employees at professional level	2022
	Students in vocational schools (per 1,000 inhab.)	2019
	Students at universities (per 1,000 inhab.)	2021
	% of graduates with higher education level	2022
	Expenditure on direct project funding (in € per inhab.)	2021
	Federal expenditure on university funding (in € per inhab.)	2021
	Tax revenue (in € per inhab.)	2021
	% of households with min. bandwidth of 1,000 Mbit/s	2022
	% of residential buildings with renewable energy sources	2022
	Travel time to intermodal terminals (in min)	2021
	% of employees working in the industrial sector	2021
	% of employees working in the secondary sector	2021
	% of gross value added in the secondary sector	2021
	Passenger car density (per 1,000 inhab.)	2022
Association of supra-regional gas transmission companies Germany	Minimal distance to planned hydrogen core network pipelines (in km)	2023

To create indices for assessing regional potentials we used an exploratory principal component analysis (PCA) (Jolliffe, 2002). After testing for suitability using Kaiser-Meyer-Olkin test and Bartlett's test of sphericity, we conducted three separate PCAs to identity relevant indicators for constructing representative indices of location factors and hydrogen potential from the above dataset. Following Mayer (2018), we first computed PCA based on eigenvalues to determine the number of relevant components in an iterative process by analysing the respective screeplots. The resulting components were then interpreted in terms of their factor loadings in the component matrices (using varimax rotation if applicable). Each index variable was normalised using z-score transformation.

Finally, the compiled indices were used to perform a cluster analysis in order to detect and classify regions with similar potentials. Based on the analysis of these cluster specific potentials it is possible to draw conclusions about cluster specific needs and requirements for hydrogen infrastructure planning. Following Backhaus et al. (2017) and Kimes et al. (2021), we conducted a hierarchical cluster analysis using the Ward method with a subsequent cluster centre analysis. For the cluster centre analysis, we use k-means clustering to extract eight clusters in the process.

4. Results

This section describes the results of the exploratory principal component analysis and the subsequent cluster analysis. Following our research objective, we first constructed indices from different regional location potentials in order to analyse their prevalence and spatial distribution in the following. Finally, we derived context-specific planning strategies based on the results of the cluster analysis.

4.1 Measuring of regional potentials

In total, four indices were created. According to the research concept, two indices describe the regional hydrogen demand and supply potential while the other two represent regional location potentials. We named each index variable according to their most influential indicators[2].

First, the index, *Knowledge and Innovation Potential* (RIP), was created in a separate PCA. It explained 49 per cent of the total variance between variables used (Table 2). Table 2 shows that the RIP index is predominantly characterised by educational indicators such as the number of students at universities or the level of expenditure on university funding. While the RIP index shows positive factor loadings for indicators that measure education, it is also compromised by negative factor loadings. In this respect, the percentage of employees at the professional level and the average age of the population indicate a possible shortage of skilled workers and a younger population at the same time. We use the RIP index as representative to assess regional location potential for the development of hydrogen research and innovation centres.

Table 2. Factor loadings of the Research and Innovation Potential (RIP) index

	Research and Innovation Potential (RIP)
Average age of population (in years)	**-0.720**
% of employees at professional level	**-0.812**
Students in vocational schools (per 1,000 inhab.)	0.630
Students at universities (per 1,000 inhab.)	**0.777**
% of graduates with higher education level	0.625
Expenditure on direct project funding (in € per inhab.)	0.636
Federal expenditure on university funding (in € per inhab.)	**0.736**
Tax revenue (in € per inhab.)	0.652
% of households with min. bandwidth of 1,000 Mbit/s	0.707
% of variance explained by the factor	49.4

Second, the indices, *Infrastructure and Connectivity Potential* (ICP) and *Hydrogen Supply Potential* (HSP) were created in a combined PCA. The HSP index, as the first principal component, explained 41 per cent of the total variance (Table 3). As Table 3 shows, the HSP index is characterised by indicators of RES such as average wind power density and the area share of wind farms. There are negative factor loadings for the minimum distance to seaports, indicating close access to import opportunities from overseas. We use this factor to assess regional hydrogen supply potential.

[2] To facilitate labelling the indices, the dominant indicators (factor loadings >0.75) are marked bold in the tables.

