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Coordinating social dynamics for integrating hydrogen in the Netherlands

Mahshid Hasankhani [a,*], Renske van 't Veer [b], Sine Celik [a], Amineh Ghorbani [b], Jan Carel Diehl [a], Jo van Engelen [a]

[a] *Industrial Design Engineering Faculty, Delft University of Technology (TU Delft), the Netherlands*
[b] *Technology, Policy and Management Faculty Delft University of Technology (TU Delft), the Netherlands*

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ABSTRACT

Integrating hydrogen into energy systems presents challenges involving social dynamics among stakeholders beyond technical considerations. A gap exists in understanding how these dynamics influence the deployment of hydrogen technologies and infrastructure, particularly in infrastructure development and market demand for widespread adoption. In the Netherlands, despite ambitious strategies and investments, comprehensive explanations of social dynamics' impact on integration processes and market development are lacking. This study addresses this gap by analyzing the hydrogen value chain and stakeholder interactions in the Dutch hydrogen sector. A literature review highlights system integration challenges and the need for decentralized coordination and cross-sector collaboration. Using the Dutch energy grid and its hydrogen initiatives as a case study, social network analysis and semi-structured interviews are applied to analyze over 60 hydrogen initiatives involving more than 340 stakeholders. Initiatives are categorized into large-scale centralized and decentralized local types based on scale and stakeholder involvement, allowing targeted analysis of stakeholder interactions in different contexts. Findings reveal that centralized networks may limit innovation due to concentrated influence, while decentralized networks encourage innovation but require better coordination. These insights guide strategic planning and policymaking in hydrogen energy initiatives, aiming to enhance scalability and efficiency of hydrogen technologies for sustainable energy solutions.

1. Introduction

Hydrogen is increasingly recognized as a key driver in the transition towards more sustainable energy systems, serving as an alternative to fossil fuels by enabling energy storage, transportation, and conversion [1,2]. The adaptability of hydrogen for electricity storage and its integration into existing energy systems makes it particularly promising for hard-to-abate end-use sectors such as heavy industry, heavy-duty transport, and power generation, which are all major sources of greenhouse gas emissions. However, its broad application faces significant technological and institutional challenges, and progress has been slower than expected [3,4].

Technical challenges persist in the production, storage, transportation, and conversion of hydrogen, as well as its integration into the energy system [5]. As hydrogen moves from raw material to a major energy carrier, it necessitates transformations in energy infrastructure and market dynamics, requiring modifications to existing infrastructure, business models, and stakeholder relationships. A significant challenge is the interdependence between infrastructure development and market demand: infrastructure development depends on market demand, yet demand is unlikely to grow without established infrastructure, necessitating coordinated efforts among stakeholders to break this impasse. This creates a classic 'chicken-and-egg' problem that necessitates coordinated efforts among stakeholders to overcome. Additionally, the absence of established strategies to improve decision-making processes contributes to stakeholder uncertainty at the operational level.

Addressing these challenges requires enhanced coordination and collaboration among a wide array of stakeholders to align efforts and resources [6] effectively. Defining coordinated roles and relationships across various sectors and supply chain levels can prevent overlapping efforts and ensure effective contributions [6]. Additionally, cross-sectoral collaboration among established entities such as the chemical industry, newcomers from the power and renewable sectors, and other key stakeholders across the entire value chain is imperative for consensus on the siting and access to hydrogen production facilities, utilization, storage, transport infrastructure, equitable resource allocation, and for fostering innovation through shared knowledge [7,8].

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* Corresponding author.
E-mail address: m.hasankhani@tudelft.nl (M. Hasankhani).

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Abbreviations

CCS	Carbon capture and storage
CHP	Combined heat and power
TU Delft	Delft university of technology
DEMO	Demonstration stage
DSO	Distribution system operator
FID	Financial investment decision
H2	Hydrogen
IEA	International Energy Agency
P2G	Power-to-Gas
P2P	Power-to-Power
R software	R programming language (statistical computing and graphics software)
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands enterprise agency)
SNA	Social network analysis
SMEs	Small to Medium-Sized Enterprises
TSO	Transmission system operator

Several studies have examined aspects of social dynamics and market structuring in the emerging hydrogen market [6,9–11]. For instance, in Germany, shifts in stakeholder roles have highlighted the need for structured analysis of social dynamics to address coordination challenges, requiring targeted policy measures for effective market alignment and long-term strategy development [9]. Another study employs discourse network analysis to investigate stakeholder views on hydrogen within Germany's energy transition, mapping public debates to identify conflicts and agreements across sectors [6]. This approach provides valuable insights into how stakeholder dynamics affect policy and market reactions to hydrogen technology.

In the context of regional market development, studies in sectors like natural gas emphasize leveraging the unique capabilities of national and provincial regions to create manageable market clusters [12]. For example, an empirical analysis of China's regional natural gas market using spatial and social network perspectives reveals uneven infrastructure development and proposes shifting from a vertically integrated system to a more competitive, horizontally integrated market structure supporting multiple suppliers [12].

Furthermore, adopting new perspectives on social-ecological and socio-technical frameworks provides valuable insights by viewing infrastructure as an integrated system of stakeholders and components [13,14], emphasizing the intricate interactions within these systems and deepening the understanding of the key dynamics that shape infrastructure management.

Despite significant contributions in the field, a gap remains in integrating social dynamics with the deployment of hydrogen technologies and infrastructure, particularly in understanding how these dynamics influence infrastructure and market demand development for widespread adoption. This gap is especially pronounced in the Netherlands, which, despite its ambitious hydrogen infrastructure strategies and substantial investments, lacks comprehensive explanations of how social dynamics impact integration processes and market development.

To address this gap, the study analyzes the state of the hydrogen value chain and the dynamics of stakeholder interactions across different sectors and scales within the emerging Dutch market. The central question is: How do social dynamics influence the strategic planning and deployment of hydrogen infrastructure to facilitate its widespread adoption? Beginning with a literature review on the technical and institutional aspects of hydrogen integration, the study highlights challenges in system integration and emphasizes the need for decentralized coordination and cross-sector collaboration. This foundation sets the stage for understanding how social dynamics among stakeholders influence these challenges and the strategic planning required for infrastructure deployment.

Building upon these insights, the study employs Social Network Analysis (SNA) on over 60 hydrogen initiatives in the Netherlands, involving more than 340 stakeholders from various entities. Network science, which examines the common principles governing complex systems—from biological networks to social structures [15–17]—provides the theoretical foundation for SNA. Leveraging concepts from network science, SNA enables the mapping and analysis of relationships and roles among stakeholders in the hydrogen sector. This approach identifies key stakeholders, maps information and resource flows, evaluates network structures and collaboration patterns in decision-making, and detects potential bottlenecks or critical gaps in coordination that hinder effective market development and infrastructure planning strategies [18,19].

Data for the SNA were collected from the International Energy Agency (IEA) public database and other public records. Initiatives were categorized into large-scale centralized initiatives and decentralized local initiatives to enable targeted analysis of stakeholder interactions in different contexts. The study presents results supported by quantitative data from SNA, validated by qualitative insights from semi-structured interviews. The discussion delves into the findings, providing deeper context and understanding of the implications arising from the analysis of the hydrogen sector's development from both quantitative and qualitative perspectives.

This study provides a comprehensive conceptual and experimental approach to map, understand, and model stakeholder interactions in quantifiable terms. By analyzing the layout and connectivity of technical components and mapping relationships and roles among stakeholders, it pinpoints areas where targeted strategies are needed, identifies organizational bottlenecks or critical gaps in coordination that could hinder effective integration, and emphasizes the need for decentralized coordination and cross-sector collaboration to enhance integration. By examining the relationships and roles among stakeholders within both centralized and decentralized hydrogen initiatives in the Netherlands, the study offers insights into how social dynamics influence infrastructure and market development. This approach not only delves into the practicalities of integrating hydrogen infrastructure but also links these aspects to social dynamics. By doing so, the study contributes to the wider adoption of hydrogen technologies and addresses the identified gap in the literature.

The findings provide actionable insights into the complexities of stakeholder interactions, emphasizing the importance of collaborative networks for the successful implementation of hydrogen initiatives. Understanding the dynamics between centralized and decentralized networks allows practitioners to tailor strategies that leverage stakeholder strengths, foster innovation, and mitigate risks like bottlenecks and over-reliance on dominant entities. For policymakers, the study highlights the critical role of supportive policies and financial incentives in reducing investment risks and fostering stakeholder commitment. Insights into stakeholder dynamics inform policy development aimed at promoting inclusivity, facilitating cross-sector collaboration, and establishing governance structures that enhance coordination and communication among diverse stakeholders. This approach creates a stable policy environment that encourages investment, innovation, and the effective integration of hydrogen technologies into the energy system.

Following this introduction, Section 2 elaborates on the background. Section 3 outlines the study approach. Results are delineated in Section 4, followed by a discussion in Section 5 and concluding remarks in Section 6.

2. Background: system integration and decentralized coordination

This section outlines the research background. Section 2.1 reviews the integration challenges of hydrogen technologies and infrastructures, delving deeper into the practical aspects of implementation in the Netherlands. Section 2.2 examines the Dutch energy grid and its growing hydrogen initiatives as a case study. It uses empirical data to perform a comprehensive analysis that emphasizes the importance of these concepts.

2.1. Integration of hydrogen technology and infrastructure in the Netherlands

The Netherlands is pursuing an ambitious hydrogen infrastructure strategy, aiming to establish a national "Hydrogen Backbone" that connects industrial clusters, storage facilities, and ports by partially repurposing existing natural gas pipelines [20]. This initiative involves significant investments in pipeline systems, large-scale storage facilities, and electrolyzers to integrate hydrogen into 30 % of the national energy mix by 2050 [21]. However, technical challenges persist in production, storage, transport, and conversion processes [7,22].

