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Transformation of regional energy systems – An integrative approach to optimised site planning for regional hydrogen production

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Abstract

Hydrogen plays a central role in the energy transition by decarbonising energy-intensive industries and enabling the storage of energy from fluctuating renewable energy sources via electrolysis. As demand for hydrogen is expected to increase in the near future, there is a need to identify an increasing number of suitable sites for electrolysis. This development should be supported by innovative planning tools that align with sustainable energy policies and planning cultures. The suitability of sites for electrolysers is highly dependent on local conditions, including environmental resources, public supply infrastructure and local demand potential. In this paper, we conduct a GIS-based multi-criteria decision analysis to identify the most suitable locations for electrolysers, ensuring environmental compatibility, cost effectiveness and supply security. The criteria were weighted using the Analytic Hierarchy Process, based on an expert survey, and applied in a case study to identify sites with high suitability. A total of 3000 locations were identified as potentially suitable for electrolysis within the designated study area, meeting all relevant planning regulations and technical requirements. The results indicate that 1.93 % of the study area, corresponding to 82.12 km^2, is suitable for electrolysis. The most influential factors are connectivity to the planned hydrogen core network and the local hydrogen demand.

Keywords: Energy policy ▪ Energy planning ▪ Sustainable development ▪ Hydrogen infrastructure ▪ Multi-criteria decision analysis

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Transformation regionaler Energiesysteme – Ein integrativer Ansatz zur optimierten Standortplanung für die Wasserstofferzeugung

Zusammenfassung

Wasserstoff spielt eine zentrale Rolle bei der Energiewende, indem er die Dekarbonisierung energieintensiver Industrien ermöglicht und die Speicherung schwankender erneuerbarer Energien durch Elektrolyse unterstützt. Angesichts der prognostizierten Zunahme der Wasserstoffnachfrage müssen immer mehr geeignete Standorte für Elektrolyseure ermittelt werden. Diese Entwicklung sollte durch innovative Planungsinstrumente unterstützt werden, die mit einer nachhaltigen Energiepolitik und einer entsprechenden Planungskultur im Einklang stehen. Die Eignung für Elektrolyseure ist stark von lokalen Bedingungen abhängig, einschließlich verfügbarer Umweltressourcen, öffentlicher Versorgungsinfrastruktur und dem lokalen Nachfragepotenzial. In diesem Beitrag wird eine

GIS-basierte multikriterielle Entscheidungsanalyse durchgeführt, um die optimal geeigneten Standorte unter Berücksichtigung von Umweltverträglichkeit, Kosteneffizienz und Versorgungssicherheit zu gewährleisten. Die Kriterien wurden mithilfe des *Analytic Hierarchy Process* auf Basis einer Expertenbefragung gewichtet und in einer Fallstudie angewendet. Insgesamt wurden 3000 potenziell geeignete Standorte identifiziert, die die relevanten planerischen und technischen Anforderungen erfüllen. Die Ergebnisse zeigen, dass 1,93 % des Untersuchungsgebiets, entsprechend 82,12 km², für die Elektrolyse geeignet sind. Die entscheidenden Einflussfaktoren sind der Anschluss an das geplante Wasserstoffkernnetz und die lokale Wasserstoffnachfrage.

Schlüsselwörter: Energiepolitik ▪ Energieplanung ▪ Nachhaltige Entwicklung ▪ Wasserstoffinfrastruktur ▪ Multikriterielle Entscheidungsanalyse

1 Introduction

An increased use of hydrogen offers significant opportunities to advance both climate and energy policy objectives and therefore plays a central role in the energy transition. In particular, green hydrogen produced from renewable energy sources via electrolysis contributes to decarbonising the energy system, without producing direct emissions during utilisation. The combustion of hydrogen results in chemically pure water (Frey/Golze/Hirscher et al. 2023: 122). Beyond its environmental benefits, hydrogen can support the integration of volatile renewable energy sources by providing flexible storage options and can simultaneously enable sector coupling across electricity, heat and mobility (Kötter/Schneider/Sehnke et al. 2016; Kuhn/Kühne/Heilek 2017). As the sectoral coupling of power and gas networks gains attention, more potential applications in which hydrogen could generate value are being identified.

The need for decarbonisation has brought the transformation of energy systems and the development of appropriate policy frameworks into focus. Hydrogen is considered a key energy carrier for decarbonising and transforming energy-intensive industries, particularly in sectors that are difficult to electrify, such as steelmaking and chemical production (Hamacher 2017: 4). At the European level, the REPowerEU Plan sets an ambitious target of producing 10 Mt of renewable hydrogen domestically by 2030 (EC 2022), which requires member states to establish appropriate policies and measures. Germany is likewise committed to establishing a hydrogen economy based primarily on renewable energy sources (Moskalenko/Hanto/Bornemann et al. 2026). In terms of domestic industrial hydrogen demand, Neuwirth, Fleiter, Manz et al. (2022: 10) estimate a total potential of 14.5–16 Mt per year, with the chemical and steel industries alone accounting for more than 7 Mt annually.

However, the deployment of hydrogen in energy systems has so far been limited. Odenweller and Ueckerdt (2025) identify a substantial global implementation gap in the hydrogen economy. Based on data from the International Energy Agency (IEA), they show that only around 7 % of the green hydrogen production capacity initially announced had been realised by 2023 (Odenweller/Ueckerdt 2025: 111). A similar gap can be observed in Germany. According to the National Hydrogen Strategy, 10 GW of electrolyser capacity is planned for domestic use by 2030 (BMWK 2023: 6). However, Annex 2 of the 2025/26 Scenario Framework for Gas, published by the Federal Network Agency of Germany (*Bundesnetzagentur*), indicates that only six projects with a total capacity of 0.9 GW are currently in operation.[1] In this context, Klaas and Schmidt (2026) find that project development in Germany is significantly delayed. They estimate that capacity could reach a maximum of only 8.7 GW by 2030, assuming all announced projects are implemented (Klaas/Schmidt 2026: 3).

This is primarily because the economic feasibility of hydrogen remains uncertain, particularly in comparison to natural gas, resulting in limited competitiveness, low industrial uptake and a stagnating rollout of hydrogen infrastructures (Odenweller/Ueckerdt 2025). High production and delivery costs, uncertain demand and insufficient infrastructure continue to constrain industrial uptake. Consequently, the expansion of hydrogen infrastructure, alongside reductions in hydrogen production costs, is considered essential for a successful market ramp-up (Rasul/Hazrat/Sattar et al. 2022).

At the same time, the optimal configuration of hydrogen production remains subject to debate. While some studies identify economic advantages for decentralised electrolysis systems connected directly to the electricity grid (Lundblad/Taljegard/Johnsson 2023), others favour large-scale electrolysers located in proximity to renewable energy sources (Amrani/Merrouni/Touili et al. 2024). The optimal location and cost-efficiency of different hydrogen production systems are influenced by spatial conditions. For example, locating electrolysers close to renewable energy sources can reduce production costs by facilitating access to low-cost renewable electricity, but this may increase the distance to centres of demand and, consequently, transportation costs (Lundblad/Taljegard/Johnsson 2023).

[1] http://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/NEP/DL_Szenariorahmen/Anl2_Kons_Elektrolyseure.xlsx (03.11.2026).

Another issue arises from the mismatch between the geographical distribution of renewable energy sources and the location of centres of hydrogen demand (Çelikdemir/Özdemir 2026: 2). This is also evident in Germany, where renewable energy capacities are distributed unevenly across the country. While the installed capacity for wind energy is particularly high in northern Germany, significant potential demand for hydrogen is concentrated in industrial regions to the west and south, including North Rhine-Westphalia and the chemical industry clusters around Leuna and Ludwigshafen (Moskalenko/Hanto/Bornemann et al. 2026).