The second principal component, the ICP index, explained 26 per cent of the variance (Table 3). It is mainly characterised by positive factor loadings for travel time to intermodal terminals and negative loadings for the area share of corridors of electricity transmission lines. The factor loads were reversed for this index with higher loadings representing lower potential. In order to ensure consistency with the other indices, we inverted its score values so that positive scores represent higher potential. This third index is likely to represent regional location potential for the availability of energy infrastructure and spatial connectivity in the assessment.

Table 3. Factor loadings of the Infrastructure and Connection Potential (ICP) index and the Hydrogen Supply Potential (HSP) index

	Indices	
	1 – Hydrogen Supply Potential (HSP)	2 – Infrastructure and Connectivity Potential (ICP)
Minimal distance to seaports (in km)	**-0.884**	0.118
Average wind power density at 150m height (in W/m^2)	**0.929**	0.055
Area % of windfarms out of total area	**0.778**	0.132
Travel time to intermodal terminals (in min)	0.005	**0.832**
Area % of 2km-corridores around electricity transmission lines out of total area	-0.177	**-0.758**
Minimal distance to planned hydrogen transmission pipelines (in km)	-0.427	0.518
% of variance explained by the factor	41.1	26.2

Finally, the fourth index *Hydrogen Demand Potential* (HDP) was created in another separate PCA and explained 63 per cent of the total variance (Table 4). For this index table 4 indicates high factor loadings for the share of employees working in the secondary and the industrial sector as well as for the share of gross value added in the secondary sector. Since the HDP index is highly influenced by indicators of industrial density, we use this index as a representative to assess regional hydrogen demand potential.

Table 4. Factor loadings of the Hydrogen Demand Potential (HDP) index

	Hydrogen Demand Potential (HDP)
% of residential buildings with renewable energy sources	0.625
% of employees working in the industrial sector	**0.808**
% of employees working in the secondary sector	**0.936**
% of gross value added in the secondary sector	**0.878**
Passenger car density (per 1,000 inhab.)	0.673
% of variance explained by the factor	62.8

The scores of each index and its spatial distribution are presented in Figure 1 to 4 for administrative units at NUTS-3 level in Germany. In all cases, higher value scores represent a higher regional potential and vice versa.

For both the RIP and the ICP index, there is a spatial concentration of high scores in high density urban areas. We assume that this is due to the amount of educational and technical infrastructure such as universities or electricity hubs provided in cities. The HSP index shows an increasing

gradation of higher values towards the northern regions. As data of the Global Wind Atlas (2023) indicates, this is closely related to the wind power density and in coastal regions. This pattern is further reinforced by including seaports. The HDP index shows higher values in rural regions with an increasing gradation towards the south.

