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Emerging decentralized infrastructure networks

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Decentralized hydrogen infrastructure networks have emerged as a complementary element in the quest for sustainable energy solutions, with potential applications in regions featuring high industrial demands and spatially resolved negative residual loads. These infrastructures can contribute to the decarbonization of electricity, heating, and transport sectors while enhancing local renewable energy consumption and supporting energy storage and demand-side management. However, their development presents unique design challenges, calling for a comprehensive understanding of stakeholder roles and relationships in the evolving ecosystem. This study examines stakeholder network dynamics within the distributed hydrogen ecosystem, focusing on the Netherlands' built environments. Through the analysis of 16 case studies, we employ Social Network Analysis (SNA) to identify and analyse the stakeholder network involved in the early design and implementation of decentralized hydrogen infrastructure networks. Our findings highlight emerging roles and relationships due to the rise of such infrastructures, emphasizing the need for adaptable stakeholder relations. The paper explores stakeholder categories, providing insights into their interactions and coordination strategies. In this vein, it offers valuable guidance to practitioners and policymakers, promoting stakeholder collaboration for successful decentralized hydrogen infrastructure networks deployment in pursuit of a sustainable, low-carbon energy future.

Keywords: decentralized hydrogen infrastructure network; stakeholder network analysis; social network analysis; participatory design

1 Introduction

Transitioning to renewable energy systems presents a multitude of hurdles including varying supply, security concerns, and escalating costs (Borne et al., 2018; Holttinen et al., 2013; B. P. Koirala et al., 2016). A promising solution to these issues lies in the adoption of hybrid energy systems. These systems, which combine multiple infrastructures, energy carriers, and storage solutions, are becoming particularly focused on integration of hydrogen due to its role as both an energy carrier and storage medium (Haghi et al., 2018; B. Koirala et al., 2021).

Hydrogen’s potential lies in its ability to be produced from a variety of renewable sources, and its ease of transport and storage (Momirlan & Veziroglu, 2005). Consequently, it is gaining prominence in Europe's pursuit of a carbon-neutral future by 2050 and the Netherlands, in particular, is leading the way in establishing a national hydrogen pipeline network (Gasunie, 2022; Stiller et al., 2008). This pipeline is projected to connect hydrogen producers and consumers, decarbonize industrial sectors, and lay the groundwork for decentralized energy hubs in regions featuring high industrial demands and spatially resolved negative residual loads (Klimaat, 2020; Topsector Energy, 2022a).

The increasing interest in hydrogen technology and its varied applications, such as Power-to-Power (PtP), hydrogen refueling, Stationary Fuel Cells (SFC), and Power-to-Gas (PtG), despite certain hurdles like the high costs and complexity associated with PtP, is evident (dos Santos et al., 2021; Parra et al., 2017) .The development of decentralized hydrogen infrastructure networks for these applications is needed to offer an alternative to the dependency on primary grids, reducing wait times associated with centralized transmission systems as well as minimizing financial and security risks inherent in these projects.

However, incorporating decentralized hydrogen infrastructure networks into the energy network necessitates significant cooperation among a diverse group of stakeholders. Early stages of implementation, characterized by high initial costs and uncertain returns, make the harmonization of supply, demand, and infrastructure dynamics especially critical (Odenweller et al., 2022). The complexity of such projects, spanning numerous technical elements and stakeholder interactions, introduces uncertainties about roles, responsibilities, and coordination.

However, incorporating decentralized hydrogen infrastructure networks into the energy network necessitates significant collaboration among a diverse group of stakeholders in the early stages of development. This process is often characterized by high initial costs and uncertain returns (Odenweller et al., 2022) and requires careful management to balance supply, demand, and infrastructure. Thus this wide-ranging complexity can lead to uncertainties about individual roles, responsibilities, and the coordination required between parties.

Traditional linear models of technological progression struggle to address the complexities associated with early project stages, such as uncertainties and conflicting interests. To manage potential conflicts, intricate interdependencies, and unpredictable outcomes resulting from multiple stakeholders, a more dynamic and nuanced approach is necessary (van de Kerkhof et al., 2009). One effective way to tackle these complexities is by employing a participatory design process (Reed et al., 2009). In this approach, stakeholders actively contribute to the project design, fostering alignment, inclusivity, and a shared vision, which are key to successful infrastructure development.