Advancements in hydrogen production techniques such as steam methane reforming, biomass and coal gasification with carbon capture and storage (CCS), and green hydrogen production via electrolysis aim to meet varying scales and efficiency requirements. However, green hydrogen remains more expensive than hydrogen derived from natural gas unless supported by affordable renewable energy or influenced by high carbon pricing [5,23]. Developing safe and efficient storage and transport strategies is critical [4,24], involving options like underground seasonal storage, compressed or liquefied hydrogen, and innovative carriers to enhance transport efficiency [22,23]. Decisions regarding hydrogen storage and transportation from centralized production facilities to refueling stations involve choices between gaseous trucks, liquefied trucks, pipelines, or local production at refueling stations. Balancing production costs against logistical considerations varies by method and distance [5,25].

Fuel cell systems serve as combined heat and power (CHP) units, bridging production methods, and practical applications that range from residential to industrial-scale power generators [23,26]. Integrating hydrogen technologies into broader energy systems requires addressing operational challenges, ensuring compatibility with grid requirements, and developing safety and cybersecurity standards [7]. Applications are showcased through power-to-power (PtP) and power-to-gas (PtG) systems. PtP systems modulate hydrogen production to complement renewable energy fluctuations, maximizing resource use and stabilizing the grid, though they require advanced forecasting and storage techniques [27,28]. PtG systems convert excess renewable energy into hydrogen for power generation, blending into natural gas pipelines, or use in refueling systems [29–31]. These systems can also utilize by-products like heat and oxygen for industrial processes.

Integrating hydrogen infrastructure signifies a shift toward interconnected energy systems, enhancing service delivery, a progression similar to the historical expansion of the Dutch energy grid from isolated city systems to a national network [32]. However, this integration is not solely a technical endeavor; it is deeply intertwined with social dynamics among stakeholders. For example, reducing the cost of green hydrogen depends on coordinated efforts to develop supportive policies, subsidies, and investment strategies. Establishing safe and efficient storage and transport systems requires consensus on standards and regulations, as well as shared investments in infrastructure development. Aligning the interests and actions of stakeholders like utility companies, grid operators, and regulatory bodies is essential. Given the constraints of altering existing infrastructure, it is crucial to adopt decentralized coordination. This approach moves away from conventional centralized decision-making towards a framework where information and decision-making responsibilities are spread across multiple stakeholder groups [18,33–35].

2.2. Enhancing system integration with decentralized coordination and cross-sector collaboration

In the Netherlands, hydrogen development is progressing along two complementary pathways: large-scale centralized systems and decentralized local systems [36–39]. Centralized systems typically encompass massive production and storage facilities to serve significant economic areas such as ports or heavy industry, transport, gas, heating, and power. Conversely, decentralized local systems involve community-driven, smaller initiatives aimed at catering to the needs of local areas, both urban and rural, and involve sectors such as local industries, distribution of power and heating for the built environment (commercial and residential), and transportation [40].

Centralized hydrogen systems typically involve initiatives with multiple stakeholders, such as infrastructure providers, transmission system operators (TSO), established industry stakeholders from the chemical, petrochemical, oil, and gas sectors, small and medium-sized businesses, and new entrants from (renewable) energy and utility sectors. These initiatives are strategically located near major industrial and energy hubs under these authorities to leverage existing infrastructure and logistics capabilities for large-scale hydrogen production and distribution. The primary aim is to meet the substantial energy demands of end-use sectors in these hubs through the generation of hydrogen at a scale ranging from megawatts to gigawatts, supporting industrial processes, heavy transport fuels, and chemical production [5,41]. Among these initiatives, the Holland Hydrogen and H2-Fifty initiatives in Rotterdam exemplify this approach, with significant investments in electrolysis capacity to produce green hydrogen, thereby facilitating the transition towards renewable energy sources and reducing emissions in the port area [42].

Despite the apparent opportunities, such as the adaptation by established industry stakeholders of existing fossil fuel infrastructures for hydrogen use and the development of new business models, there are rising concerns about the environmental sustainability of these initiatives and the potential overshadowing of innovation in low-carbon technologies [43–45]. There are risks associated with heavy reliance on infrastructures, including disruption, scaling challenges, and difficulties in modifying systems to meet the unique needs of hydrogen for storage and transportation. Additionally, the infrastructure's inability to quickly adapt to fluctuating demands leads to operational inefficiencies and increased costs, particularly when the systems are not fully utilized or when they encounter unexpected spikes in demand [46]. The dominance of established stakeholders may hinder smaller, innovative initiatives, reducing market diversity and competition [9]. Centralized systems may overlook the specific needs of local markets, such as the practicality of storage and transportation solutions and the development of appropriate safety and standards protocols. The result is often a market concentration, where a few large companies control supply and demand, which could lead to higher prices and less innovation over time. In contrast, new entrants from (renewable) energy and utility sectors are adopting a more collaborative approach and supporting the integration of hydrogen technologies as a complement to the increasing share of renewable energy sources. This approach promotes a model of cooperation where large and small initiatives can work together, fostering synergies. Such collaborations can help balance the market, encourage diversity in energy solutions, and ensure the development of infrastructures that meet different sectoral needs [6].

In parallel, decentralized local systems engage local stakeholders, including local governments, community organizations (energy cooperatives), distribution system operators (DSOs), commercial infrastructure providers, and potential end users, to develop hydrogen initiatives that are sustainable and tailored to provincial and local needs [47]. These initiatives strive to supply on a small to medium scale and enhance the distribution and service provision by tapping into renewable resources in the local communities [26,48,49]. They contribute to energy security and self-reliance, especially in remote areas, by offering environmentally friendly options for transportation and heating [23, 26]. Moreover, they aim to play a critical role in power storage and delivery of essential grid services, including congestion management, frequency regulation, and rapid power restoration during emergencies. The H2GO project in Goeree-Overflakkee Island is a prime example, showcasing hydrogen integration to meet the diverse energy demands of local communities [50].

Underdeveloped infrastructure for energy storage and transport hinders efficient energy sharing and utilization, impacting operational efficiency, scalability, and reliability [51]. Addressing this gap demands substantial investments in both the development of physical infrastructure and its intricate market management [52], which is particularly challenging in economically disadvantaged areas due to limited funding. Decentralized local systems, while offering the potential for efficient and localized energy distribution, demand continuous investment in maintenance and safety. This includes significant costs for advanced monitoring technologies, emergency response planning, and educational initiatives to meet regulatory standards and actively engage local communities [53].

The regulatory landscape for the emerging hydrogen sector in the Netherlands presents significant challenges—especially regarding land acquisition, construction permitting, and compliance with rigorous safety and environmental standards—which often lead to project delays or cancellations. There is notable ambiguity concerning the roles and responsibilities among DSOs and third-party entities. While DSOs have the operational experience and are involved in hydrogen initiatives, their participation in energy production or storage as envisaged for hydrogen could conflict with the unbundling rules. Distribution tariffs, which presently mirror that of natural gas, fail to adequately account for the distinct physical properties of hydrogen or the dynamic state of its market [54]. Unclear or inconsistent regulations are negatively impacting efforts to maintain a unified market and promote fair competition.

The Netherlands is adopting a dual approach by developing both large-scale centralized systems and decentralized local systems to address diverse sectoral needs and provincial energy demands. This strategy is facilitated by decentralized decision-making processes and aims to mitigate the financial and developmental risks associated with emerging technologies and infrastructures [55]. By leveraging its strategic location, extensive industrial base, and varied energy sources, the Netherlands enhances its existing facilities to address operational and logistical challenges and to establish a resilient hydrogen supply chain [56]. However, the interconnectedness of centralized and decentralized systems in the hydrogen value chain presents challenges. Centralized systems primarily focus on hydrogen production and large-scale storage, while decentralized systems handle distribution; challenges in one segment can impact others, potentially leading to widespread infrastructure failures [57,58].

Integrating hydrogen infrastructure requires a comprehensive assessment that goes beyond merely evaluating technical capabilities and cost-efficiency of production. It demands an in-depth analysis of the available existing infrastructure, resources, and land necessary for hydrogen production. Additionally, the demand at refueling stations is crucial to devising an optimal setup for infrastructure. This complexity is further amplified by the need to balance the upfront costs of technology and infrastructure with ongoing expenses associated with various storage and transportation methods. Decision-making in this context is profoundly influenced by the pace of technological progress, market fluctuations, and local nuances.

This underscores the importance of developing customized adaptation strategies that address specific needs related to storage, transportation, safety, and standards, which vary significantly across different geographical regions. The imperative to integrate hydrogen infrastructure into energy systems with minimal physical changes calls for a shift towards more decentralized planning and coordinated efforts [33]. Furthermore, enhanced collaboration across sectors is needed. Through a bottom-up approach to collaboration, sectors can forge synergistic solutions that maximize the use of resources and infrastructure, minimize overlap, and introduce beneficial services for consumers and communities, thereby facilitating a smoother integration process. Collaborative efforts can take various forms, such as licensing, minority investments, joint ventures, research and development partnerships, funding opportunities, alliances, consortiums, networking events, and outsourcing contracts [59]. The choice of collaboration model depends on strategic objectives, projected timelines, budgetary constraints, and preferred levels of oversight. Regardless of the chosen approach, the ultimate goal is to leverage these partnerships to gain a competitive advantage that promotes growth and increases value for all involved entities [60]. This requires revising regulatory frameworks to align with hydrogen energy's unique properties, while clearly defining stakeholder roles and relationships and fostering a fair competitive environment.

In this context, it is crucial to delve deeper into the social dynamics of the hydrogen sector. Understanding the roles and relationships among various stakeholders is essential for shaping the strategic planning and deployment of hydrogen infrastructure, and for understanding how stakeholders interact, collaborate, and make decisions. Additionally, grasping these dynamics is key to effectively integrating hydrogen technology into the broader energy system, which is vital for its widespread adoption.

3. Research approach

This section outlines the research approach. Section 3.1 provides theoretical justifications for the selected framework and metrics. Section 3.2 details the research design and objectives, explaining the selected objectives and anticipated outcomes. Further, Section 3.3 elaborates on the processes for data collection, data transformation methods, and analysis techniques.