Therefore, planning for hydrogen infrastructure needs to account for this uneven spatial distribution (Neuwirth/Fleiter/Manz et al. 2022: 13). Identifying optimal locations for hydrogen production consequently requires consideration of local conditions, particularly supply infrastructure and demand centres (Lundblad/Taljegard/Johnsson 2023). However, knowledge of the spatial distribution of local demand remains limited, especially for the medium- and long-term future (Neuwirth/Fleiter/Manz et al. 2022). A high spatial resolution of demand structures and supply infrastructure, combined with a comprehensive energy system perspective, is therefore essential for sustainable infrastructure planning (Neuwirth/Fleiter/Manz et al. 2022: 13).

In light of these considerations, the present study aims to provide a more precise and differentiated pre-assessment approach for the regional site planning of electrolysers. By integrating all principles of the energy policy triangle, namely environmental compatibility, supply security and affordability in line with the German Energy Industry Act (Section 1)[2], the investigation provides a holistic planning approach. This supports regional sustainable development by incorporating socio-economic and environmental aspects while accelerating the planning process.

We developed a transferable geospatial multi-criteria model that relies almost exclusively on open-access data to enable transparency and transferability in the decision-making process. A key feature of our approach is that the model integrates demand and supply structures on a local level. This ensures that selected locations support supply security and are more likely to be both environmentally sound and economically viable. Another novel aspect of the methodology is that it considers all legally and technically feasible sites in the analysis. This provides results comparable to the optimised land-use potentials gained in the LANUV (2023) suitability analysis for renewable energy sources.

In the following section, the current state of research into site planning for electrolysers is outlined (Section 2) before the developed methodology is explained in Section 3. Section 4 presents the results of the method applied within a study area as part of a case study. Following a reflective discussion of the findings in Section 5, the paper concludes with a summary and an outlook on further research needs (Section 6).

2 State of research

2.1 Regulatory framework

The planning of electrolysers in Germany is subject to a wide range of legal, technical, infrastructural and environmental requirements. However, the regulatory framework is the primary determining factor. In 2024, these frameworks were revised and further specified at national level (LAI 2025). The Federal Immission Control Act (BImSchG)[3] sets out the conditions for the construction and operation of electrolysers. The applicable permitting procedure depends on the size of the planned facility, which is defined either by its nominal electrical capacity or by its hydrogen production capacity.

Electrolysis plants with a nominal electrical capacity of less than 5 MW are exempt from permit requirements under emission control law. Electrolysers with a nominal electrical capacity of 5 MW or more require approval under the simplified permitting procedure pursuant to Section 19 BImSchG, which does not involve public participation. Should the production capacity reach 50 tonnes or more of hydrogen per day, a formal permitting procedure is required, which includes public participation (Section 10 BImSchG).

All electrolysers and the entire electrolysis facility must comply with building regulations and, where required, obtain the necessary construction permits (Schulz/Glandien/Hüttenrauch et al. 2025: 22). As the permissibility of a project under planning law depends on its location (LAI 2025: 14), compliance with the applicable planning regulations is a crucial factor in site selection.

The relevant legal provisions can be found in the Federal Building Code (Sections 29 ff. BauGB)[4] and the Federal

[2] Energiewirtschaftsgesetz (EnWG) of 7 July 2005 (BGBl. I S. 1970, 3621), as last amended by Article 8(6) of the Act of 23 July 2026 (BGBl. 2026 I Nr. 226).

[3] Bundes-Immissionsschutzgesetz (BImSchG) in the version published on 17 May 2013 (BGBl. I S. 1274; 2021 I S. 123), last amended by Article 3 of the Act of 18 June 2026 (BGBl. 2026 I Nr. 183).

[4] Baugesetzbuch (BauGB) in the version published on 3 November 2017 (BGBl. I S. 3634), last amended by Article 8(2) of the Act of 23 July 2026 (BGBl. 2026 I Nr. 226).

Land Use Ordinance (BauNVO).[5] These provisions determine that the construction of an electrolyser may be permitted in both planned and unplanned built-up areas (inner built-up zones), assuming compliance with zoning and development regulations (Sections 2-9 BauNVO). Moreover, the installation of electrolysers is generally permitted in designated industrial zones (Section 9 BauNVO), with certain restrictions also applicable in commercial zones as specified in Section 8 BauNVO.

In the event of the planning of an electrolysis plant in an undeveloped (non-built-up) area, approval may be granted if the project qualifies as a privileged development. However, such areas are generally intended to remain largely free of development in order to prevent urban sprawl. Compliance with the relevant requirements must be assessed on a case-by-case basis (Schulz/Glandien/Hüttenrauch et al. 2025: 24).

In this study, we consider electrolysers with a capacity of up to 50 MW, following a decentralised production approach at the regional scale. Such production units are of great importance in the short to medium term, due to their lower investment requirements and improved ability to match decentralised production and demand profiles (DVGW 2025).

2.2 Requirements for hydrogen production

The topicality of the field has resulted in a number of studies on hydrogen infrastructures, which predominantly concentrate on the technical feasibility and economic viability of technologies along the hydrogen supply chain (Budny/Madlener/Hilgers 2015; Kötter/Schneider/Sehnke et al. 2016). In light of this, Rasul, Hazrat, Sattar et al. (2022) address the future challenges of hydrogen production, storage and distribution, concluding that costs are expected to decrease and that comprehensive infrastructure, from production to delivery, will be necessary to meet future demand.

Another field of research focuses on the comparison of different hydrogen production methods and pathways, incorporating sustainability aspects into the analytical framework (Acar/Beskese/Temur 2018; Schnülle/Kenkel/Wassermann 2020; Manafzadeh/Habibiyan/Hosseinpour et al. 2024). In this context, Schnülle, Kenkel and Wassermann (2020) consider investment requirements and efficiency metrics in their analysis, and also water and land requirements for electrolysers.

In recent years, many studies on location analysis and siting optimisation of hydrogen production facilities have been published in the applied sciences literature. However, this research varies widely in terms of the production requirements considered, the spatial scale of the study areas and the methodologies applied. With the exception of a few studies that adopt high-resolution approaches (Soha/Hartmann 2022), most analyses are conducted at broader, supra-regional scales.

Several studies focus on the co-location of hydrogen production with renewable energy sources, particularly solar and wind power (Haumaier/Hauser/Hobbie et al. 2020; Amrani/Merrouni/Touili et al. 2024; Boubé/Bhandari/Saley et al. 2025). These studies often limit site selection primarily to the vicinity of renewable energy sources and related production criteria. Consequently, other potentially suitable areas and relevant criteria remain underexplored, representing a key shortcoming in the existing literature. Furthermore, environmental and infrastructural criteria are generally well represented in spatial suitability analyses, alongside a focus on energy supply from renewable energy sources (Wang/Hsueh/Lin 2019; Soha/Hartmann 2022).

However, analyses that explicitly incorporate local energy demand structures remain limited. Although Çelikdemir and Özdemir (2026) consider local demand potential as a composite index by accounting for proximity to industrial zones, their results remain at a regional level. While this enables general comparisons, it does not sufficiently support preliminary assessment or concrete site planning at the local level. Regional infrastructure planning frameworks, such as the Gas Distribution Transformation Plan (DVGW 2025), support planning of electrolysers by drawing on demand capacities identified in the Integrated Gas and Hydrogen Network Development Planning (KO.NEP 2026). However, these planning frameworks aggregate several industries and processes and focus mainly on reported hydrogen potentials at district level (KO.NEP 2026: 144). Other studies estimating future industrial hydrogen demand often focus solely on hydrogen as a feedstock (Neuwirth/Fleiter/Manz et al. 2022: 2).

Consequently, detailed modelling and mapping of potential industrial hydrogen demand, encompassing both energy-related and feedstock uses, at the site-specific level, is required for optimised hydrogen production site planning. In this study, we aim to address this research gap by adopting a site-specific approach that explicitly accounts for local conditions and integrates comprehensive criteria in line with the energy policy triangle.

As the literature shows, identifying suitable locations for electrolysers is a complex decision-making problem involving multiple criteria that may sometimes conflict with one another and vary depending on the objective and the

[5] Baunutzungsverordnung (BauNVO) in the version published on 21 November 2017 (BGBl. I S. 3786), last amended by 2 of the Act of 3 July 2023.

spatial scale. Multi-criteria decision-analysis methods provide a structured framework for systematically assessing, analysing and addressing such challenges.