Here, the initial crucial step is a thorough stakeholder network analysis, identifying stakeholders, roles, and influence. This not only clarifies the project's ecosystem but also enables early detection of potential challenges and opportunities. In this vein, active stakeholder engagement assists in pinpointing areas of collaboration and voids, hence improving problem-solving, decision-making, and the development of project-specific interventions (Vezzoli et al., 2014).

Despite its importance, early-stage comprehensive studies on stakeholder network analysis in hydrogen infrastructure development in a systematic way are scarce. This study fills that gap by investigating stakeholder roles in the Dutch distributed hydrogen infrastructure network. We use a literature review, policy document analysis, and Social Network Analysis (SNA) to analyse relationships.

Our study findings underscore the role of different stakeholder groups in the development of hydrogen decentralized infrastructure networks. This includes entities involved in transmission and distribution, technology providers, energy companies, aggregators, end-users, and support entities. Understanding their individual influence and interests is vital, as it guides the formulation of tailored strategies that meet distinct requirements or preferences, promoting collaboration, and reducing potential disputes. Nevertheless, stakeholder relationships are dynamic and to untangle this intricate web of diverse interests, potential conflicts, and synergies, additional qualitative research is indispensable. Such in-depth investigations will provide valuable insights for more effective project planning and policy decisions.

The rest of the study is structured as follows: Section 2, details the data collection and analysis processes. The results are presented in Section 3 and then explored and interpreted in the discussion in Section 4. The study concludes in Section 5, where a summary of the findings is provided, limitations are discussed, and recommendations for future research are suggested.

2 Material and methods

2.1 Method of data collection

In this study, we use an explorative approach to gain insights into the hydrogen decentralized infrastructure networks with a focus on the initiation and implementation involving private-public collaboration in the built environment. This approach is executed by utilizing a hydrogen project database to identify and categorise relevant stakeholders involved in 16 hydrogen-related pilot projects in Table 1. To ensure the reliability and validity of the data, information is sourced from credible and verifiable sources such as International Energy Agency (IEA) project databases (IEA, 2022), official announcements, and websites (Topsector Energy, 2022a).

Table 1. Overview of considered hydrogen projects in the built environment.

Numbers	Projects	Location	Application	Start Date
1	Autonomous Hydrogen Heating System	-	Hydrogen powered Home Heating Systems	2019
2	Hydrogen Eeserwold	Steenwijk-Overijssel	Business Park with a Hydrogen Energy Hub	2020
3	Hydrogen District Wagenborgen	Wagenborgen-Groningen	Local Hydrogen Network	2021
4	H2@Home, Research of In-house Installations with Hydrogen	Green Village-South Holland	In-house installations with hydrogen	2020
5	The Green Whale	Graft-De Rijp,North Holland	Converting Existing Grid to a Local Produced Hydrogen Grid	2020

6	InnovaHub /District (Hylife Innovation)	-	A Sustainable Power Station for the Built Environment in GO	2021
7	H₂ydroGEM-BOILER(Hylife Innovation)	-	A Hydrogen Boiler without Incineration and Electricity for Homes	2021
8	H2H nu	Wageningen-Gelderland	Application of Hydrogen as an Energy Carrier in Wageningen	2022
9	Retrofit Hydrogen Condensed Boiler	-	Retrofit Hydrogen Condensed Boiler	2020
10	Power to Gas (P2G) Phase2	Rozenburg-South Holland	Power to Hydrogen for Residential Heating of Apartments in Rozenburg	2018
11	Hydrogen Church	Arnhem-Gelderland	Heating the Monumental Eusebius Church with Hydrogen	2019
12	Hydrogen Neighbourhood Hoogeveen	Hoogeveen-Drenthe	100 Newly Built Houses and 430 Existing Houses Connected to Hydrogen	2020
13	Hydrogen City	Stad aan 't Haringvliet-South Holland	Stad aan 't Haringvliet Switching to Green Hydrogen	2017
14	Hydrogen Neighbourhood	Lochem-Gelderland	Pilot Heating with Hydrogen in Neighbourhood	2020
15	Green Village	Green Village-South Holland	Research into Possibilities for Reusing the Natural Gas Grid	2020
16	Hydrogen Hospital	Elst-Gelderland	Development of a Sustainable Hydrogen Smart Grid in Elst	2021

2.2 Networked stakeholder analysis

The stakeholder network analysis unfolds in two stages. The initial stage identifies the key stakeholder groups within the hydrogen sector by collating data from a variety of sources, inclusive of hydrogen ecosystem literature (Decourt, 2019; Eames & McDowall, 2010; Enevoldsen et al., 2014; Murray et al., 2008; Peter Andreasen & Sovacool, 2014; Schlund et al., 2022; Schmidt & Donsbach, 2016), and policy documents (European Commission, 2020; Klimaat, 2020). The purpose of this stage is to discern the network of stakeholders engaged.