3.1. Social network analysis (SNA)

Social Network Analysis (SNA) is an interdisciplinary approach to exploring the dynamics within social networks, drawing from sociology, psychology, mathematics, and computer science [61,62]. These disciplines focus on mapping complex systems, extracting information from noisy data, and assessing system robustness against disruptions. This method transcends traditional analysis approaches, which typically focus on isolated entities, by examining how individuals and entities are interconnected and how they interact. In infrastructure management, it assists in understanding complex social dynamics, coordinating supply and demand, and aligning stakeholder interests to enhance market efficiency and decision-making [6,9,13,14]. By disentangling complex social structures and clarifying the roles and relationships among network participants, SNA plays a critical role in developing strategic approaches for network management and operational efficiency.

SNA utilizes graph theory, a branch of mathematics, to represent social structures [15–17]. While rooted in graph theory, it primarily focuses on real-world data and practical applications rather than abstract mathematics, validating its theoretical tools through their effectiveness in explaining and predicting behaviors in actual systems. In this context, a graph consists of nodes (representing entities like individuals, organizations, or any other relevant unit) and edges (representing interactions or relationships between these entities). These edges can represent various types of interactions, such as communication, advice, trust, and influence, and can be directed or undirected. Often, these interactions are weighted to signify the strength or intensity of the interaction. The data collection and analysis process in SNA includes gathering data, conducting statistical analyses, and applying algorithms to explore network dynamics [63].

A set of metrics can be adopted to examine the network's architectural properties, pinpoint influential nodes, and evaluate the efficiency of communication and resource distribution across the network [64,65].

These metrics, in this context, are categorized at two levels: the stakeholder level and the network level, and are listed in Table 1. Stakeholder-level metrics—degree, eigenvector, betweenness, and closeness centrality—determine individual nodes' influence and innovative capacity within the network. These centrality measures highlight nodes that are strategically positioned as hubs or bridges, significantly impacting innovation and technology transfer processes, and affecting the dynamics of collaboration and competition. Network-level metrics, including density, average degree, diameter, and average clustering coefficient, offer a comprehensive overview of the network's overall functioning. They indicate both the efficiency of communication and the strength of relational bonds among nodes. Understanding these metrics enables stakeholders to better strategize network management, foster innovation, and improve collaborative dynamics, ultimately enhancing the network's performance and effectiveness.

However, there are some limitations, such as capturing the dynamic nature of social networks, where relationships between nodes can change over time, and static analysis might not fully reflect the network's evolving state. Reliance on quantifiable data can oversimplify complex interactions, potentially overlooking nuanced dynamics. This underscores the need for incorporating further qualitative data to gain a more comprehensive understanding of network behaviors [66,67].

Table 1
Social network analysis metrics: Stakeholder and network level indicators.

Stakeholder Level Metrics	
Degree Centrality	Measures the number of direct connections a node has, indicating a stakeholder's active involvement in the network. A high degree of centrality is often associated with influential nodes that play a central role in the network's structure, possessing superior access to information and a stronger influence over others.
Eigenvector Centrality	Assesses a node's influence based on its connections to high-scoring nodes. This metric identifies not just well-connected nodes but those that are connected to other influential nodes, amplifying their potential impact on the network.
Betweenness Centrality	Measures a node's role as an intermediary within the communication paths between other nodes. A high betweenness centrality indicates that a node acts as a critical bridge or 'gatekeeper' between different parts of the network, controlling the flow of information and resources.
Closeness Centrality	Indicates how close a node is to all other nodes in the network, measured by the average length of the shortest paths to all other nodes. Stakeholders with high closeness centrality can spread information or resources more quickly across the network due to their shorter path lengths to other nodes.
Network Level Metrics	
Density	This metric calculates the ratio of actual connections to the maximum possible connections within the network. It provides insight into the network's overall connectivity, with higher densities indicating a more interconnected network.
Average Degree	Represents the average number of connections per node within the network, reflecting the general level of activity and engagement across the network.
Network Diameter	The diameter of a network is the longest of all the shortest paths in the network. It gives a measure of the "largest separation" between any two nodes in the network. A small diameter indicates that the network has a "small-world" property, meaning most nodes are not far from each other.
Average Clustering Coefficient	Measures the degree to which nodes tend to cluster together, forming tightly knit groups. High clustering coefficients suggest that stakeholders are connected, and their connections are mutually interconnected, enhancing the spread of information or influence and cohesiveness of group dynamics.

3.2. Study design

This study investigates how social dynamics influence the strategic planning and deployment of hydrogen infrastructure by establishing three interrelated objectives, each utilizing specific SNA metrics. The focus is on examining relationships, power structures, and collaborative networks within the hydrogen sector, emphasizing both centralized and decentralized initiatives.

First objective: Identify and analyze key stakeholders crucial to both large-scale centralized and decentralized local hydrogen infrastructure initiatives. Degree centrality and eigenvector centrality are employed as primary indicators. Degree centrality highlights stakeholders with numerous direct connections, indicating active engagement and potential roles in disseminating information and resources, thus accelerating innovation and adoption. Eigenvector centrality assesses stakeholders' influence based on the quality of their connections, reflecting that connections to influential nodes amplify a stakeholder's own influence. These indicators help pinpoint stakeholders who can drive acceptance and effective implementation of hydrogen technologies across the supply chain.

Second objective: Map the flow of information and resources within the network to understand how these flows influence operational efficiency and strategic integration of hydrogen initiatives. Betweenness centrality and closeness centrality serve as indicators. Betweenness centrality identifies stakeholders acting as essential intermediaries, facilitating connections and collaborations across the network—acting as gatekeepers or brokers crucial for cohesion and knowledge transfer. Closeness centrality determines the speed at which stakeholders can disseminate information, based on the idea that those closer to others can spread innovations more rapidly, reducing delays and enhancing coordination. These metrics are essential for identifying potential communication and logistical bottlenecks that could hinder integration efforts.

Third objective: Evaluate the overall structure of the network to understand its effectiveness in facilitating or obstructing the strategic integration of hydrogen infrastructure. This involves assessing network density, average clustering coefficient, average degree, and network diameter. Network density and average clustering coefficient gauge the interconnectedness and cohesiveness of the network, which are crucial for infrastructure planning. High network density suggests strong interconnectivity among stakeholders, promoting robust collaboration and resource sharing. The average clustering coefficient provides insights into how tightly knit stakeholder groups are, fostering trust and collective action. Analysis of average degree and network diameter offers insights into stakeholder engagement levels and the network's spatial extent. These indicators reveal structural dynamics affecting the network's capacity to support or impede collective actions and decision-making, aiding in crafting strategies that are efficient and scalable.

Each objective offers a distinct perspective on how social dynamics influence hydrogen infrastructure planning and deployment. The selection of these specific SNA indicators is grounded in their theoretical relevance to key aspects of social dynamics within the hydrogen sector, aiming to inform strategies for effective integration and coordination.

The Netherlands is selected as a case study due to its well-established industrial base, strategic location, and existing infrastructure, such as pipelines and storage facilities that can be repurposed for hydrogen use. This setting allows for an expedited and cost-effective integration into the national energy mix. Additionally, the country's focus on decentralized energy systems aligns with the need for hydrogen integration, which requires coordination and collaboration across sectors. With over 60 hydrogen projects, the Netherlands offers a rich setting to analyze complex stakeholder interactions and social dynamics, providing valuable insights for similar energy transitions across various geographical contexts.

3.3. Material and methods

The study approach for data extraction, transformation, and analysis comprises four phases, as illustrated in Fig. 1.

In the initial data collection phase, the primary sources used were the IEA public database and other public records [68]. The research began by assembling a dataset from the IEA's publicly available project archives. This dataset includes initiatives that were planned to take place between 2003 and 2043 in the Netherlands [68].In this phase, each project was verified against public records and online sources such as reports, websites, and news [40,68,69]. Initiatives with verifiable websites or official stakeholder announcements were selected and references were added for further analysis. From an initial list of 89 initiatives, 61 were chosen based on information availability, involving over 340 stakeholders from different entities. In parallel, according to the existing categorization of stakeholders in the emerging value chain in the Netherlands, stakeholders were categorized into seven distinct groups: primary producers and suppliers; infrastructure, storage, and distribution entities; intermediaries; technology and service providers; end-users; policymakers and regulators; and research and education institutions. Their roles in developing the hydrogen sector were underscored [6]. If a stakeholder's primary engagement spanned various sectors, they were grouped according to their main activity. The interactions among these groups were simply recorded as yes or no to establish basic connectivity.

In the second phase, data cleaning was performed to ensure the dataset's integrity: to standardize terms, rectify spellings, and harmonize various expressions, such as reconciling "Province Groningen" with "Groningen Province." The dataset encompasses project reference, name, location by country, operational start and decommission dates, status, employed technology, electricity type used in electrolysis, dedication to renewable sources, produced substance, its end use, and the announced project size. To provide a view of stakeholders' interactions, initiatives are divided into two primary categories. The first category encompasses large-scale industrial initiatives and heavy transport, also known as centralized initiatives. The second category comprises ecosystem initiatives, as well as demonstration initiatives for power, transportation, and domestic heating, referred to as decentralized local initiatives. This phase resulted in a refined dataset. The lead researcher spearheaded the data analysis, with associate researchers contributing to mitigate bias and enhance the analysis's credibility.

In the third phase, SNA began by importing data into the R software using the 'readxl' library, ensuring that raw data was readily available for analysis. The following step involved cleaning the data, where missing values were addressed, and formats were standardized to maintain consistency. Information regarding the initiatives and involved parties, including publicly named companies such as Company A, Company B, etc., is publicly available to ensure data transparency. This transparency enhances the credibility of the analysis by allowing for independent verification [69]. The network was constructed using the 'igraph' library, where stakeholders were represented as nodes and their interactions as edges. The resulting visual model depicted the network dynamics, highlighting all interactions within a project and emphasizing repeated collaborations by strengthening edges. This model demonstrated that stakeholders could participate in multiple initiatives and interact, assuming active interactions among partners in a project. The intensity of these interactions was quantified to measure the relationship strength among stakeholders.