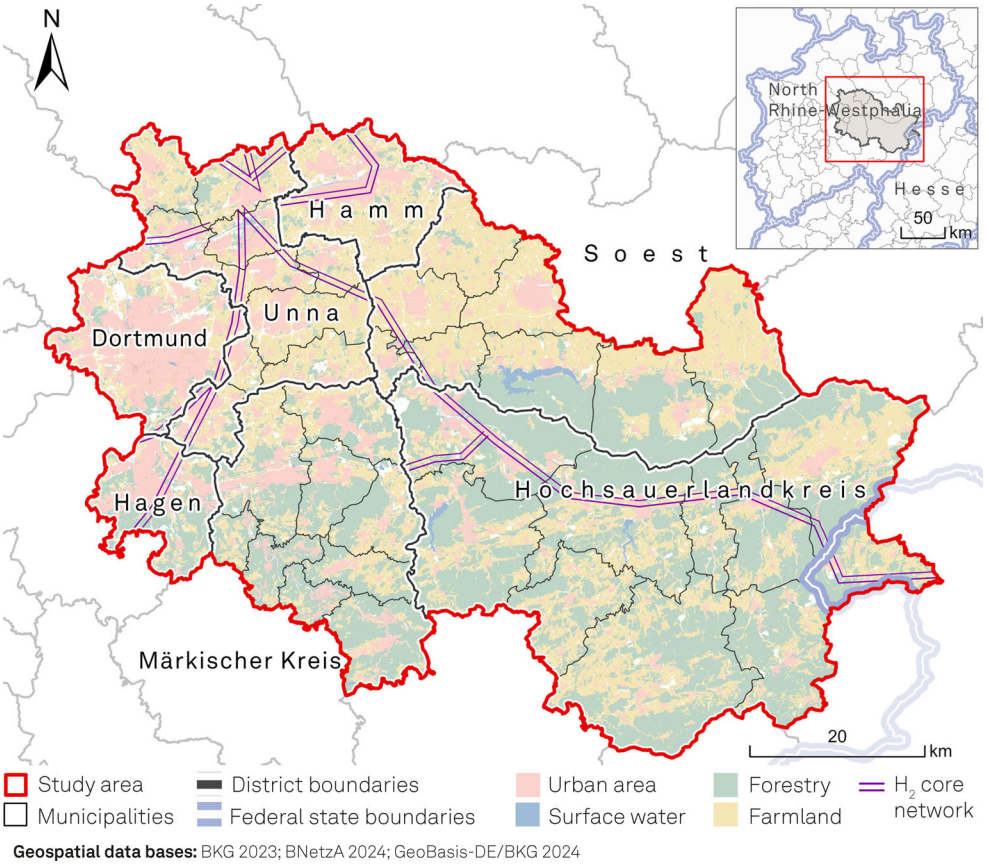
2.3 Multi-criteria decision analysis in site suitability analysis

Decisions in the energy and hydrogen infrastructure sectors are characterised by relatively large investment requirements and lead to the construction of infrastructure that is used for several decades (IEA 2019). Due to this longevity and the impact on a large number of stakeholders with conflicting interests, it is necessary to consider several different kinds of criteria, such as economic, ecological and social factors (Pokehar/Ramachandran 2004).

Numerous multi-criteria decision-analysis methods have been developed to help with decision-making in such situations. Two main categories of methods can be distinguished: MADM (Multi-Attribute Decision-Making) for discrete decision spaces and MODM (Multi-Objective Decision-Making) for continuous ones (Mardani/Jusoh/Zavadskas et al. 2015). As choosing a site for an electrolyser usually means dealing with a number of discrete locations, multi-attribute decision-making methods are the group of choice for this study.

Many multi-attribute decision-making methods require a weighting component to reflect the relative value of criteria in the decision-making process. Weighting methods can be divided into subjective and objective approaches (Keršulienė/Zavadskas/Turskis 2010; Mukhametzyanov 2021). While objective approaches derive weights from data or statistics, the strategic importance of energy-sector decisions often favours subjective methods for weightings based on expert or stakeholder input (Kahraman/Kaya/Cebi 2009). Established subjective methods include the AHP (Analytic Hierarchy Process) (Saaty 1987), the Best-Worst (Rezaei 2015), Delphi (Turoff/Linstone 1975) and SMART (Simple Multi-Attribute Rating Technique) (Edwards 1977) methods, as well as SWARA, the Stepwise Weight Assessment Ratio Analysis (Keršulienė/Zavadskas/Turskis 2010).

Of these, the analytic hierarchy process is frequently chosen in hydrogen and energy-related decision processes (Pokehar/Ramachandran 2004; Mardani/Jusoh/Zavadskas et al. 2015; Albadwi/Elzein/Bashir et al. 2025; Coquette/Lauven/Faulstich 2026). This approach uses pairwise expert assessments to determine criterion weights, thereby



Geospatial data bases: BKG 2023; BNetzA 2024; GeoBasis-DE/BKG 2024

Figure 1 Land coverage within the designated study area

Table 1 Data sources

Dataset	Source	Pre-processing steps
Administrative Areas 1:250,000	BKG 2023	Selection of municipalities within the study area
Digital Basic Landscape Model (Basis-DLM) of North Rhine-Westphalia and Hesse	Geobasis-DE/BKG 2024	Feature selection of criteria; creation of point features for renewable energy sources in Hesse; merging of datasets
Energy use by local units in manufacturing	Destatis 2025	Data filtering by sector-specific natural gas demand
Hydrogen core network	Bundesnetza-gentur 2024	Georeferencing and line mapping to create dataset
Industrial companies	North Data Pre-mium 2025	Export companies in selected branches; dataset cleaning
Renewable energy sources and electricity-generating plants in North Rhine-Westphalia	LANUV NRW 2025	Creation of point features; merging of datasets
Official Building Polygons of North Rhine-Westphalia	Geobasis-DE/BKG 2023	Erasing existing buildings from industrial and commercial areas
Official Building Polygons of Hesse	Geobasis-DE/BKG 2025	Erasing existing buildings from industrial and commercial areas
Persons employed and turnover of local units in man-ufacturing	Destatis 2026	Data filtering for relevant branches

Note: All geospatial datasets were extracted using a 10 km buffer zone surrounding the study area.

incorporating expert knowledge into the decision-making process (Saaty 1990). As it was possible to conduct an expert survey in this research project, the AHP method was chosen for the multi-criteria assessment of suitable electrolyser sites.

3 Optimised site suitability analysis

3.1 Study area

The study area, located in eastern North Rhine-Westphalia in Germany, comprises of 40 towns and municipalities. Covering an area of approximately 4,250 km^2, the region extends 60 km from north to south and 100 km from east to west. It encompasses five administrative districts (Dortmund, Hagen, Hamm, Hochsauerlandkreis and Unna), with additional coverage extending to municipalities of the districts of Soest and Märkischer Kreis (see Figure 1). One district from Hesse was included to assess the transferability of the approach to other federal states, particularly with regard to potential differences in data availability and consistency.

Two major factors influenced the selection of the study area. First, the planned hydrogen core network, as defined by the German gas transmission system operators and approved by the Federal Network Agency (Bundesnetzagentur 2024), extends into this area, thereby establishing its significance for the future development of a hydrogen economy. Consequently, municipalities in close proximity to this planned infrastructure were selected, regardless of administrative district boundaries, as illustrated in Figure 1. Second, the geographical delineation of the study area corresponds to the spatial scope of the HydroNet[6] project, which focuses on Arnsberg and the surrounding districts. The region encompasses a variety of urban densities, as well as a diverse distribution of transport infrastructure and public utility networks. These conditions are likely to present both opportunities and challenges for the proposed methodology.