The second phase examines stakeholder relationships using Social Network Analysis (SNA) in the context of the Netherlands, through the utilization of hydrogen project databases (IEA, 2022; Topsector Energy, 2022b). For network visualization, we use Gephi software and Force Atlas 2 algorithms, thereby providing a contextual comprehension of stakeholders, their roles, and their interactions within the decentralized hydrogen network infrastructure. This stage offers valuable insights at both the individual stakeholder and overall ecosystem level (Borgatti et al., 2009; Vezzoli et al., 2015).

The SNA offers a comprehensive framework for understanding the intricacies of social networks, which are multi-layered and context-dependent, with variable stakeholder relationships. Within specific hydrogen projects, SNA enables the creation of a social network where stakeholders are represented as nodes. Each node is assigned a label denoting the stakeholder's primary activities, facilitating their categorization into appropriate stakeholder groups (Lienert et al., 2013; Otte & Rousseau, 2002; Zedan & Miller, 2017). The study utilizes several statistical network measures including Eigenvector Centrality, Betweenness Centrality, and Degree Centrality metrics (Monge et al., 2003) to evaluate stakeholder influence within the decentralized hydrogen infrastructure networks.

- Eigenvector Centrality determines the stakeholder's influence based on their connections with other influential stakeholders. This crucial metric identifies pivotal stakeholders who can significantly impact decision-making and the adoption of hydrogen infrastructure networks and technologies.
- Betweenness Centrality gauges the stakeholder's role as a connector or mediator among other stakeholders in the network. High betweenness centrality stakeholders are essential for promoting effective communication and collaboration within the distributed hydrogen infrastructure network.
- Degree Centrality measures a stakeholder's direct connections within the network, accentuating stakeholders with extensive connectivity who can expedite information dissemination or influence others.

By considering these different measures together, the study can provide a multi-faceted view of the roles and influences of various stakeholders. This can help in identifying potential areas of cooperation, understanding where the influence lies, and foreseeing potential challenges in the network, such as stakeholders who might be bottlenecks or points of contention. Additionally, understanding these dynamics can inform strategies for engaging stakeholders and guiding the development of the hydrogen infrastructure network.

3 Results

In the stakeholder network analysis using SNA for hydrogen projects in the Netherlands, 110 stakeholders were identified based on their network relationships, as depicted in Figure 1. Each stakeholder functioned as a node, and their connections were represented as edges.

We identified five key stakeholder groups from a total of 110 entities. Network operators, crucial in ensuring efficient hydrogen transportation, navigate the complex landscape of a decentralized infrastructure that spans from local microgrids to national networks. In parallel, technology and infrastructure providers, both domestic and international, create the hydrogen ecosystem's foundation by supplying advanced technologies and solutions that promote a greener urban landscape. Energy and utility companies, partnered with aggregators, harness the potential of hydrogen as a renewable energy source. They transform energy from wind farms and solar installations into hydrogen while aggregators ensure a stable power supply by integrating various energy sources. End-users, ranging from households to businesses, form the demand segment, using hydrogen in diverse capacities, while supporting entities, including government bodies, research institutions, and consultants, guide the growth and evolution of the hydrogen ecosystem. Together, these entities contribute to the successful operation of the Dutch decentralized hydrogen infrastructure, embodying a transition towards sustainable energy use. The study calculated three centrality metrics: Eigenvector Centrality, Betweenness Centrality, and Degree Centrality to quantify the influence and importance of these stakeholder groups within a network. The top five nodes for each metric exposed the most central or influential stakeholders in the network, based on different criteria.