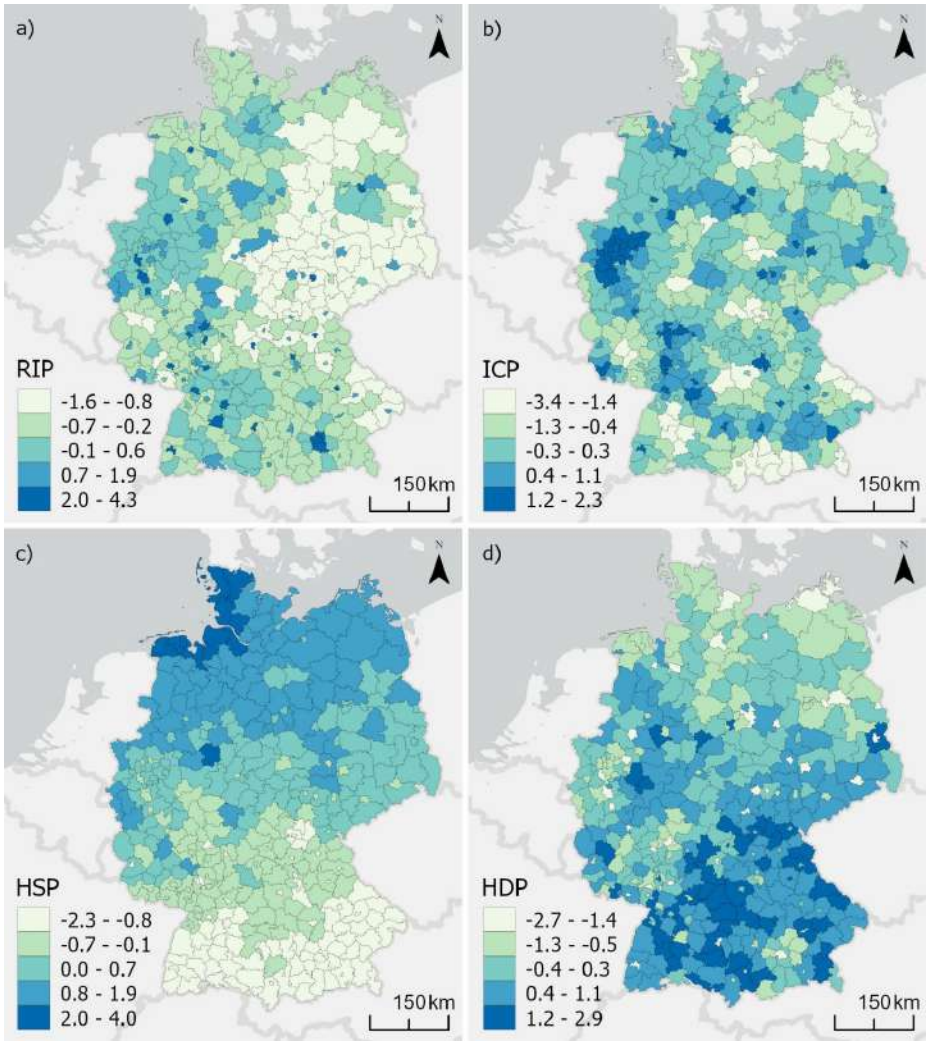

Figure 1-4. Spatial distribution of indices: RIP (a), ICP (b), HSP (c) and HDP (d) at NUTS-3 level in Germany

4.2 Clustering of regional potentials

Following the holistic approach all indices were considered equally in the analysis. As Table 5 indicates, we identified and extracted eight distinctive clusters in the research process. The average cluster distance indicates the heterogeneity that occurs within a formed cluster and allows the identification of cluster representative regions.

Table 5. Results of cluster analysis: Average cluster distance and average scores of indices

Cluster	**Average cluster distance**	**Average score values**			
		RIP	ICP	HSP	HDP
1 – Supply region with needs for infrastructure	0.97	-0.68	**-1.27**	**1.02**	-0.46
2 – Demand region with needs for infrastructure	1.03	-0.56	**-1.33**	-0.89	**0.98**
3 – R&D region with needs for infrastructure	1.24	0.66	-0.44	-0.80	-0.76
4 – Supply region with connectivity potential	1.04	-0.13	0.08	**1.54**	-0.25
5 – Activatable supply and demand region	0.77	-0.81	-0.11	0.23	0.34
6 – Infrastructure hub regions	1.05	0.54	**1.36**	-0.19	-0.78
7 – R&D centres with connectivity potential	1.38	**2.45**	0.95	-0.23	**-1.49**
8 – Demand region with connectivity potential	0.90	-0.16	0.26	-0.69	**1.03**

Each cluster is associated with corresponding mean value scores, representing the standard deviation from mean, of the compiled indices. We use these values for the characterisation and interpretation of the respective clusters[3]. The spatial distribution of the compiled clusters is shown in Figure 5 for administrative units at NUTS-3 level in Germany. Additionally respective cluster representatives are labelled on the map.

Cluster 1 (n = 29) is characterised by *supply regions with needs for infrastructure*. It contains a below average score on the ICP index and an above average score on the HSP index. These regions are suitable to supply hydrogen with renewable energy production and import possibilities. However, location potentials are indicating regions with low connectivity and a need for infrastructure development. A representative region in this cluster is Ostprignitz-Ruppin, a region with rural character in northern Germany.

Cluster 2 (n = 52) contains regions described as *demand regions with needs for infrastructure.* The value scores on the HDP index are above average and the ICP index is expressed below average. These regions are suited to apply hydrogen with a predominance of the secondary sector and energy intensive industries. On the other hand, location potentials confirm these regions a low connectivity and a need for infrastructure development. Calw, a region with rural character in southern Germany, is the representative region in this cluster.

Cluster 3 (n = 33) represents *research and development regions with needs for infrastructure.* The cluster contains below average score values on all indices except for the RIP index. These regions are considered unsuited to supply or apply hydrogen in the near future and have a need for infrastructure development. However, the RIP index suggests locational potentials for research and development in these regions. The cluster is represented by Chemnitz, a region with an average urban character and a medium-sized university. The high degree of heterogeneity in this cluster suggests that there are deviations between the regions in this cluster.