A network assessment followed, focusing on identifying key stakeholders through metrics such as degree centrality, eigenvector centrality, betweenness centrality, and closeness centrality, and examining network-wide characteristics including connectivity (density), the largest distance between any two nodes (diameter), and group cohesion (via clustering coefficients and modularity). The study employed the Fruchterman-Reingold algorithm to depict the network structure using the 'igraph' library for network visualization. Communities within the network were identified using the Louvain method for community detection and modularity analysis. This visualization was enhanced with the 'ggraph' and 'ggplot2' libraries, which allowed for the creation of clearer and more customized visual representations, complete with distinct color schemes to differentiate between various network components and communities [70].

In the fourth phase, data collection and analysis were complemented by qualitative insights from semi-structured interviews with five experts who are involved in selected hydrogen initiatives. Selected for their extensive knowledge of various initiatives and active participation in numerous initiatives designed to improve collaboration between industries and governments, as well as to facilitate connections across different sectors, these experts held key positions as innovation managers or business development professionals. Their roles positioned them at the intersection of innovation, making them particularly suited to provide valuable insights for this study. Guided by established consent and protocol guidelines, interviews were conducted, recorded, and then transcribed using Whisper for analysis [71]. The qualitative data from these interviews served a dual purpose: it verified the quantitative findings and provided adjustments, deepening the understanding of dynamics within the hydrogen value chain.

4. Results

This section outlines the results of the study, structured around the three objectives specified in the study design. Each subsection corresponds to an objective and includes quantitative data from the SNA, validated by semi-structured interviews. It outlines an overview of the developmental stages of hydrogen initiatives in Section 4.1, followed by an examination of key stakeholders' influence in Section 4.2, the dynamics of information and resource flows in Section 4.3, and the overall structure of the network in Section 4.4.

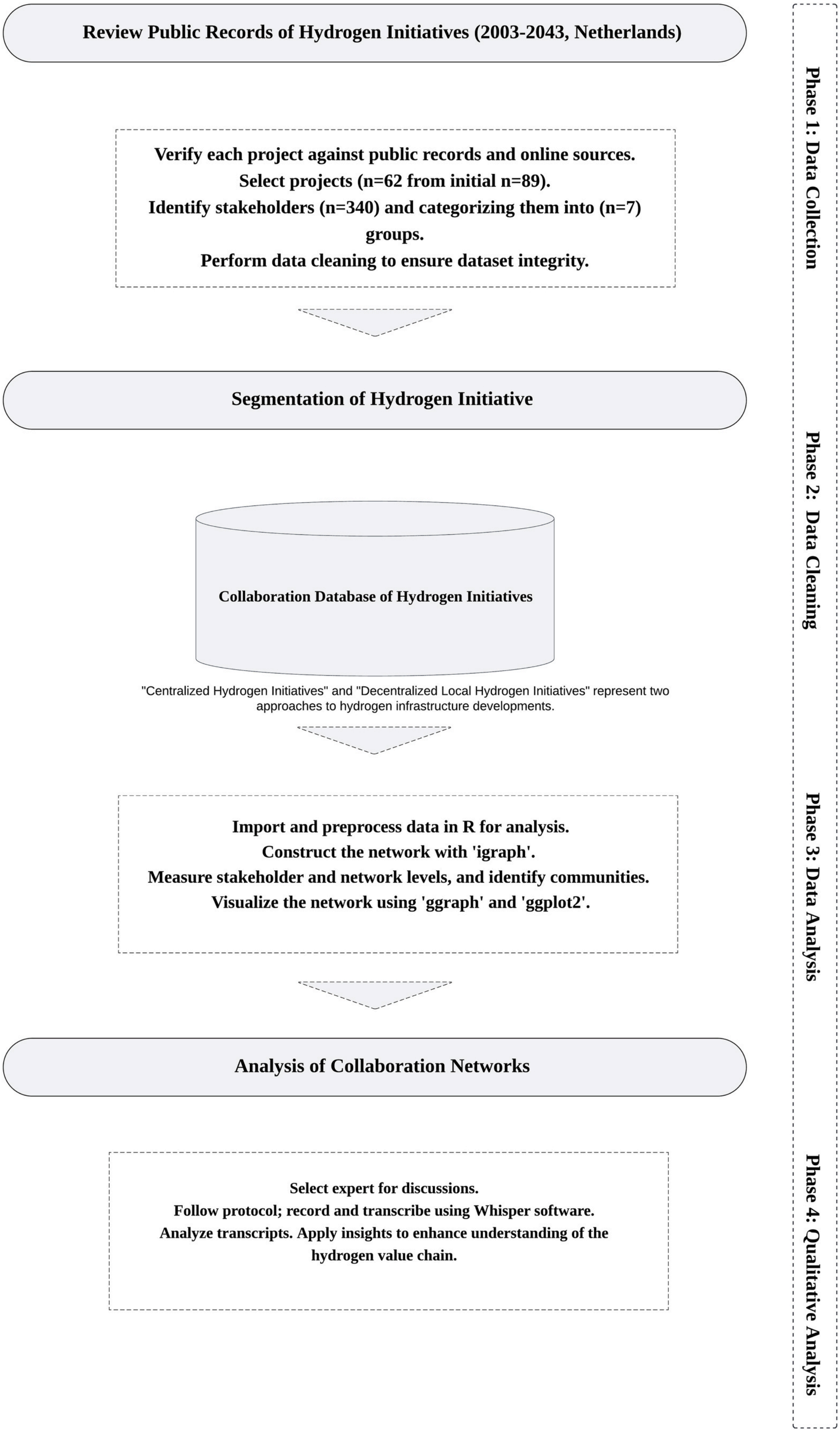
4.1. Developmental stages of hydrogen initiatives

Before examining the social dynamics, it is essential to understand the current state of hydrogen initiatives in the Netherlands. Data indicates that most initiatives are in the planning or early development stages, specifically in the Feasibility Study and Concept phases. Fewer projects have progressed to advanced stages such as Demonstration (DEMO), Operational, Financial Investment Decision (FID), and Construction. This distribution underscores a sector still in its formative stages, with a strong emphasis on developing and testing viable technologies. A notable trend is the focus on integrating electrolysis with renewable energy sources, highlighting a strategic aim for sustainability and long-term viability. The slow progression from planning to advanced stages suggests a cautious approach in investment and development strategies, possibly due to the high costs and risks associated with deploying new technologies.

4.2. Influence of key stakeholders

This subsection examines the structural influence and operational roles of various stakeholder groups within both centralized and decentralized hydrogen initiatives. Degree centrality and eigenvector centrality metrics from the SNA are used to identify key stakeholders and assess their influence. The results are summarized in Table 2 and illustrated in Figs. 2 and 3.

In centralized initiatives network, (Fig. 2), infrastructure providers, such as Gasunie (TSO), exhibit the highest degree centrality of 111 and an eigenvector centrality of 1.00. This indicates that Gasunie is the most connected and influential entity within the centralized network, actively engaging with numerous other stakeholders and reinforcing its pivotal role in infrastructure development. Other significant stakeholders include primary hydrogen producers and suppliers such as ENGIE, Air Liquide, Royal Vopak, and Yara, with degree centrality scores ranging



Verify each project against public records and online sources.
Select projects (n=62 from initial n=89).
Identify stakeholders (n=340) and categorizing them into (n=7) groups.
Perform data cleaning to ensure dataset integrity.

"Centralized Hydrogen Initiatives" and "Decentralized Local Hydrogen Initiatives" represent two approaches to hydrogen infrastructure developments.

Import and preprocess data in R for analysis.
Construct the network with 'igraph'.
Measure stakeholder and network levels, and identify communities.
Visualize the network using 'ggraph' and 'ggplot2'.

Select expert for discussions.
Follow protocol; record and transcribe using Whisper software.
Analyze transcripts. Apply insights to enhance understanding of the hydrogen value chain.

Fig. 1. Phases of data extraction, transformation, and analysis.

from 53 to 72 and eigenvector centrality values between 0.90 and 0.95. These stakeholders have extensive direct connections and significant influence within the network, highlighting their active roles in production, storage, and distribution within the hydrogen supply chain. The presence of established industry players from the chemical, petrochemical, and energy sectors underscores their importance in enhancing production capabilities and driving large-scale initiatives.

In decentralized initiatives network(Fig. 3), presents a different pattern of influence. Educational and research institutions emerge as key stakeholders, with Delft University of Technology (TU Delft) leading with a degree centrality of 93 and an eigenvector centrality of 1.00, and TNO having a degree centrality of 85 and an eigenvector centrality of 0.93. This underscores the significant role of academic institutions in driving innovation and facilitating collaborations across various sectors.

Table 2
Degree and eigenvector centrality metrics.

	Stakeholders	**Degree Centrality**	**Eigenvector Centrality**
Centralized Hydrogen Initiatives	Gasunie	111	1.00
	ENGIE	72	0.95
	Air Liquide	64	0.94
	Royal Vopak	61	0.94
	Yara	53	0.90
	Volt H2 Energy	52	0.88
	Ørsted	49	0.88
	Air Products	48	0.89
	Zeeland Refinery	48	0.89
	Dow	48	0.89
Decentralized Local Hydrogen Initiatives	TU Delft	93	1.00
	TNO	85	0.93
	Liander	80	0.28
	Cleantech Region	78	0.92
	Gasunie	76	0.92
	Toyota	72	0.95
	Nedstack	72	0.95
	Hygro	64	0.89
	Van dorp	62	0.90
	Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland-RVO)	59	0.89

Other notable stakeholders groups in the decentralized network include infrastructure providers and intermediaries. Liander, a DSO, and Cleantech Region, a regional collaborative initiative have high degree centrality scores indicate active participation in numerous projects, but their eigenvector centrality scores differ. Liander's lower eigenvector centrality of 0.28 suggests that while it is highly connected, it may not be as influential in terms of its connections to other highly connected stakeholders. Cleantech Region's higher eigenvector centrality of 0.92 indicates strong influence due to its connections with other key stakeholders.

4.3. *Flow of information and resource sharing*

This subsection analyzes the flow of information and resources in both centralized and decentralized hydrogen initiatives using betweenness and closeness centrality metrics. The results are summarized in Table 3 and illustrated in Figs. 4 and 5, providing quantitative data that highlight the importance of certain stakeholders in facilitating communication and resource flow within the networks.