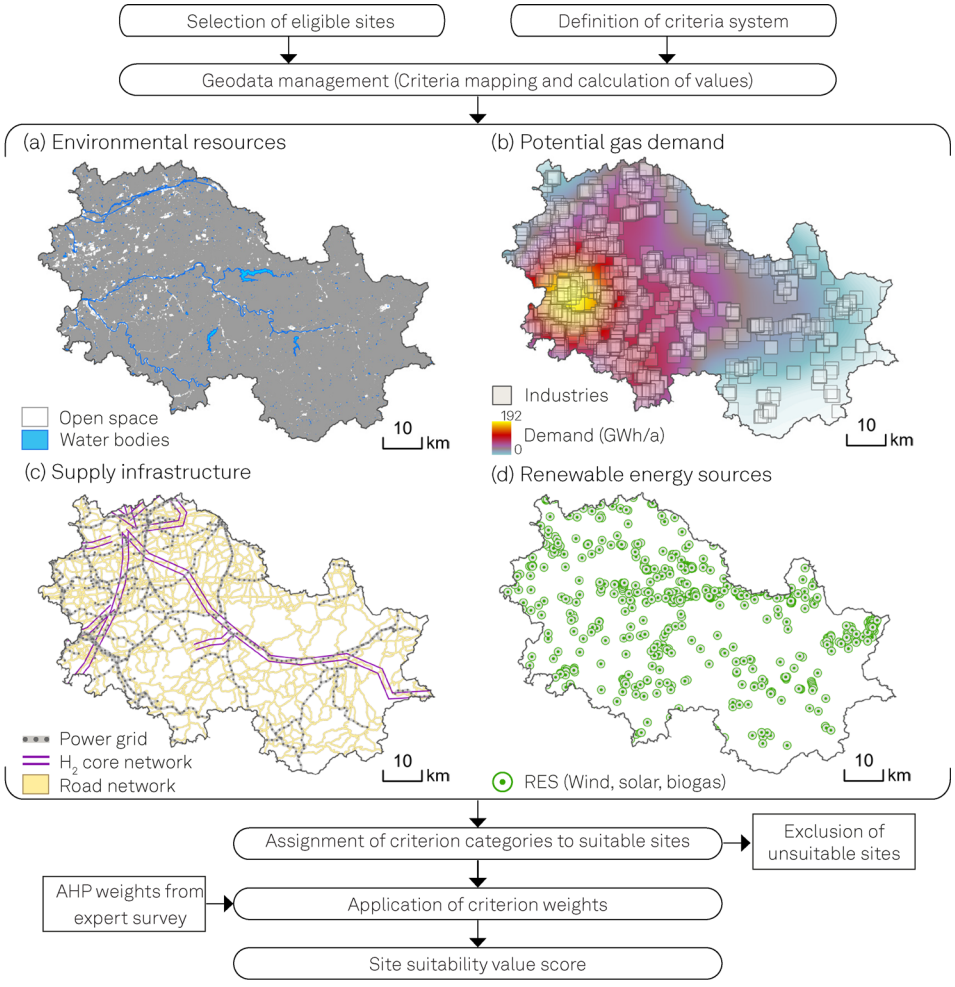
3.2 Methodological framework and data

The methodological framework for the suitability analysis is primarily based on open-access data to ensure its transferability. Table 1 displays a comprehensive overview of the geospatial and statistical datasets used in this study, their respective data sources and key preprocessing steps.

The methodological approach is structured into several steps and illustrated in Figure 2. In contrast to comparable siting approaches which typically begin with the exclusion of unsuitable areas (Höfer/Sunak/Siddique et al. 2016), this study adopts a selection-based approach as a first step. This methodological choice reflects the central objective of resource optimisation in accordance with the principles of positive planning. It is assumed that all sites compliant with planning regulations are eligible and should be considered further, rather than excluding numerous options at an early stage.

The subsequent steps of the framework follow a structure similar to that proposed by Soha and Hartmann (2022), including the definition, spatial mapping and categorisation of the selected criteria, and the application of the analytic hierarchy process for criteria weighting. The geodata manage-

[6] https://www.hydronet.energy/de.html (08.10.2026).



Geospatial data bases: BKG 2023; (a, c) GeoBasis-DE/BKG 2024; (d) LANUV, NRW 2025
Data bases: (b) North data Premium 2025; German Federal Statistical Office (Destatis) 2025, 2026; (c) BNetzA 2024

Figure 2 Workflow diagram of the proposed methodology and datasets used

ment and the derivation of a composite suitability score for each potential site within the study area are carried out in a geographic information system (GIS) environment using ArcGIS Pro 3.6.2 by ESRI. Finally, a sensitivity analysis is conducted to assess the robustness of the results.

3.3 Eligible sites and suitability criteria

The initial phase of the analysis focuses on identifying suitable sites based on technical requirements and planning regulations. According to German planning regulations, electrolysers with a capacity of up to 50 MW are preferably located in areas designated as industrial or commercial land within inner built-up zones. The site selection procedure is implemented in GIS, by utilising the attributes and spatial locations from the Basis-DLM dataset in North Rhine-Westphalia and Hesse. The resulting sites are considered formally and legally eligible for the development of electrolysers within the study area.

In the next step of the analysis, the key criteria for identifying optimal sites for electrolysers are defined. The majority of these criteria, including environmental factors such as the availability of resources (e.g. open space and water) and access to supply infrastructure (e.g. the road network and power grid), are commonly used in site suitability analyses. Furthermore, natural gas demand, access to the planned hydrogen core network and the availability of renewable energy sources are incorporated in accordance with the objective of ensuring economic efficiency and security of supply.

Subsequently, each criterion is assigned a value score across defined categories ranging from 1–10, where higher scores indicate more favourable conditions. Table 2 presents the value scores for the respective categories of each criterion, in accordance with Soha and Hartmann (2022) for the

Table 2 Categorisation and scoring of the considered criteria

Value score	Open space availability (m^2)	Potential demand (GWh/a)	Distance from (m)				
			Water bodies	Road network	Core network	Power grid	Renewable energy sources
0	< 300						
1	300–1,000	0–10	> 4,500	> 925	> 4,500	> 4,500	> 4,000
2	1,000–2,000	10–20	4,000–4,500	825–925	4,000–4,500	4,000–4,500	3,500–4,000
3	2,000–4,000	20–40	3,500–4,000	725–825	3,500–4,000	3,500–4,000	3,000–3,500
4	4,000–6,000	40–60	3,000–3,500	625–725	3,000–3,500	3,000–3,500	2,500–3,000
5	6,000–8,000	60–80	2,500–3,000	525–625	2,500–3,000	2,500–3,000	2,000–2,500
6	8,000–10,000	80–100	2,000–2,500	425–525	2,000–2,500	2,000–2,500	1,500–2,000
7	10,000–20,000	100–150	1,500–2,000	325–425	1,500–2,000	1,500–2,000	1,000–1,500
8	20,000–40,000	150–200	1,000–1,500	255–325	1,000–1,500	1,000–1,500	5,00–1,000
9	40,000–80,000	200–250	500–1,000	125–255	500–1,000	500–1,000	250–500
10	> 80,000	> 250	0–500	0–125	0–500	0–500	0–250

Note: Sites with less than 300 m^2 open space available are excluded from further calculation.

Table 3 Industrial companies with high natural gas consumption in the study area

NACE code	Industry name	N	Mean revenue (€)	Sum gas demand (GWh/a)
C11	Manufacture of beverages	16	3,584,692	8.063
C16.2.1	Manufacture of veneer sheets and wood-based panels	3	94,681,000	10.23
C16.2.9	Manufacture of other products of wood	3	13,523,333	1.46
C17	Manufacture of pulp, paper and paperboard	19	19,043,055	187.45
C19.2	Manufacture of refined petroleum products	2	47,047,539	7.49
C20	Manufacture of chemicals and chemical products	14	25,623,527	187.72
C22	Manufacture of rubber and plastic products	114	8,631,656	64.71
C23	Manufacture of other non-metallic mineral products	57	6,323,469	167.37
C24	Manufacture of basic metals	166	40,592,653	1521.03
C25	Manufacture of fabricated metal products, except machinery and equipment	852	11,509,591	561.78
C27.4	Manufacture of electric lighting equipment	41	13,467,472	8.99
C28	Manufacture of machinery and equipment n.e.c.*	401	14,579,895	114.38
C29	Manufacture of motor vehicles, trailers and semi-trailers	13	12,195,503	3.57

*n.e.c. = not elsewhere classified

distance parameters. Regarding implementation in GIS, the assigned scores are based on either the magnitude of a criterion (e.g. open space availability and potential demand) or the Euclidean distance of a criterion from a given eligible location. The Reclassify tool is then used to assign a value score to each criterion. The following sections describe the attributes of the selected criteria and their associated scorings.