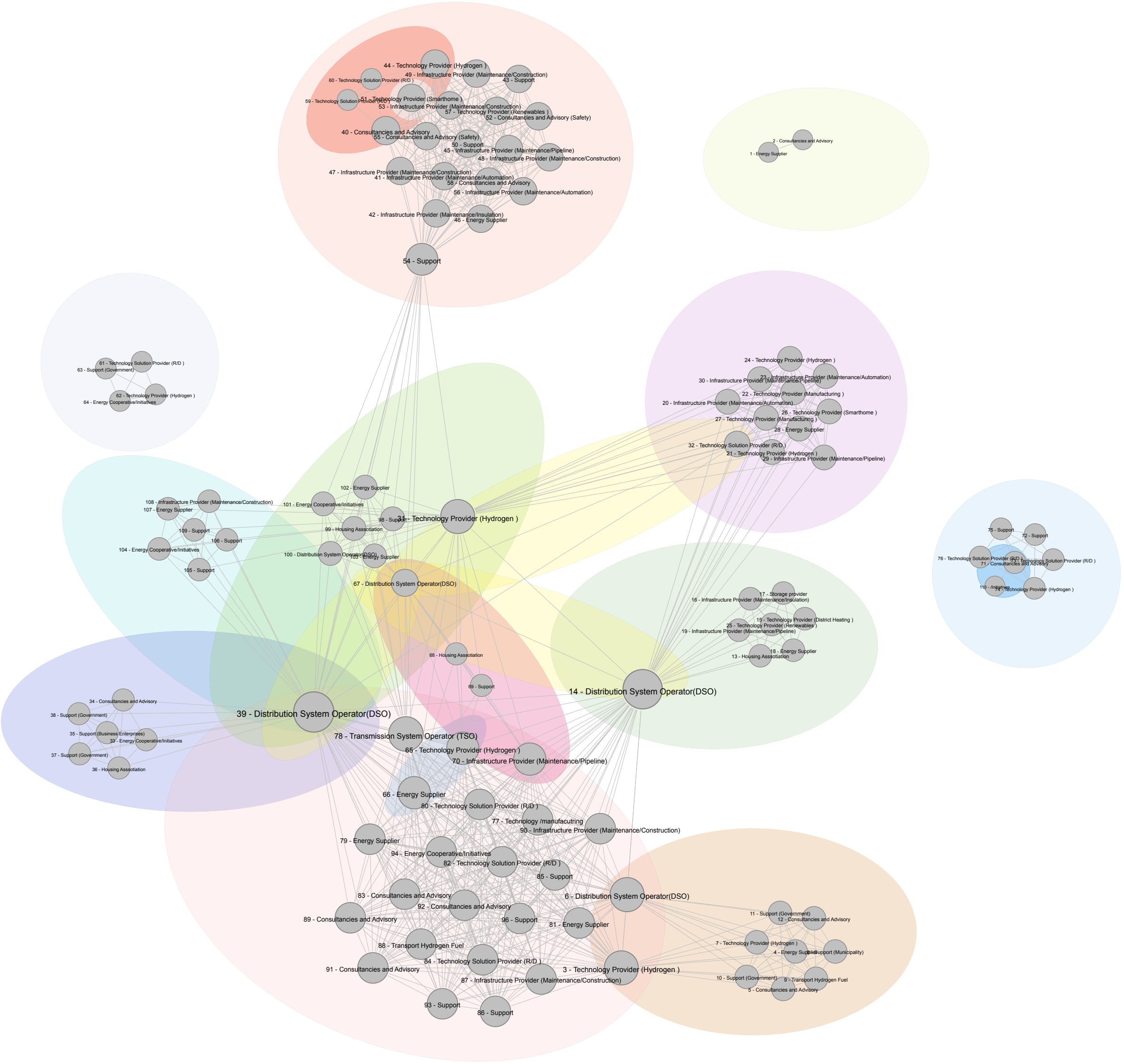

Figure 1. Network of relationship 16 highlighted projects in the built environment

Key findings from the analysis include:

- Eigenvector Centrality: This measure reveals in Figure 2-Table 2 the most influential stakeholders in the network by considering both the quantity and quality of their connections. The top influencers are found to be two Distribution System Operators (DSOs) (nodes 39 and 14), a Transmission System Operator (TSO) (node 78), an infrastructure provider (Maintenance/Pipeline) (node 70), and a hydrogen energy supplier (node 66), with DSO (node 39) as the most influential.