In centralized initiatives network, (Fig. 4), Gasunie (TSO) again stands out with a betweenness centrality of 4467.62 and a closeness centrality of 0.004. The exceptionally high betweenness centrality indicates that Gasunie frequently lies on the shortest paths between other stakeholders, effectively serving as a gatekeeper or bridge within the network. This position allows Gasunie to control or facilitate the flow of information and resources, which can significantly influence the network's operational dynamics.

Other stakeholders with notable betweenness centrality include ENGIE (1132.74), Port of Rotterdam (1095.11), and Eneco (556.84), all with closeness centrality values around 0.003. Their positions enable them to connect disparate parts of the network, fostering collaborations and ensuring that information and resources reach various stakeholders. However, their low closeness centrality scores suggest that, despite their

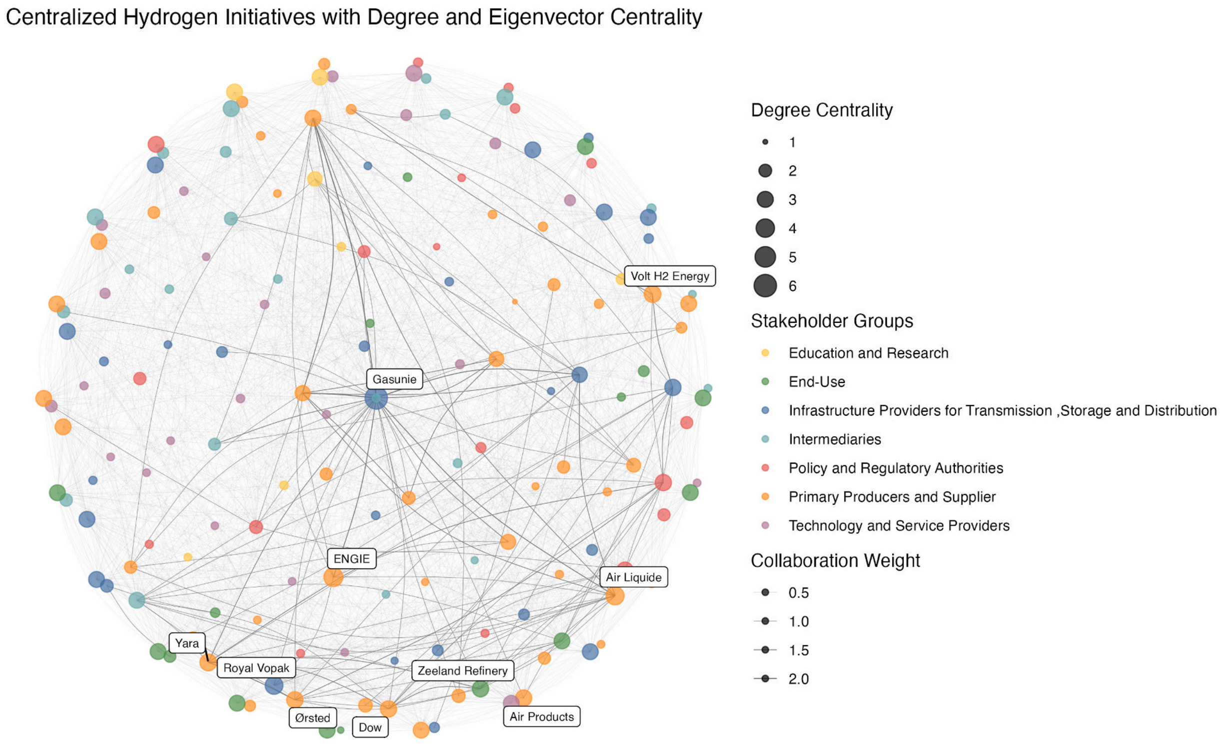


Fig. 2. Graph visualization of centralized hydrogen initiatives with degree and eigenvector centrality metrics.

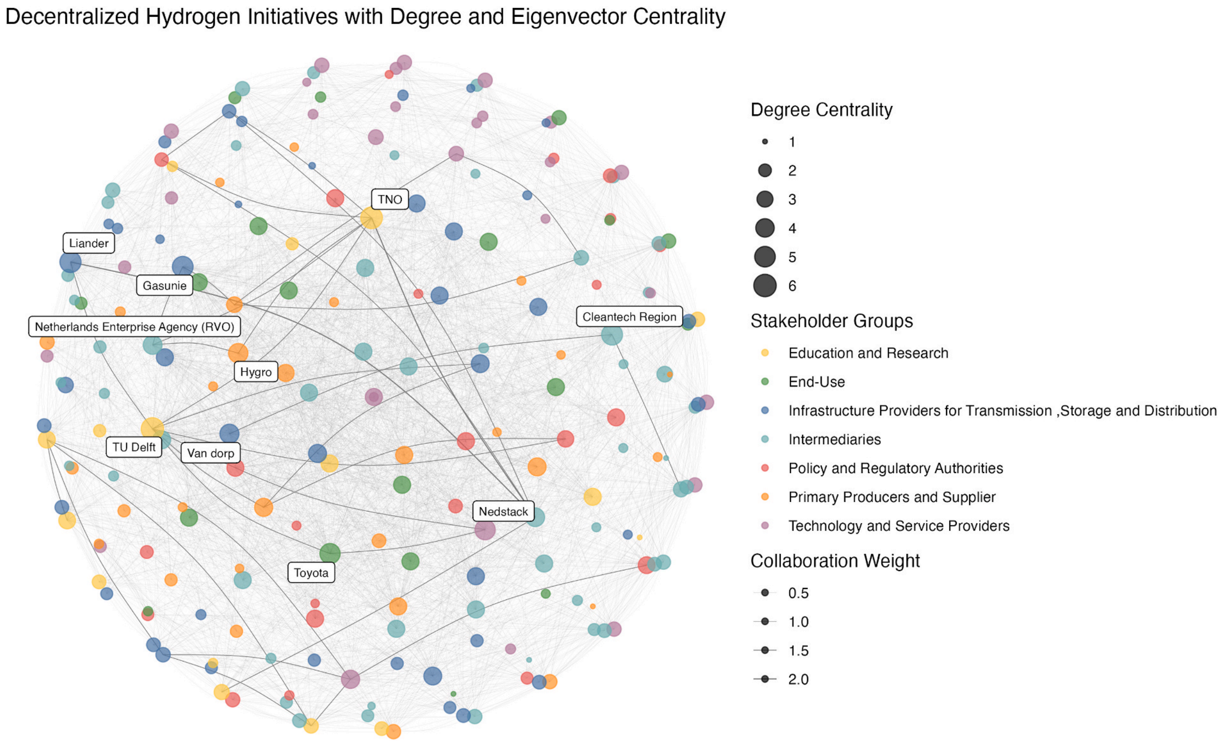


Fig. 3. Graph visualization of decentralized local hydrogen initiatives with degree and eigenvector centrality metrics.

intermediary roles, they are not the closest to all other nodes in terms of path lengths, which may affect the speed at which they can disseminate information. Several stakeholders, such as Bio Energy Netherlands BV and the Energy Research Center of the Netherlands (ECN), have a betweenness centrality of zero but a higher closeness centrality of 0.250. This indicates that while they are not intermediaries connecting different parts of the network, they are directly connected to other stakeholders and can efficiently communicate within their immediate circle. Their roles may be more localized, focusing on specific projects or collaborations without bridging broader network gaps.

In the decentralized initiatives network the betweenness centrality is more evenly distributed among multiple stakeholders (Fig. 5). Liander and TNO have high betweenness centrality scores of 2326.86 and 2016.31, respectively, with closeness centrality of 0.003. Other significant connectors include TU Delft (1553.40), Cleantech Region (1432.98), and Gasunie (1233.13). This distribution suggests a network where multiple stakeholders facilitate connections, reducing dependency on a single entity and enhancing the network's resilience. Stakeholders with high closeness centrality but zero betweenness centrality, such as Vermeulen Groep and Delphy, are closely connected within their clusters but do not act as bridges between different clusters. Their roles may be critical within their specific domains, enabling rapid information flow and collaboration in specialized areas. The decentralized network's structure, characterized by multiple intermediaries and higher closeness centrality among clusters, may facilitate faster dissemination of information and more robust collaboration. This can enhance operational efficiency and support the strategic integration of hydrogen initiatives by ensuring that innovations and best practices are widely shared.

4.4. *Structure of the network*

This subsection examines network structure using metrics like the number of relational ties, network density, average degree, network diameter, and average clustering coefficient. These metrics examine the connectivity, reach, and group cohesion within the networks. Table 4 presents these network metrics for both centralized and decentralized local hydrogen initiative networks.

In the centralized hydrogen initiatives, the network density is 0.13, with an average degree of 21.83 and an average clustering coefficient of 0.88. The network diameter is 5, indicating that the maximum distance between any two stakeholders is five steps. The moderate network density suggests that while there are substantial connections, the network is not fully saturated, leaving room for additional collaborations. The high average clustering coefficient reflects a strong tendency for stakeholders to form tightly knit groups, which can enhance collaboration within clusters but may also lead to silos if inter-cluster connections are weak. The network diameter of 5 implies that information or resources may need to traverse multiple intermediaries to reach distant stakeholders, potentially slowing down communication and coordination. This could impact the network's operational efficiency, particularly if key intermediaries are overloaded or if there are bottlenecks.

In contrast, the decentralized local hydrogen initiatives have a slightly lower network density of 0.12 but a higher average degree of 25.53 and an average clustering coefficient of 0.92. The network diameter is 4, indicating a more compact network where stakeholders are more closely connected. The higher average degree suggests that stakeholders are, on average, connected to more others, enhancing the potential for collaboration and information sharing. The higher average

Table 3
Betweenness and closeness centrality metrics.