The availability of open space for electrolysers was determined by calculating the areas of eligible polygon geometries in GIS. Prior to this, existing buildings were excluded using the building footprint dataset, ensuring that only unobstructed land was considered. Polygons smaller than the minimum required site area of 300 m^2 for 5 MW electrolysis technology (Schnülle/Kenkel/Wassermann 2020) were excluded from the analysis. The value score of each area increases with the size of available open space, following a classification scheme based on the Jenks natural breaks method (Chen/Yang/Li et al. 2013).

The site-specific demand potential for hydrogen represents a crucial factor for economic feasibility. Accordingly, industrial companies with high natural gas utilisation potential, due to processes that are difficult to electrify, are included in the analysis. Industrial gas demand is estimated using a modelling approach that analyses natural gas demand per company (both energy-related and other feedstock

uses) based on sector-specific natural gas consumption and revenue data from the German Federal Statistical Office.[7]

A total of 1,701 companies in the study area is selected based on industry branches from the Statistical Classification of Economic Activities in the European Community (NACE) and identified along with their revenue figures using North Data Premium. Refer to Table 3 for a summary of the identified companies according to their NACE codes. Finally, the estimated natural gas consumption is then aggregated within 60-minute travel-time catchment areas generated through network analysis in GIS and classified using the Jenks natural breaks method.

The water supply required for hydrogen production via electrolysis and for cooling purposes can be provided by the public water utility network. As the selected sites are predominantly located within built-up areas, access to this infrastructure is generally assumed to be available and does not constitute a critical constraint. Consequently, no exclusion zones were defined around these infrastructure features. Instead, water availability is assessed based on access to surface water bodies, accounting for seasonal variability and potential water scarcity. The value score increases with decreasing distance to surface water bodies, in intervals of 500 metres up to a maximum distance of 4,500 metres.

Similarly, the supply infrastructure criteria, namely the existing road network and power grid, are categorised. The road network is a key prerequisite for the facility's construction and is essential for ensuring the accessibility of trailers for hydrogen distribution. Only major roads (primary, secondary and tertiary) are considered in the representation of the road network (Guleria/Bajaj 2020). In this context, the assessment includes access to power lines, which reduces investment requirements and operational costs for electrolysers; an overly restrictive focus on high-voltage substations is avoided as this could unnecessarily exclude large potential areas (Brümmer/Heim/Moser et al. 2022).

Access to the planned hydrogen core network enhances the economic scalability of electrolyser technologies. In order to assess this, the designated and approved pipeline corridors for the target year of 2032 were georeferenced and incorporated into the analysis using GIS. The categorisation of this criterion follows the same approach as applied to the road and power grid infrastructure.

Finally, integrating renewable energy sources enhances the technical and economic potential of electrolysers and supports energy system flexibility by enabling the conversion and storage of fluctuating renewable energy sources (Schneider/Kötter 2015; Haumaier/Hauser/Hobbie et al. 2020) thereby contributing to supply security. In this analysis, the access of eligible sites to existing wind turbines, ground-mounted photovoltaic systems and biogas plants is considered. No renewable energy sources were identified in the municipality in Hesse. The value score increases with decreasing distance to renewable energy sources, at intervals of 250–500 metres up to a maximum distance of 4,500 metres.

To address potential multicollinearity, Variance Inflation Factor (VIF) and tolerance (1/VIF) tests were conducted before integrating the categorised criteria into the weighting process. VIF values greater than 10 and tolerance values below 0.1 indicate problematic multicollinearity (Zighmi/Zahri/Faqeih et al. 2025). The analysis yielded VIF values ranging from 1.01–1.07 and corresponding tolerance values above 0.85, indicating negligible multicollinearity. Therefore, all criteria were included in the AHP weighting, as each one provides distinct information for the suitability analysis.

3.4 AHP weighting

Following the methodology described, a structured approach was implemented to determine the weights of the criteria listed above using the analytic hierarchy process according to Saaty (1990). It should be noted that comparing or adopting criteria weights from other studies is challenging, as regional conditions and the methods used to derive the priority vectors in the analytic hierarchy process often differ. We therefore conducted a survey among local energy experts, who were asked to complete a questionnaire on the seven criteria. The 16 participants were experts selected from hydrogen-related fields, including energy plant and network operators, research institutions and public administration. The criteria were evaluated using pairwise comparison to construct the AHP matrix applied in this study (see Table 4).

Although participants occasionally held differing views on the relative importance of each criterion, the Consistency Ratio (CR) threshold of 0.1 was not exceeded. Therefore, the individual priorities of the experts were aggregated using the analytical hierarchy process to derive the criteria weights, as outlined in Table 5. Accordingly, the experts identified access to the power grid (21.9 %), hydrogen demand potential (21.4 %) and access to renewable energy sources (21.4 %) as the most important criteria.

[7] https://www-genesis.destatis.de/datenbank/online/statistic/43531/table/43531-0001 (08.10.2026); https://www-genesis.destatis.de/datenbank/online/statistic/42271/table/42271-0002/ (08.10.2026).

Table 4 The applied AHP matrix

	Open space availability	Potential demand	Access to water bodies	Access to road network	Access to core network	Access to power grid	Access to renewable energy sources
Open space availability	1	1/4	1	2	1/3	1/4	1/4
Potential demand		1	4	5	1	1	1
Access to water bodies			1	2	1/3	1/4	1/4
Access to road network				1	1/5	1/6	1/5
Access to core network					1	1	1
Access to power grid						1	1
Access to renewable energy sources							1

Consistency Ratio = 0.00442; Consistency Index = 0.00584; λmax = 7.03504

Table 5 Criteria weights derived from the analytical hierarchy process

Criteria	Criteria weights
Access to power grid	0.219
Potential demand	0.214
Access to renewable energy sources	0.214
Access to core network	0.197
Access to water bodies	0.060
Open space availability	0.060
Access to road network	0.037

3.5 Suitable sites and sensitivity analysis

To determine the suitability of sites within the study area, the Field Calculator tool in GIS was utilised to compute the overall value score for each site. This was achieved by multiplying the initial value scores of each criterion by its corresponding AHP-derived weights. The final suitability map was generated by summing the weighted criteria. This allowed each site to be assigned a suitability value score ranging from 1–10. Finally, the results were grouped into three classes: high suitability (8-10), medium suitability (5-7) and low suitability (1-4). To better observe spatial patterns, value scores were aggregated at the municipal level to create a suitability index. For selected municipalities, criterion characteristics were summarised in suitability profiles to analyse underlying regional patterns.

A sensitivity analysis was conducted to assess the impact of the AHP-derived criteria weights on site suitability scores. To evaluate weight sensitivity in MCDA methods, an equal-weight approach was employed to facilitate a straightforward comparison (Höfer/Sunak/Siddique et al. 2016), with each of the seven criteria assigned an equal weight of 14.3 %. A statistical comparison was conducted to quantify the extent of changes across the suitability value scores relative to the original results. Furthermore, a sensitivity map was generated to illustrate the absolute changes in the suitability value score for each site, and a sample-based visualisation was created to validate locations with high suitability.