- Betweenness Centrality: This metric identifies in Figure 3-Table 3 those who act as 'bridges' between different parts of the network. The stakeholders playing this role include GoereeOverflakkee local government and coalition support (node 54), DSO (nodes 39 and 14), a hydrogen technology provider (node 31), and TSO (node 78). Node 54, GoereeOverflakkee local government, acts as the most significant connector.
- Degree Centrality: This measure in Figure 4-Table 4 identifies nodes with the most direct connections. It reveals that DSO (nodes 39 and 14), TSO (node 78), and hydrogen technology providers (nodes 3 and 31) are the most connected stakeholders, with DSO (node 39) having the most connections.
- Comparing these three measures of centrality, DSO (node 39) stands out as being highly influential and connected and plays a significant role in bridging different parts of the network. Some stakeholders, like the infrastructure provider (node 70) and the hydrogen energy supplier (node 66), are influential (as per eigenvector centrality) but are not major connectors or bridges (as per betweenness and degree centrality), indicating their influence is more localized.
- Other stakeholders, like the GoereeOverflakkee local government (node 54) and the hydrogen technology provider (node 31), play specialized roles in maintaining connectivity without having broad influence or extensive connections. Beyond the centrality measures, the network's density and modularity provide insights into the overall network structure. The relatively low density of 0.1377 indicates a sparse network, meaning only about 13.78% of all possible connections between stakeholders are present. This could have implications like limited information flow, increased vulnerability, or difficulties in detecting communities or patterns.
- The modularity score of 0.5930 indicates the presence of well-defined communities within the network, meaning there are subgroups of nodes that are more densely connected internally than with the rest of the network. These communities might have specific roles or interests within the context of the hydrogen projects.

Table 2: Top 5 Eigenvector Centrality

Node	Eigenvector Centrality	Betweenness Centrality	Degree Centrality
39	0.209341	0.230045	0.439252
14	0.206203	0.169282	0.420561
78	0.202796	0.081394	0.317757
70	0.197478	0.006066	0.271028
66	0.197478	0.006066	0.271028

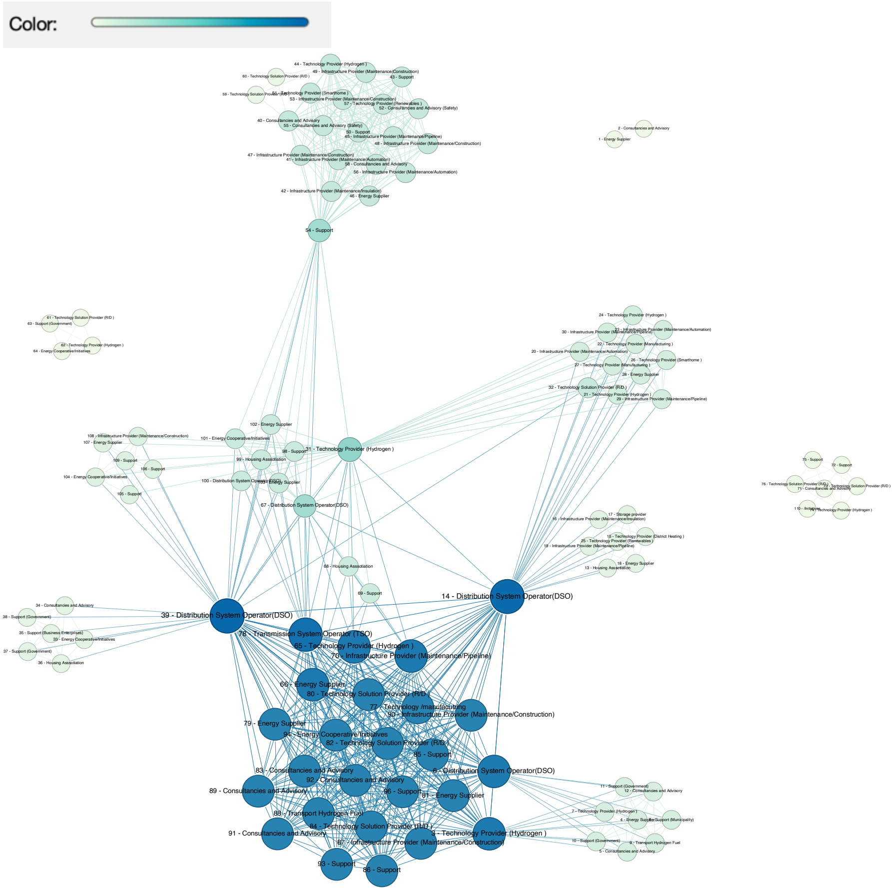

Figure 2. Visualizing Eigenvector Centrality in the network of stakeholder relationships