	Stakeholders	Betweenness Centrality	Closeness Centrality
Centralized Hydrogen Initiatives	Gasunie	4467.62	0.004
	ENGIE	1132.74	0.003
	Port of Rotterdam	1095.11	0.003
	Eneco	556.84	0.003
	Uniper	461.29	0.003
	Vattenfall	425.21	0.003
	Air Liquide	417.31	0.003
	Netherlands Enterprise Agency (RVO)	410.06	0.003
	RWE	407.95	0.003
	Volt H2 Energy	391.09	0.003
	Bio Energy Netherlands BV	0	0.250
	Energy Research Center of the Netherlands (ECN)	0	0.250
	MAN Energy Systems	0	0.250
	ERDF (European Regional Development Fund)	0	0.250
	AKEF (Amsterdam Climate & Energy Fund)	0	0.250
	Royal Vopak	317.06	0.003
	Shell	346.84	0.003
	OCI N.V.	367.78	0.003
Decentralized Local Hydrogen Initiatives	Liander	2326.86	0.003
	TNO	2016.31	0.003
	TU Delft	1553.40	0.003
	Cleantech Region	1432.98	0.003
	Gasunie	1233.13	0.003
	Hygro	1192.28	0.003
	Nedstack	503.53	0.003
	New Energy Coalition	1084.70	0.003
	Enexis	998.97	0.002
	European Fund	975.37	0.002
	HyMatters	842.62	0.002
	Vermeulen Groep	0	0.500
	Delphy	0	0.500
	Nettenergy	0	0.500
	Brightlands	0	0.500
	Groene Chemie Nieuwe Economie (GCNE)	0	0.500
	Torrgas	0	0.500
	Evonik	0	0.166
	E.ON, Innogy SE	0	0.166
	Hynetwork Services	0	0.166
	RWE	0	0.166
	OCI N.V.	0	0.166
	Linde	631.54	0.002
	Province of Groningen	0	0.166

clustering coefficient in the decentralized network indicates even stronger clustering, with stakeholders forming tight-knit groups. While this can promote trust and effective collaboration within clusters, it also underscores the importance of maintaining strong inter-cluster connections to prevent fragmentation. The smaller network diameter means that information and resources can traverse the network more quickly, potentially improving operational efficiency and responsiveness. The decentralized network's structure may therefore be more effective in facilitating strategic integration, provided that clusters remain interconnected.

5. Discussion

Integrating hydrogen into the energy system involves complex challenges that extend beyond technical considerations, deeply entwined with the social dynamics among stakeholders. This study examined how these dynamics influence the strategic planning and deployment of hydrogen infrastructure in the Netherlands, revealing critical insights into stakeholder roles, information and resource flows, and the structural differences between centralized and decentralized networks. Understanding these aspects is crucial for devising strategies that enhance collaboration, innovation, and efficient resource utilization in the hydrogen sector.

The predominance of hydrogen projects in preliminary phases, such as feasibility studies and conceptual development, reflects a sector navigating foundational uncertainties. This cautious progression aligns with previous literature highlighting technological and institutional challenges in hydrogen adoption. Stakeholders exhibit hesitancy to commit substantial investments without clear regulatory frameworks and guaranteed returns, emphasizing the necessity for supportive policies and financial incentives to mitigate risks. This situation underscores the critical role of government intervention in providing a stable policy environment that encourages investment and facilitates the transition from planning to operational stages.

The SNA highlights clear differences in structure and relationships within the Netherlands' centralized and decentralized hydrogen networks, each offering distinct benefits and facing unique challenges. Understanding these dynamics is essential for stakeholders planning and implementing hydrogen infrastructure effectively.

In the centralized network, the concentration of influence among a few key stakeholders, such as Gasunie, ENGIE, and Air Liquide, indicates a hierarchical structure. This centralization facilitates decision-making and resource allocation due to clear leadership and established communication channels. However, it also introduces potential vulnerabilities. The monopolization of influence can lead to decision-making that prioritizes the interests of dominant stakeholders, possibly at the expense of smaller entities or broader societal goals. This also aligns with concerns highlighted in the literature about the potential overshadowing of innovation in low-carbon technologies due to the predominance of established industry players situated near major industrial centers, who focus on large-scale hydrogen production and distribution.

Additionally, reliance on key intermediaries increases the risk of bottlenecks. If these stakeholders face capacity constraints, strategic misalignments, or disruptions—such as financial difficulties or policy changes—the efficiency of the entire network could be compromised. Smaller stakeholders may feel disenfranchised, leading to decreased motivation to participate or contribute ideas, potentially stifling grassroots innovation and reducing the network's adaptability to emerging trends or technologies.

Interviews highlight a significant risk associated with heavy reliance on Gasunie. Delays in pipeline development and reliance on Gasunie as the central network operator could obstruct the integration of the system into both the energy network and market. Additionally, the absence of a clearly defined role for the DSO might cause further setbacks. This issue is especially critical for "Cluster Six," which includes regional industries and business parks slated for connection to Gasunie's "Hydrogen Backbone." Such centralized planning could overlook the needs of local stakeholders, limiting their engagement in the hydrogen economy and restricting broader economic integration.

In contrast, the decentralized network features a more distributed influence with multiple stakeholders like TU Delft, TNO, Liander, and Cleantech Region playing critical roles. This model encourages a multiplicity of viewpoints, thanks to the involvement of academic institutions, research organizations, regional groups, and private companies, all contributing to a vibrant exchange of ideas. Such diversity drives creativity, enhances problem-solving capabilities, and leads to the development of innovative solutions that are well-suited to local demands. These stakeholders actively contribute to innovation and knowledge transfer, crucial for addressing the technical challenges associated with hydrogen technologies. Their engagement leads to the creation of solutions customized to meet local requirements concerning storage, transportation, safety, and standardization.

Nonetheless, the absence of major industrial stakeholders with significant resources could impede the practical implementation and

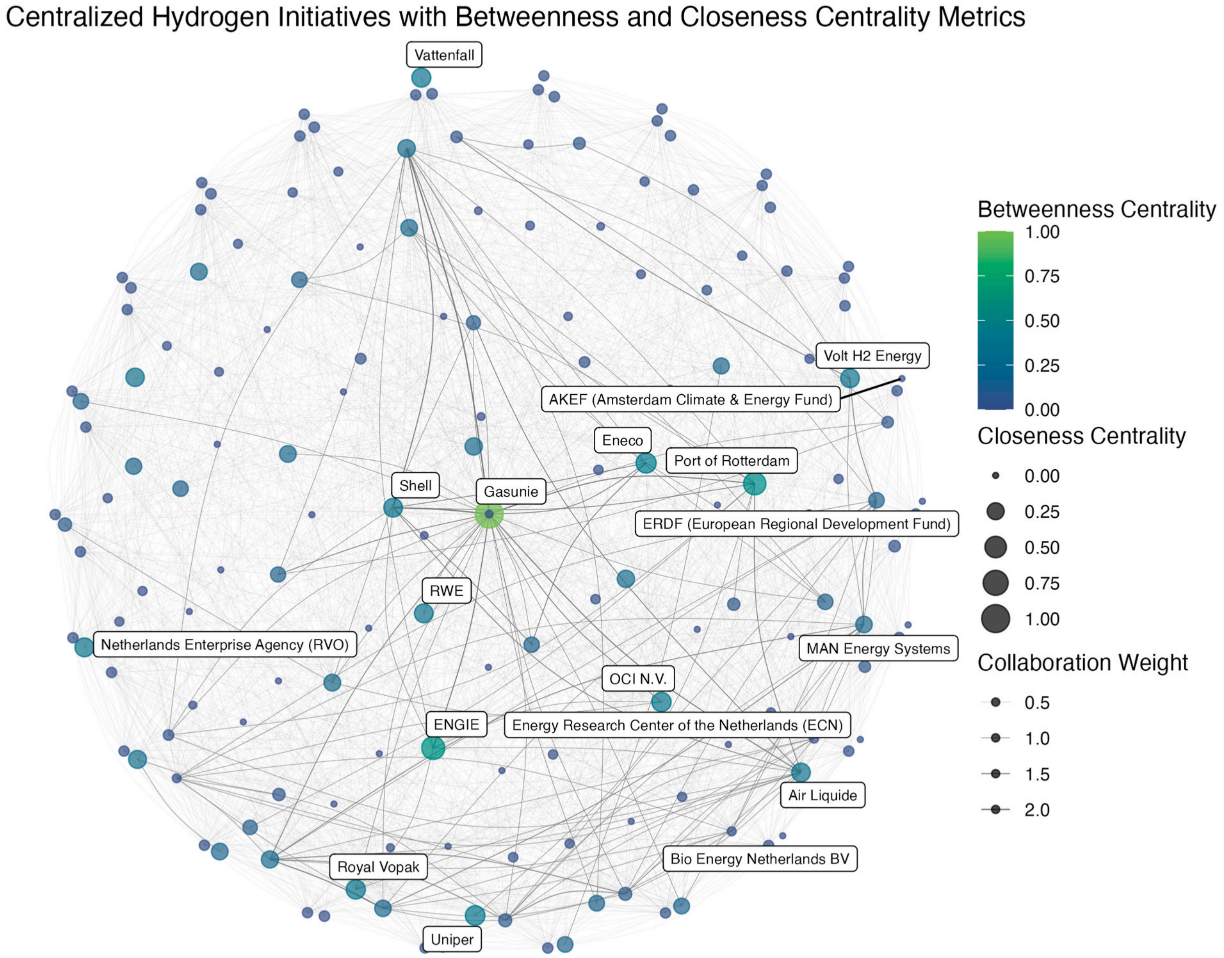


Fig. 4. Graph visualization of centralized hydrogen initiatives with betweenness and closeness centrality metrics.

scaling of these innovations, highlighting a persistent gap between research breakthroughs and their commercial application—a point frequently raised in interviews. Furthermore, the network's resilience and adaptability are strengthened by the broad distribution of influence among various stakeholders, reducing the risk of disruption from any single source. This distributed structure also allows for more agile reactions to changes, such as new technological developments or shifts in policy. Additionally, the extensive participation of diverse stakeholders fosters a deeper commitment to common objectives, enhancing ongoing efforts to strategically integrate hydrogen infrastructure. Effective coordination mechanisms are vital to synchronize these efforts and increase operational efficiency. Interviews with stakeholders underscore the necessity for clear and formal communication protocols to facilitate the timely exchange of crucial information, minimize redundant efforts, and prevent misalignment of activities.