4 Results

4.1 Electrolyser site suitability analysis

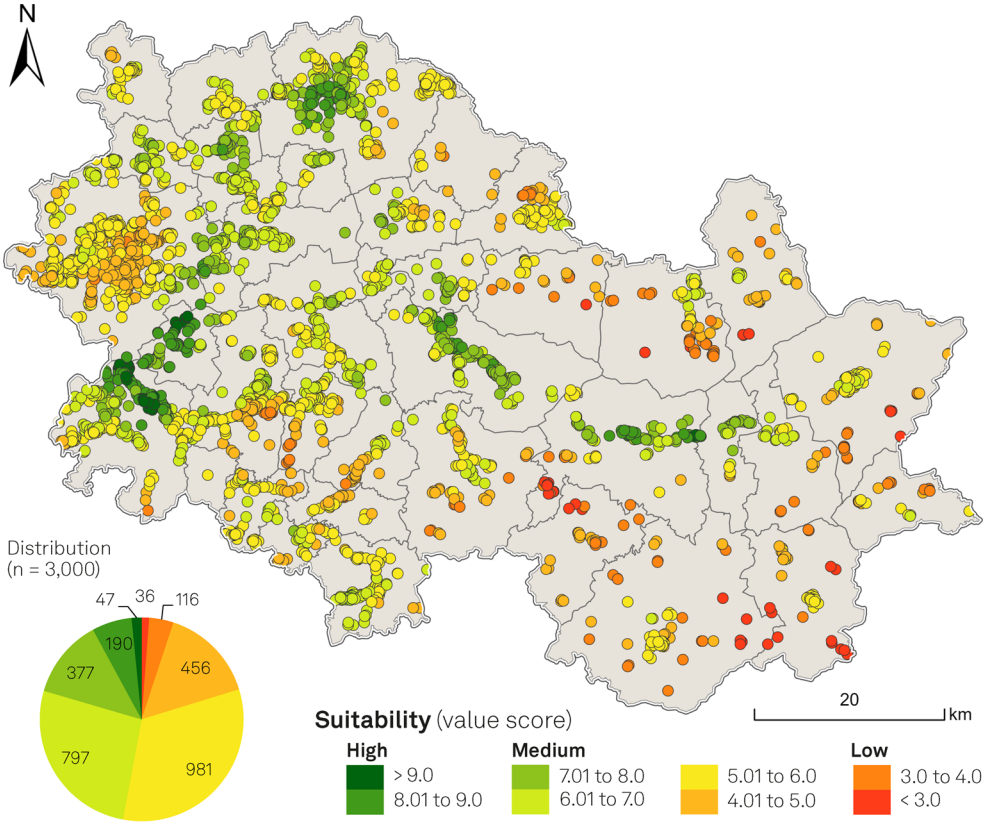
A total of 3,000 sites were identified as potentially suitable for electrolysis within the designated study area, meeting the relevant planning regulations and technical requirements. The total area represented by these sites is 82.12 km², corresponding to 1.93 % of the total study area. Table 6 provides an overview of the key descriptive statistics of the calculated attribute values and unweighted categorised scores for all suitable locations. It should be noted that some criterion attributes show relatively high standard deviations, particularly open space availability and access to the core network, indicating considerable spatial heterogeneity. Furthermore, the water-body criterion has a minimum score of 4, indicating that all potential sites are within 3.5 km of a water body.

The results of the summarised and weighted criteria are illustrated in the suitability map shown in Figure 3. Locations with a high suitability value score (n = 237) account for approximately 8 % of the potential sites in the study area, while locations with a low suitability value score (n = 152) represent about 5 % of the sites. Note that no location received the maximum score of 10 or the minimum of 1. All remaining locations received a medium suitability value score.

Table 6 Descriptive statistics

	Criteria	N	Min	Max	Mean	Standard Deviation
Attributes	Open space availability (in m^2)	3,000	307.1	617,253.1	27,372.6	37,763.7
	Potential demand (in GWh/a)	3,000	0.0	481.4	79.2	83.2
	Access to water bodies (in m)	3,000	0.0	3,417.0	730.8	547.5
	Access to road network (in m)	3,000	2.0	2,402.4	220.9	232.6
	Access to core network (in m)	3,000	8.1	2,6679.9	6,554.6	5,487.7
	Access to power grid (in m)	3,000	0.3	8,932.4	1,235.1	1,320.2
	Access to renewable energy sources (in m)	3,000	4.4	6,643.2	1,727.0	1,087.9
Categories	Open space availability	3,000	1	10	6.5	2.4
	Potential demand	3,000	1	10	4.6	2.6
	Access to water bodies	3,000	4	10	9.0	1.1
	Access to road network	3,000	1	10	8.5	2.1
	Access to core network	3,000	1	10	3.7	3.4
	Access to power grid	3,000	1	10	8.1	2.4
	Access to renewable energy sources	3,000	1	10	6.1	2.2

Note: Potential demand is aggregated within 60-minute travel time from the respective location.



Geospatial data bases: BKG 2023; GeoBasis-DE/BKG 2024

Figure 3 Suitability map for electrolyser sites in the study area

According to the suitability map, the number of suitable sites increases from east to west across the study area. The majority of sites characterised by high suitability value scores are situated in the central and southwestern regions of the study area. Conversely, the lowest suitability value scores are generally observed in the peripheries of the study area, particularly in the southeast, as well as along the northern outer boundaries.

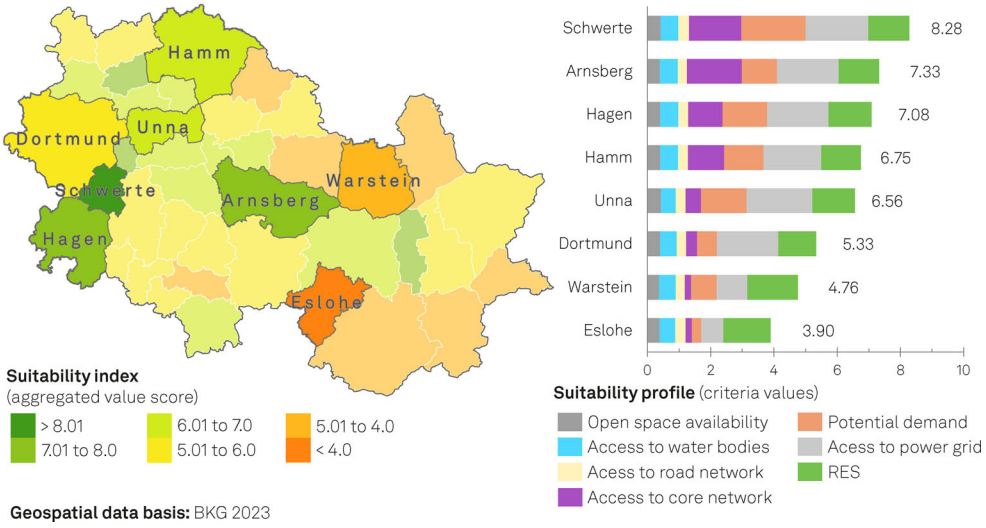


Figure 4 Suitability index in the study area and suitability profiles in selected municipalities

Table 7 Descriptive statistics of total difference between suitability and sensitivity analysis

	N	Min	Max	Mean	Standard Deviation
Suitability analysis with AHP weights	3,000	1.58	9.73	6.01	1.28
Sensitivity analysis with equal weights	3,000	2.71	9.43	6.64	1.03
Difference (%)	–	1.14 (72.0 %)	−0.30 (−3.1 %)	0.62 (10.4 %)	−0.25 (−19.7 %)

Note: The difference values refer to changes relative to the AHP-based weighting.

Aggregating value scores at the municipal level into an average suitability index (see Figure 4) allows us to identify five municipalities with high suitability for hydrogen production, regardless of urban density or size. The results indicate a tendency towards higher suitability in suburban municipalities such as Schwerte, Arnsberg and Hagen. These municipalities are located along the periphery of rural areas, offering convenient access to environmental resources while simultaneously exhibiting significant demand potential through proximity to urban centres. As reflected in their generated suitability profiles, key advantages include access to utility networks, renewable energy sources and potential hydrogen demand.

In contrast, the lowest indices of suitability are generally observed in rural municipalities in the southeastern and northern parts of the study area, including Eslohe and Warstein. These areas characteristically exhibit lower densities of public utility networks, accompanied by comparatively weaker demand potential. As an urban centre, Dortmund also exhibits a comparatively low suitability index. This can primarily be attributed to limited access to renewable energy sources and the proximity to the planned core network, as illustrated by the suitability profile in Figure 4. The availability of open space, access to water bodies and the road network remain relatively constant across all selected municipalities.