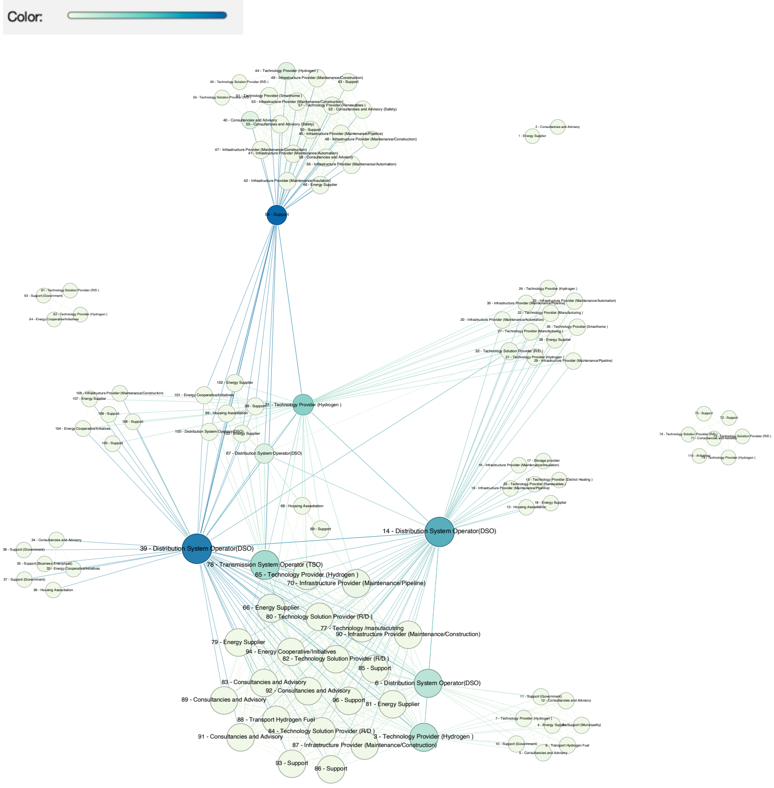

Figure 3. Visualizing Betweenness Centrality in the network of stakeholder relationships

Table 3. Top 5 Betweenness Centrality

Node	Eigenvector Centrality	Betweenness Centrality	Degree Centrality
54	0.030709	0.260977	0.261682
39	0.209341	0.230045	0 .439252
14	0.206203	0.169282	0.420561
31	0.071965	0.114674	0.308411
78	0.202796	0.081394	0.317757