The centralized network's moderate density and larger diameter suggest that while clusters of stakeholders are well-connected internally, the overall connectivity across the network is less optimal. High clustering within subgroups can lead to communication silos, where tight-knit clusters focus on internal collaboration with limited interaction with other groups. This can hinder the sharing of knowledge and best practices across the network, reducing overall innovation potential. Additionally, with a network diameter of five, information or resources may take longer to reach distant stakeholders, potentially slowing the adoption of new technologies or processes and impacting the network's operational efficiency.

In contrast, the decentralized network, with a higher average degree and smaller diameter, facilitates more efficient information flow. The smaller diameter means that stakeholders are more closely connected, allowing innovations, insights, and resources to spread quickly throughout the network. Despite high clustering coefficients, the presence of multiple intermediaries enhances inter-cluster connections, promoting the cross-pollination of ideas and collaborative efforts that transcend individual clusters. The dense interconnections enable stakeholders to identify complementary capabilities and resources, fostering synergistic partnerships that can accelerate project development and implementation.

These findings have significant practical and policy implications. The development of hydrogen networks, both centralized and decentralized, presents unique challenges and opportunities that are pivotal for the broad adoption and innovation of hydrogen technology. Effective management strategies, regulatory frameworks, and collaborative efforts are critical to leveraging their strengths and mitigating inherent risks.

Centralized hydrogen networks provide the necessary scale for widespread adoption of hydrogen technologies, but they also pose risks of over-centralization and potential monopolistic tendencies. To mitigate these risks, it is essential to diversify connectivity roles by empowering additional stakeholders. Developing policies that encourage broader participation, reduce barriers for smaller entities, and promote fair competition is crucial. Regulatory frameworks should focus on ensuring transparency and inclusivity in decision-making processes. Additionally, fostering partnerships between established industry players and emerging innovators can create a dynamic and resilient network structure, supporting both innovation and large-scale implementation.

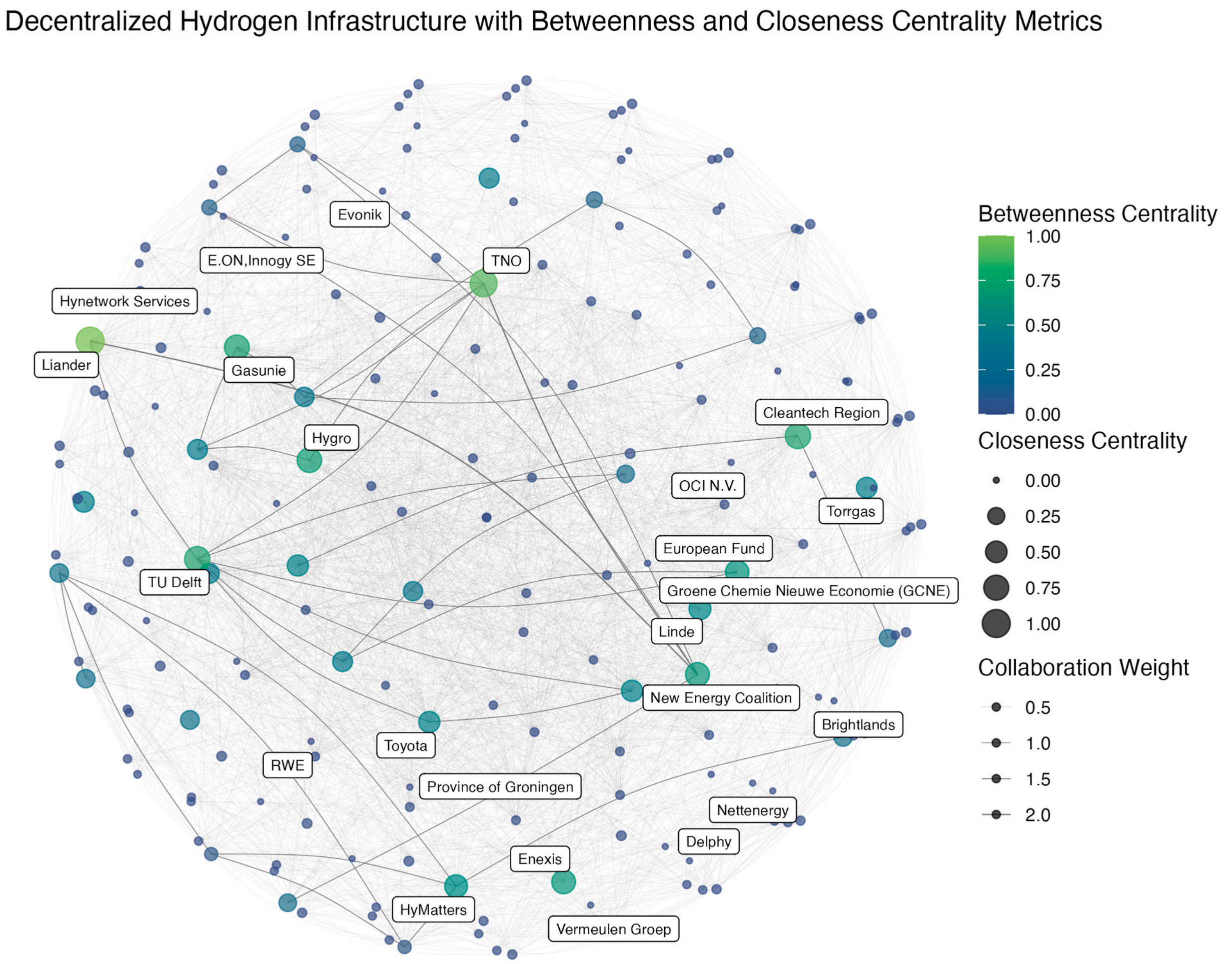


Fig. 5. Graph visualization of decentralized local hydrogen initiatives with betweenness and closeness centrality metrics.

Table 4
Network metrics.

Interactions	Centralized Hydrogen Initiatives	Decentralized Local Hydrogen Initiatives
Number of Relational Ties	1769	2668
Network Density	0.13	0.12
Average Degree	21.83	25.53
Network Diameter	5	4
Average Clustering Coefficient	0.88	0.92

Conversely, decentralized networks cater to localized needs and encourage innovation but face challenges related to coordination and scalability. Establishing effective coordination mechanisms is crucial to manage complexity and enhance scalability. Developing shared platforms, standardizing communication protocols, and implementing collaborative governance models can align stakeholder efforts and prevent fragmentation. Partnerships with established industry players are essential for integrating innovative solutions into large-scale projects and bridging the gap between research and practical implementation. The coexistence of both network types can lead to inefficiency and fragmentation without strategic efforts to integrate them. To overcome these challenges, establishing platforms or councils that unite stakeholders from each network type can improve coordination and facilitate knowledge exchange. Initiatives that combine elements of both centralized and decentralized systems, such as regional hubs linking local projects to national infrastructure, can enhance synergy. Establishing knowledge-sharing programs between large corporations and smaller entities can also promote mutual learning and innovation diffusion.

6. Conclusion

The successful deployment of hydrogen infrastructure depends not only on technological advancements but also on the ability to manage and optimize the complex social networks that underpin the sector. Continued research and attention to stakeholder dynamics will be pivotal in shaping the future of hydrogen as a key component of a sustainable energy landscape. Addressing the challenges identified in both centralized and decentralized networks can lead to more resilient, innovative, and inclusive approaches to hydrogen integration, ultimately contributing to the broader goals of energy transition and environmental sustainability. The findings provide critical insights for regions interested in integrating hydrogen technologies into their energy frameworks, emphasizing the need for stakeholder coordination to navigate technical, operational, and regulatory hurdles. Encouraging decentralized collaboration and cross-sector engagement can expedite hydrogen adoption, aiding in greenhouse gas reduction, energy security, and achieving climate goals.

Despite the aim for rigorous design for the research approach, several limitations exist that impact outcomes. Reliance on publicly available data may not capture all stakeholder interactions or the depth of relationships within the hydrogen sector in the Netherlands. Informal collaborations, emerging partnerships, and undocumented exchanges are likely underrepresented, potentially leading to an incomplete understanding of network dynamics. The static nature of the SNA presents a constraint, providing a snapshot of the network at a specific point in time without accounting for the dynamic and evolving relationships among stakeholders. Focusing exclusively on the Netherlands limits the generalizability of the findings, as the country's unique regulatory environment, market structure, and cultural context may not reflect conditions elsewhere.

To address these limitations, future research should incorporate longitudinal studies that track the evolution of stakeholder networks over time, providing a dynamic view of changing social dynamics in the hydrogen sector. Integrating qualitative methods such as interviews, focus groups, and case studies can enrich the analysis by capturing nuanced motivations, informal relationships, and barriers to collaboration. Expanding the scope of research to include comparative analyses across different countries or regions would enhance the generalizability of the findings, allowing for the identification of universal patterns and context-specific factors influencing strategic planning and deployment of hydrogen infrastructure.

CRediT authorship contribution statement

Mahshid Hasankhani: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Renske van 't Veer:** Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Sine Celik:** Methodology, Validation, Writing – review & editing. **Amineh Ghorbani:** Methodology, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Jan Carel Diehl:** Methodology, Validation, Writing – review & editing. **Jo van Engelen:** Methodology, Validation, Formal analysis, Supervision, Writing – review & editing.

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Declaration of competing interest

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Appendices.

Extended details regarding data gathering and analysis are provided.

Appendix A: Validation of Project Overview and Stakeholder Categories

This project overview has been validated through various sources, as depicted in Table 5 [40,68,69].