4.2 Sensitivity analysis

The results of the sensitivity analysis are summarised in Table 7, presenting the total difference values between the suitability analysis based on AHP weightings and the results obtained from the sensitivity analysis across all suitable sites. Although the mean difference increases by less than 10 %, the effect is more apparent in the rise of minimum values and the decrease in standard deviation.

Therefore, the sensitivity of individual value scores should be examined. Figure 5 illustrates the variation in the number of suitable sites per value score. Differences in the distribution of suitability value scores are reflected in their relative percentage shares. A notable increase is observed in areas classified as highly suitable (value scores of 6.01 to 9.0), accompanied by a decrease in areas with medium or low suitability. Additionally, the analysis shows a reduction in extreme values, with both the highest scores (10) and the lowest scores (below 3) representing a considerably smaller share in the sensitivity analysis results. Consequently, the sensitivity analysis produces a more

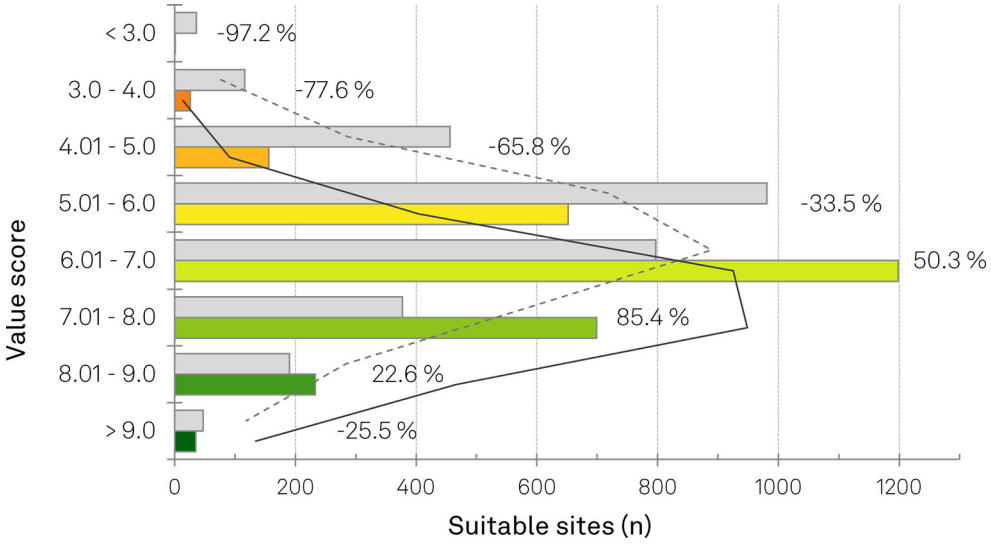
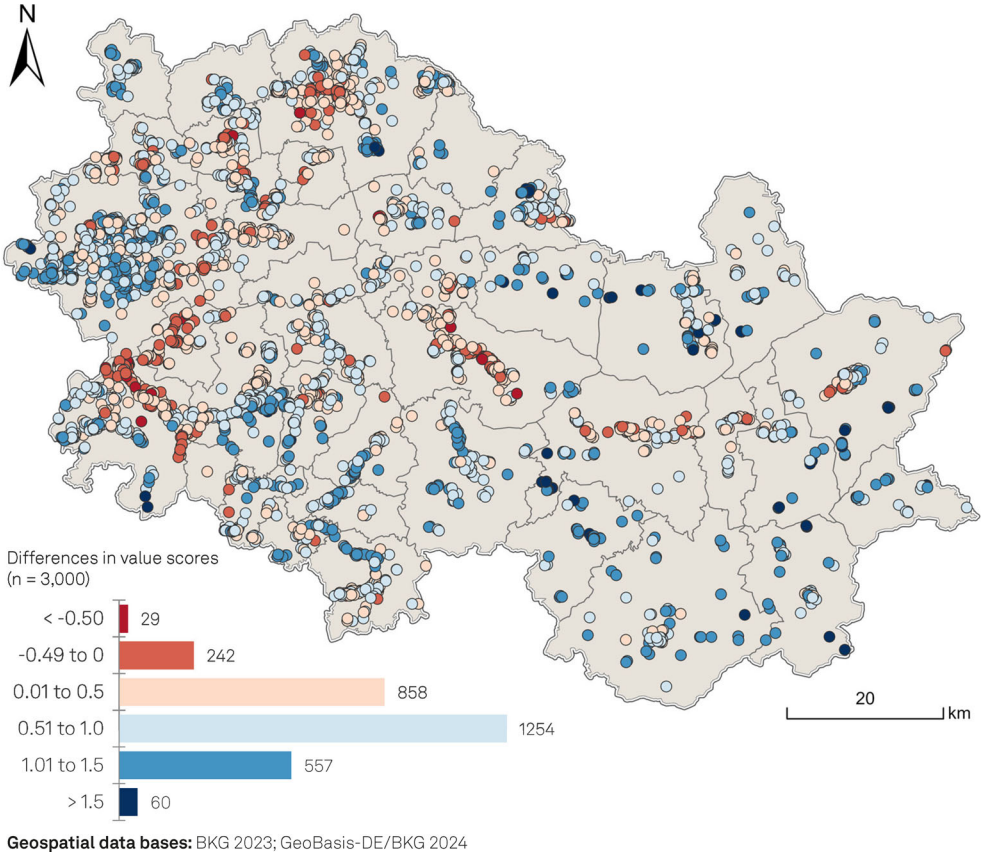
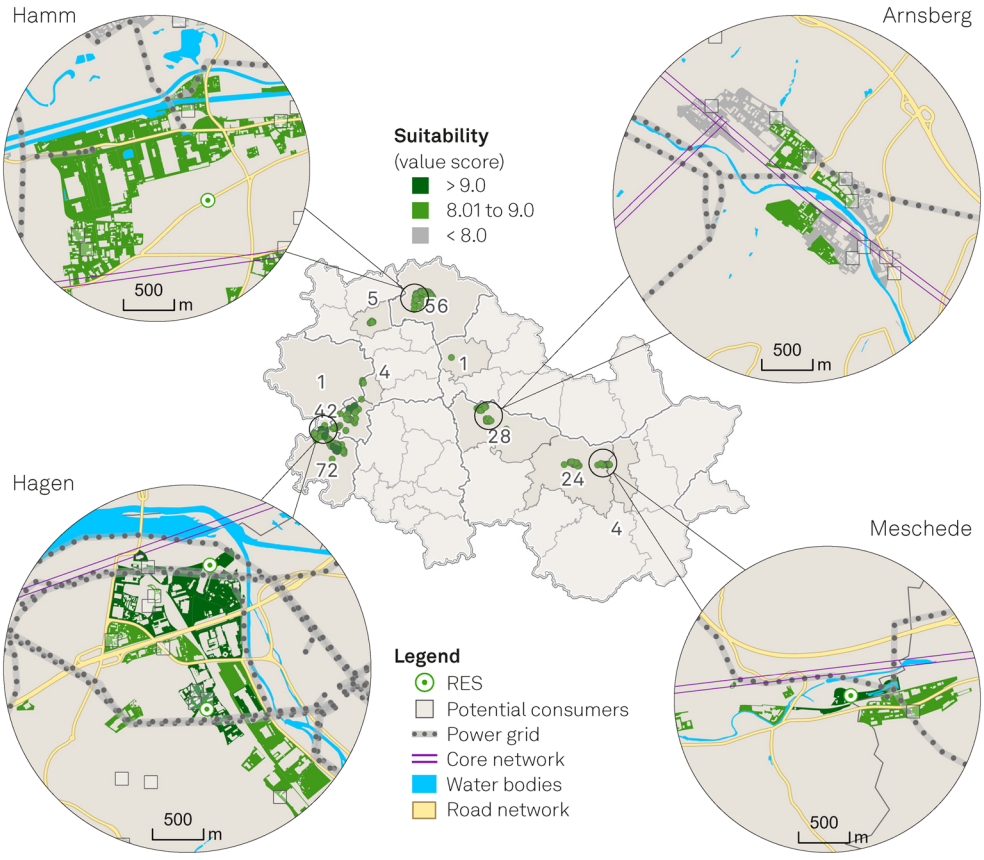


Figure 5 Histogram of value scores with moving average according to suitability (grey) and sensitivity analysis (coloured)



Geospatial data bases: BKG 2023; GeoBasis-DE/BKG 2024

Figure 6 Sensitivity map for suitable electrolyser sites



Geospatial data bases: BKG 2023; BNetzA 2024; GeoBasis-DE/BKG 2024; LANUV, NRW 2025

Figure 7 Visualisation and number of highly suitable sites

homogeneous distribution than the results obtained using AHP weighting.