Cluster 4 (n = 57) represents *supply regions with connectivity potential* and contains the highest average score values of the HSP index. All other indices contain score values in the average range. Regions in this cluster are highly suitable for hydrogen supply. Additionally, locational

[3] To facilitate characterising different clusters, the dominant values (average score value >1.0) are marked bold in the tables.

factors are indicating average connectivity potential to existing networks of energy infrastructure. A representative region in this cluster is Steinfurt, a region with rural character in north-west Germany.

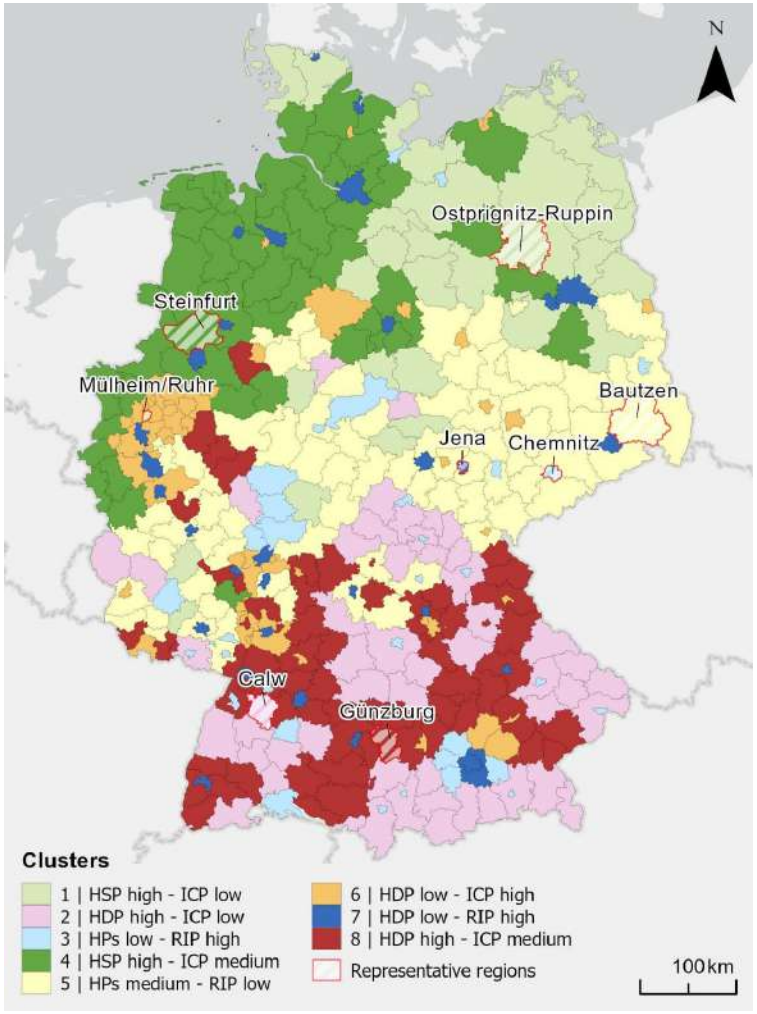

Fig 5. Spatial cluster distribution and related cluster representatives at NUTS3-level in Germany

Cluster 5 (n = 76) is labelled as *activatable supply and demand regions*. These regions contain a slightly above average score on the HSP and the HDP index indicating a general suitability for regional hydrogen potenials. Whereas, the average score on the RIP is below average, which points to a lack of regional locational potential in terms of expertise. Bautzen, a rural region in eastern Germany is considered as a representative region within this cluster. Heterogeneity is least pronounced in this cluster, suggesting a homogeneous composition within the cluster.

Cluster 6 (n= 57) focuses on regions described as *infrastructure hub regions*. It contains the highest average score value of the ICP and HSP and HDP values below average. These regions are unsuited to supply or apply hydrogen within their region, but contain a high regional potential to be connected to existing networks of energy infrastructure. A representative region for this cluster is Mülheim an der Ruhr, a region with urban character in western Germany.