Table 5
Overview of Validated Projects

Project Group	Project Number	Project Name	Date	Status	Technology	Product
I	1	NortH2	2030–2040	Feasibility study + Concept	Other Electrolysis	H2
	2	Hystock (EnergyStock)	2021	Operational	PEM	H2
	3	HyNetherlands	2024–2028	Feasibility study	Other Electrolysis	H2
	4	H2-Fifty		Feasibility study	Other Electrolysis	H2
	5	E-Thor		Feasibility study	Other Electrolysis	MeOH
	6	Multiphly	2023	Operational	SOEC	H2
	7	PosHYdon	2024	Feasibility study	PEM	H2
	8	Holland Hydrogen	2025–2027	FID/Construction + Feasibility study	ALK	H2
	9	H-Vision	2027–2030	Feasibility study	NG w CCUS	H2
	10	GZI Next	2024	Feasibility study	PEM	H2
	11	DJEWELS Chemiepark	2026–2030	Feasibility study	ALK	Various + Synfuels + MeOH
	12	H2ermes	2025	Feasibility study	Other Electrolysis	H2
	13	Porthos CCS	2005–2024	Feasibility study-Operational	Oil w CCUS	H2
	14	Bio Energy Netherlands		Feasibility study	Biomass	H2
	15	H2-gateway	2027	Feasibility study	NG w CCUS + Other	H2
	16	Curthyl	2026	Feasibility study	Other Electrolysis	H2
	17	Deltaurus	20240–2027	Feasibility study	Other Electrolysis	H2
	18	Vlissingen - VoltH2	2025–2030	Feasibility study	Other Electrolysis	H2
	19	Terneuzen - VoltH2	2025–2030	Concept-Feasibility study	Other Electrolysis	H2
	20	Delfzijl-VoltH2	2026	Feasibility study	Other Electrolysis	H2
	21	Uniper Maasvlakte	2026–2030	Feasibility study	PEM + Other Electrolysis	H2
	22	Synkero synfuels project	2027	Feasibility study	Other Electrolysis	Synfuels
	23	SeaH2Land	2030	Feasibility study	Other Electrolysis	H2
	24	North Sea Wind Power Hub	2032	Concept	Other Electrolysis	H2
	25	Energiepark Eemshaven West	2024–2027	Feasibility study	Other Electrolysis	H2
	26	ELYgator	2026	Feasibility study	Other Electrolysis	H2

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Table 5 (*continued*)

Project Group	Project Number	Project Name	Date	Status	Technology	Product
	27	Zeeland Refinery CCS, H2ero	2026	Feasibility study	Other Electrolysis + NG w CCUS	H2
	28	FUREC	2025	Feasibility study	Biomass	H2
	29	H2opZee	2031	Concept	Other Electrolysis	H2
	30	AMpHytrite demonstrator	2024	DEMO	PEM	H2
	31	H2era	2027	Feasibility study	Other Electrolysis	H2
	32	MoU Shell - Mitsubishi	2030–2043	Concept	Other Electrolysis	Ammonia
	33	Ineratec Port of Amsterdam	2027	Concept	Other Electrolysis	Synfuels
	34	Yara Sluiskil fertiliser	2026	Feasibility study	NG w CCUS	Ammonia
	35	Lhyfe Delfzijl	2026	Feasibility study	Other Electrolysis	H2
	36	Onyx plant	2028	Feasibility study	NG w CCUS	H2
	37	Floating Green Hydrogen & Ammonia project	2027	Concept	Other Electrolysis	Ammonia
	38	Hydrogen 2 Magnum (H2M)	2027	Feasibility study	NG w CCUS	H2
	39	Zenid Initiative		Concept	Other Electrolysis	Synfuels
	40	Hemweg hub Amsterdam - Hy4Am	2026	Feasibility study	Other Electrolysis	H2
II	41	H2GO Energy Park Oude-Tonge,H2Agro, H2ARVESTER	2023-2025-2030	DEMO, Feasibility study, FID/Construction/Concept	Other Electrolysis	H2
	42	Rozenburg Power2Gas,DNV Kema/DNV GL	2011-2013-2019	DEMO + Operational	PEM	CH4+ H2
	43	Hydrogen Plant for Westereems Wind Farm (RWE Eemshydrogen)	2026	Feasibility study	PEM	H2
	44	GreenH2UB	2024–2030	Feasibility study	PEM + Other Electrolysis	H2
	45	HyFLEET:CUTE, Amsterdam	2003–2009	DEMO	ALK	H2
	46	Ameland	2008–2011	DEMO	PEM	H2
	47	GldH2	2023	FID/Construction	Other Electrolysis	H2
	48	GROHW	2023	Operational	Other Electrolysis	H2
	49	Enowatts-Energy Demo Field-P2P IPKW		Feasibility study	Other Electrolysis	H2
	50	H2-based residential area in Van der Veen		FID/Construction	Other Electrolysis	H2
	51	Alliander Oosterwolde - solar park of GroenLeven-Sinnewetterstof-Hydrogenpilot Oosterwolde	2022	Operational	ALK + Other Electrolysis	H2
	52	Duwaal, Hydrogen Wind Turbine	2023–2024	Feasibility study + FID/Construction	PEM + Other Electrolysis	H2
	53	Hysolar Green on Road	2022	Operational	Other Electrolysis	H2
	54	Cyrus Smith		DEMO	Other Electrolysis	H2
	55	GH2	2023	DEMO	Biomass	H2
	56	BrigH2	2025	Feasibility study	Biomass	H2
	57	WAviatER	2023	DEMO	Other Electrolysis	H2
	58	Hynoca Alkmaar	2023	DEMO	Biomass	H2
	59	H2UB Laren	2025	Feasibility study	Biomass	H2
	60	Cleanup Gas		DEMO	Biomass	H2
	61	H2Stroom		Feasibility study	Other Electrolysis	H2

The overview of stakeholders' categories has been adopted from previous studies, as depicted in Table 6 [7,9,11].

Table 6
A Holistic View of the Stakeholders' Categories Across the Value Chain

Stakeholder Categories	Stakeholder Name
Primary Producers and Suppliers	Petrochemical Industries Chemical Industries Energy Utilities (Gas, Power) Renewable Energy Provider Oil and Gas Suppliers
Technology and Service Providers	Hydrogen Technology Providers Public and Private Research and Development Institutions Equipment and Component Manufacturers Engineering, and Technical Service Providers Startups and Small Enterprises (SMEs) Information and Communications Technology (ICT) and Automation providers
Infrastructure Providers for Storage and Distribution	Power and Gas Network Operators Supply Chain Logistics Storage Providers (material based, physical) Seaport Authorities Transportation Companies Hydrogen Infrastructure Accelerators (HIA) Construction Companies Housing Associations, Project Developers Energy Aggregators (Energy Hub Operators Fuel Station Operators (Mobile, Stationary) Regional fuel suppliers Hydrogen Retailers

(continued on next page)

Table 6 (*continued*)

Stakeholder Categories	Stakeholder Name
	Energy Retailers
End-Use	Mobility sector Petroleum Refining Industries (Steel, cement, glass, industrial gas) Semiconductor Pharmaceutical Industry Agriculture Food Industry Water Treatment Waste Management Built Environment Energy Cooperatives Private Consumers
Intermediaries	Industry Associations Consultancy and advisory firms Safety and Regulatory Service Providers Certification Organizations for Hydrogen Facilities Environmental and Resource Management Water Management Partnership Initiatives Banks and Financial Institutions Institutional Investors (Pension Funds, Insurance Companies, etc Legal Firms Social Impact and Advocacy, NGOs
Policy and Regulatory Authorities	Policy Makers, Regulators, and Government on Different Scales
Research and Education	Research and development, Training and Skills Development

Appendix B: Overview of Interview: Questions Themes and Examples

In compliance with ethical standards, interviews were conducted with participants listed Table 7, with strict adherence to anonymity and informed consent. Objectives for each interview were clearly established in advance. Furthermore, the questions, themes, and examples detailed in Table 8, were explored during the interviews.

Table 7
Overview of Interviews

Interview Number	Interview Duration	Interview Type	Role	Organization
1	61′	Individual	Member of the Strategy Department	Gasunie
2	65′	Individual	Program Manager of GroenvermogenNL	GroenvermogenNL
3	63′	Individual	Innovation Manager Hydrogen	TU Delft Innovation Hub for Hydrogen
4	64′	Individual	System and Infrastructure Commission	NLHydrogen
5	63′	Individual	Senior Business Developer	InnovationQuarter

Table 8
Overview of Questions Themes and Examples

Questions Themes	Examples of Questions	Emerged Themes
Interaction Analysis	Which stakeholders are frequently communicating with each other within the network? Are there any stakeholders who are isolated or not communicating with others? If so, who are they? What topics or issues are most commonly discussed among stakeholders? Is there a recognizable pattern in the interaction frequencies among specific groups of stakeholders?	Frequent communication between industrial energy producers and network operators, often centered on infrastructure and technology projects or new technologies. Smaller companies and regional operators often report feeling isolated due to a lack of access to major networks and decision-making forums. Topics frequently discussed include project development, regulatory compliance, technology deployment, and sustainability practices. Higher frequency of communication is observed among stakeholders with aligned interests, especially in collaborative projects.
Collaboration Analysis	Who are the primary and potential stakeholders in collaborative projects? What types of collaborations are predominant, and what forms do they take? How are collaborative endeavors initiated, and what sustains them? What are the main obstacles to effective collaboration within the network?	Major industrial companies, technology providers, and research institutions dominate collaborations, often overlooking smaller startups. Common collaborations include joint technology development, shared research facilities, and co-authored publications. Collaborations are often initiated at industry conferences or via direct outreach by established stakeholders, sustained through formal agreements and regular interaction Challenges include goal misalignment, uneven cost and benefit distribution, regulatory challenges, and IP concerns.
Resource Distribution Analysis	Which stakeholders are key resource providers, and what resources are most commonly shared?	Large companies and research institutions provide resources like funding, data, and access to technology.

(*continued on next page*)

Table 8 (*continued*)

Questions Themes	Examples of Questions	Emerged Themes
	Where are there gaps in resource provision within the network, and what resources are most needed?	Smaller entities need more support in engaging in large projects, training programs, and access to market and technological insights.
	How are decisions regarding resource distribution made, and who decides?	Resource support decisions are often based on strategic alignment with organizational goals, potential impact, and through competitive bids.
	What mechanisms are established for resource requests and distribution, and are there notable success stories?	Mechanisms include formal grant applications, partnership agreements, and internal allocations for collaborative projects.

Data availability

Data will be made available on request.

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