Overall, the results indicate that the methodological framework is sensitive to variations in the criteria weights. To further explore how these differences manifest within the study area, a sensitivity map was generated (see Figure 6). The map illustrates the absolute changes in suitability value scores for each site and their geographic distribution, thereby highlighting the locations most affected by variations in criteria weights. Sites demonstrating negative differences are predominantly situated in the central and western region of the study area, where there is a great concentration of highly suitable sites. In contrast, sites along the southern and northern borders of the study area show increases in value scores.

5 Discussion and limitations

It is evident from the visualisation of selected sites with high suitability (see Figure 7) that the analysis generally produces plausible results, as all relevant infrastructures and resources required to meet the defined criteria are found in close proximity. The distribution of potential electrolyser sites with high suitability value scores is geographically concentrated in the municipalities of Hagen, Hamm, Arnsberg and Meschede, which are characterised by a high density of utility networks and resource availability. In Hamm, areas in and around the port exhibit particularly high levels of suitability, while in the other three municipalities, these sites are located in proximity to the Ruhr River.

In particular Hagen, Hamm and Arnsberg benefit from strong connectivity and well-developed infrastructure despite their somewhat suburban character. Furthermore, they host a wide range of small and medium-sized enterprises as well as more than 80 large, globally operating industrial companies in the districts of Hochsauerlandkreis and Märkischer Kreis alone (Block/Moritz/Benz et al. 2021: 66). These companies can be regarded as critical regional users and contribute to a stable regional hydrogen economy (Cao/Singh/Caldwell et al. 2025). In these municipalities, planning for hydrogen production and distribution has

already begun, with initiatives such as hydrogen hubs in Hamm and Arnsberg.[8]

In terms of achieving the study's objectives, the approach enhances transparency in site selection, facilitates the transfer of results to local actors and therefore supports faster decision-making. The method provides a holistically structured framework that integrates key requirements for electrolysers. The approach thus reduces the spatial mismatch between hydrogen supply and local centres of demand (Çelikdemir/Özdemir 2026: 2), while integrating a comprehensive energy system perspective for sustainable infrastructure planning (Neuwirth/Fleiter/Manz et al. 2022: 13). This analysis identified highly suitable sites in the study area, supporting cost-effective and environmentally compatible hydrogen production while contributing to energy security.

With regard to the state of research, our method enables the integration of local supply infrastructure and high-resolution, site-specific demand structures. The selection of suitable electrolyser locations is strongly influenced by local demand, as reflected in its high weighting in the decision-making process (see Table 5) and the suitability profiles in Figure 4. The results further indicate that local hydrogen demand and the planned hydrogen core network play a decisive role.

However, the latter finding should be interpreted with caution, as the hydrogen core network is still in the planning stage and has not yet been implemented (Bundesnetzagentur 2024). This indicates a particular limitation of the proposed site selection approach, as the georeferenced representation of the planned corridors may be subject to positional inaccuracies due to its coarse spatial resolution. Furthermore, potential delays or route changes may substantially affect the suitability results, given the high weighting assigned to this criterion.

The sensitivity analysis and visual validation revealed that proximity to the power grid and other public utilities has a strong influence on site suitability. As demonstrated in Figure 6, there is even a slight overemphasis on these criteria, as sites located farther from these infrastructures regain suitability. This effect is further reinforced by the expert weighting, which assigns very high importance to power grid and core network connections. Despite the consistent implementation and application of the AHP methodology (CR < 0.10), the relatively small number of local experts who were consulted limits the robustness of the criteria weighting.

Regarding the GIS-based implementation using geospatial data, several limitations were identified. Firstly, it should be noted that the industrial and commercial land-use categories in the Basis-DLM are not necessarily directly equivalent to the corresponding planning-law categories defined in the Federal Land Use Ordinance. Furthermore, certain industrial and commercial areas were included in the analysis because they meet the minimum open space requirements but are not realistically feasible due to their irregular or non-compact shapes, particularly in inner-city locations. Clearly, individual site-level verification of suitability remains necessary.

The data utilised here is transferable to other federal states, as demonstrated by the inclusion of a municipality in Hesse. This is unsurprising since the data used are almost exclusively high-resolution and are available throughout in Germany, primarily in the Basis-DLM dataset. Additionally, the data generated by North Data Premium are based on official information from the German Federal Gazette and the German Commercial Register and are therefore also available nationwide. Overall, data accuracy appears sufficient for the purposes of this analysis. However, including existing gas network corridors in the analysis would be beneficial, although this is rarely feasible due to critical infrastructure protection.

With regard to future developments, there is potential for conflict between the economically optimal locations preferred by private operators and the broader objectives of spatial planning. For potential consumers and investors, economic viability and the feasibility of deployment are key factors (Neuwirth/Fleiter/Manz et al. 2022: 1). At the same time, the planning of electrolyser projects, which represent an important interface between the electricity and hydrogen networks, should be closely coordinated with transmission grid planning (Bundesnetzagentur 2025: 58).

Therefore, regional spatial coordination is needed to ensure compatibility with existing land uses and fair consideration of private interests and public planning objectives. This requires balancing security of supply, cost efficiency and environmental compatibility to support local socio-ecological and economic transformation (BMWK 2023: 10). However, it should be noted that although the analysis incorporates fundamental planning and regulatory requirements, no sites are excluded for political or social reasons, such as proximity to residential areas. Depending on legislation and political priorities, such exclusions could be implemented in the future to further increase acceptance levels.

[8] https://www.wirtschaft.nrw/land-foerdert-hochlauf-der-gruenen-wasserstoffwirtschaft-hamm-und-lichtenau (08.10.2026); https://www.energieforschung.de/de/aktuelles/news/2025/projekt-hydronet-will-wasserstoff-ganzheitlich-in-die-praxis-bringen (08.10.2026).

6 Conclusion

The present study proposes a methodology to facilitate the selection of optimal locations for the production of hydrogen. The complexity of techno-economic deployment conditions and supply security requirements necessitates comprehensive consideration of sustainability criteria within the regional site suitability analysis. The proposed site selection procedure, as a pre-assessment, fills a methodological gap and hence complements existing approaches to site suitability analysis for other energy-related technologies.

It is recommended that further research should conduct a qualitative, on-site assessment of individual locations, building on the results, to actively involve local stakeholders. While this study provides strong indications of suitable sites or municipalities, local structures and conditions may differ, as exemplified by the specific consideration of the sizes and shapes of potential sites. Further research is required in order to develop future scenarios based on the assigned weightings. Additionally, factors that become increasingly important at larger scales should be considered. In particular, the suitability assessment could be further refined by including the utilisation of by-products such as oxygen or waste heat and by adjusting distance parameters when considering pipeline connections to meet potential demand instead of trailer-based delivery.

Although hydrogen is currently comparatively expensive and the economic viability of hydrogen infrastructures within the energy system is sometimes in doubt (Budny/Madlener/Hilgers 2015; Kötter/Schneider/Sehnke et al. 2016), the need for hydrogen in future low-carbon energy systems remains clear and is expected to increase (Abid/Østergaard/Skov et al. 2025; Gomonov/Permana/Handoko 2025). This assessment seems particularly pertinent in times characterised by an urgent need to reduce dependence on oil and gas imports (as highlighted by the current conflict in Iran and its effects on oil and gas prices) and to advance the energy transition. Thus, the development of methods to support the planning of hydrogen infrastructures is likely to become increasingly important.

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