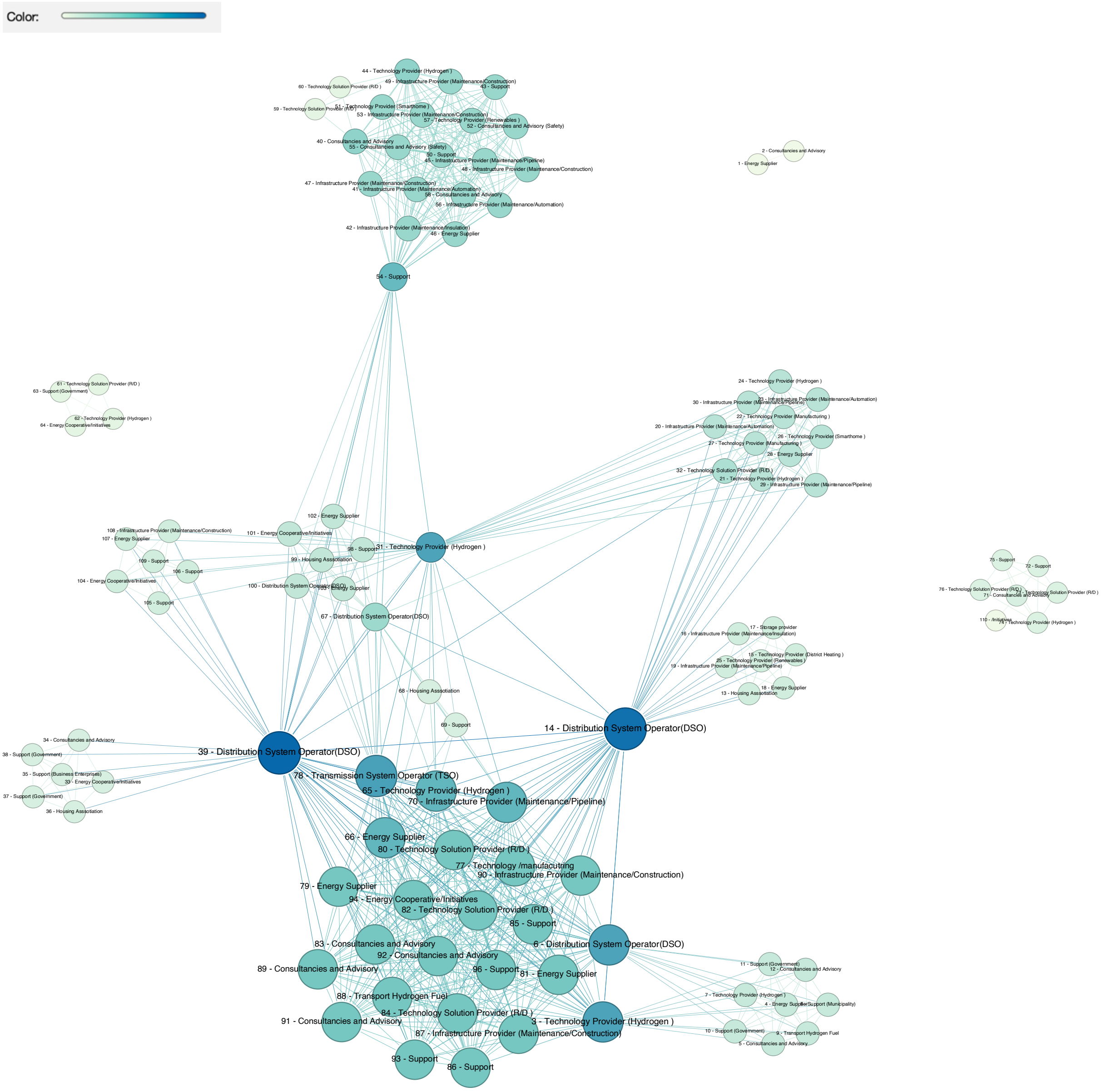

Figure 4. Visualizing Degree of Centrality in the network of stakeholder relationships.

Table 4. Top 5 Degree Centrality

Node	Eigenvector Centrality	Betweenness Centrality	Degree Centrality
39	0.209341	0.230045	0.439252

14	0.206203	0.169282	0.420561
78	0.202796	0.081394	0.317757
3	0.196626	0.059954	0.308411
31	0.071965	0.114674	0.308411

4 Discussion

In our exploratory study of the Dutch decentralized hydrogen infrastructure network, specifically within the built environment, we were able to identify 110 critical stakeholders involved in public-private projects. These key stakeholders could be broadly divided into five main categories: network operators (transmission and distribution), technology and infrastructure providers, energy and utility companies with aggregators, end-users, and supporting entities which include policymakers, regulatory bodies, and intermediaries. Each of these stakeholder categories plays a unique role and carries out distinct activities within the network. A graphical representation of these relationships can be seen in Figure 5. This system map visually encapsulates the complexity and interconnectivity present within this network. Importantly, these stakeholders do not function in isolation but are deeply interconnected within the network. Their influence and roles are not merely qualitative but can be quantified using certain centrality metrics. Specifically, we used Eigenvector Centrality, Betweenness Centrality, and Degree Centrality metrics to assess the prominence and the reach of these stakeholders within the network.