Cluster 7 (n = 31) consists of *research and development centres*. It contains the highest average score values of the RIP index. While the ICP index scores above average both HSP and HDP index contain below average scores. Although these regions are considered unsuitable for hydrogen supplying and applying hydrogen, location factors indicate a high potential for research and development centres. A representative region in this cluster is Jena, a region with urban character and a large university in eastern Germany. There is a high degree of heterogeneity within this cluster.

Cluster 8 (n = 65) is composed by *demand regions with connectivity potential* and contains the highest average score values on the HDP index. This implies a high suitability for hydrogen demand due to the industrial character of the region. Additionally, these regions contain an above average score value on the ICP index, indicating a potential to connect these industrial regions to existing energy infrastructures. A representative region in this cluster is Günzburg, a region with an average urban character in southern Germany.

Our results indicate increased needs for action in cluster regions one, two, four, five and eight. In particular, clusters one and two show high potentials for hydrogen production and consumption while being poorly connected to the existing energy infrastructure. Due to the potentially large amount of green hydrogen produced or consumed in these regions, they should be given priority when connecting to infrastructure networks such as the hydrogen core pipeline network. Regions in clusters four and eight, with exceptionally high production and consumption capacities, should also focus on connecting to a centralised green hydrogen infrastructure network in the near future.

Concerning cluster five, there are average potentials for producing and consuming hydrogen with relatively low regional location potentials. Because these areas are classic remote and rural regions, the focus should be on decentralised strategies for hydrogen infrastructure planning. This means focusing on local on-site production, appropriate storage facilities and transportation via trailers. With the development of initial projects and model regions new expertise in the field of hydrogen infrastructure planning can be acquired.

In cluster three and seven there are high location potentials for research and development. Especially cluster seven contains potentials in becoming centres for hydrogen related research and development when granted appropriate support and funding. The conditions for connecting to existing infrastructure networks are also relatively high in cluster seven. Regions of cluster six are considered to be future infrastructure hubs that can be connected to central infrastructure networks in the process of expanding the hydrogen core pipeline network.

Discussion and Conclusion

Strategies for green hydrogen infrastructure planning need to consider spatial characteristics of demand and supply (Baufumé et al., 2013) as well as existing regional potentials (Mai et al.,

2023). Selecting suitable concepts in alignment with the respective regional context is essential when planning green hydrogen infrastructure (Luise et al., 2023). In accordance to the literature, we developed a holistic concept for the detailed assessment of relevant regional potentials for green hydrogen infrastructure planning.

Our results determined four main regional potentials of importance, which were derived from a selected dataset of 20 indicators: research and development, infrastructure connectivity, hydrogen demand and hydrogen supply. After assessing these potentials, we were able to characterise eight clusters. By applying these clusters to the regional dataset, we identified different type regions with context-specific suitabilities, opportunities and needs for action and planning throughout the case of Germany. This will provide the basis for developing strategic approaches to green hydrogen infrastructure planning. In conclusion, by combining technical with socio-economic location factors at a regional scale, we developed a holistic concept for assessing regional potentials for green hydrogen infrastructure planning.

Nevertheless, it should be noted that the conducted assessment is not a true reflection of the reality and that a detailed analysis of the specific region is still required. As the statistical analysis only shows indicator-based suitability, the selection process of variables has a strong influence on the results. In the course of the analysis, seemingly relevant factors were excluded from the data set due to statistical insignificance. In the case of the HSP index, photovoltaic production was excluded, which should be viewed critically in terms of its interpretative value. Also, large-scale storage facilities and existing hydrogen projects were not included in the analysis due to low data availability and missing or inconsistent values.

Furthermore, the reduction of information density during the PCA should be viewed critically. The data set used is not considered exhaustive for all relevant regional potentials for hydrogen infrastructure planning. Whether or not the predictive power of the indices holds true in reality needs to be verified in a detailed analysis. However, for an initial assessment and exploration of possible actions and strategies, this method can support and accelerate the planning process.

The application of the developed concept is generally possible, but highly dependent on the availability of data at regional level. Significant differences in factor loadings are highly likely not only depending on the spatial but also on the temporal relation of the used data (Jolliffe 2002).

Finally, a critical look at hydrogen as an energy carrier is in order. Although currently the use of hydrogen energy technologies seems promising, there is still great debate on it. (Dou et al., 2023). The true potential of this climate-friendly technology will be revealed in this decade as the hydrogen infrastructure develops. In addition to green hydrogen, other production pathways and technologies may need to be applied.

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