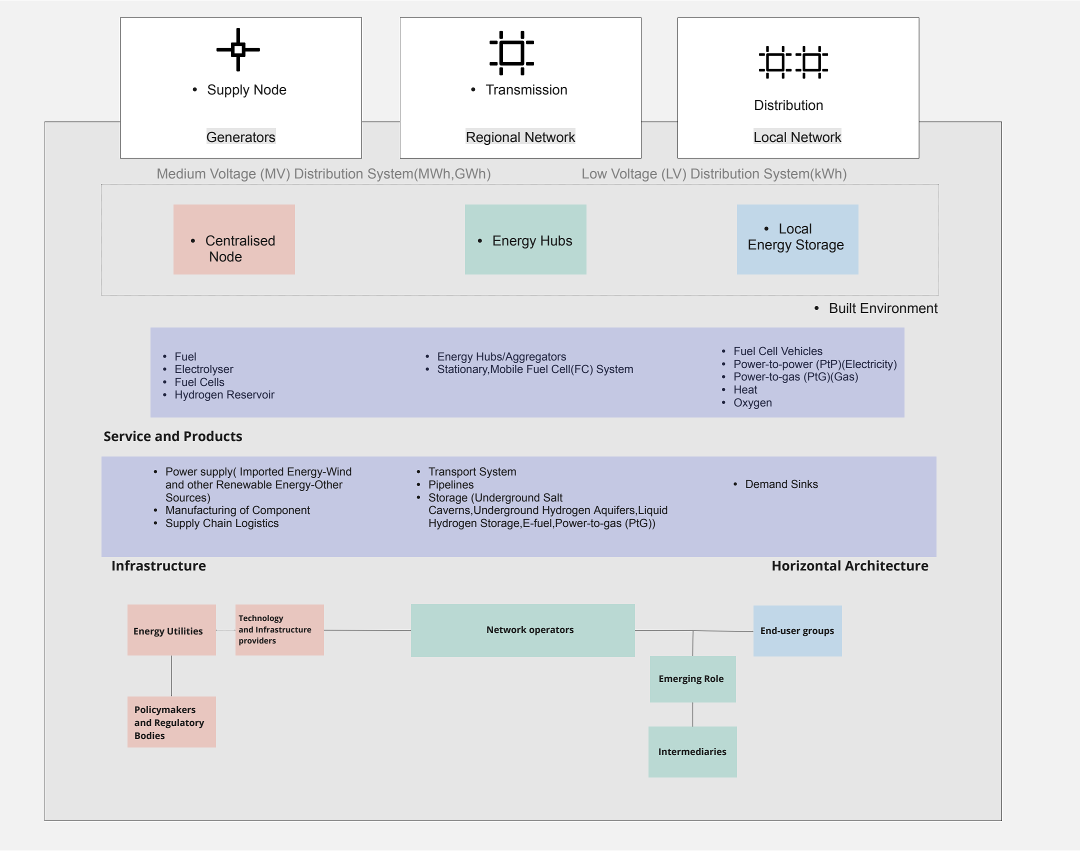

Figure 5: Stakeholder relationship in emerging hydrogen infrastructure network in the built environment.

From these centrality metrics, one essential finding is the noteworthy role of network operators, particularly the Transmission and Distribution System Operators (TSOs and DSOs for both natural gas and electricity). These operators have emerged as fundamental forces, shaping the network infrastructure, steering storage applications, infrastructure upgrades, and even influencing regulatory frameworks. This was further confirmed through our data which showed high engagement of DSOs in many hydrogen projects, hence emphasizing their high eigenvector and degree centrality, particularly for node 39. This demonstrates their broad reach and influence across the network and the substantial sway they hold over other influential stakeholders.

However, an interesting dichotomy was observed for stakeholders like the infrastructure provider (node 70) and the hydrogen energy supplier (node 66). They held high eigenvector centrality but were lacking in degree or betweenness centrality, suggesting that while they hold significant sway within their immediate circle, their influence across the broader network is not as pronounced. This dynamic indicates that these stakeholders may be pivotal in their localized sub-networks, but not the main conduits linking different sub-networks.

In contrast, stakeholders such as the local government of GoereeOverflakkee (node 54) and the hydrogen technology provider (node 31) execute critical yet specialized roles as intermediaries or bridges, without possessing widespread influence or connections. These stakeholders, along with regulators, are instrumental in establishing legislative frameworks that promote innovative business models through demonstration projects and industry consultations.

The low density of the network (0.1377) implies a sparse structure, where only 14% of all potential ties are realized. While such a sparse network might initially appear more manageable due to its simplicity, several challenges emerge from this structure. One of the primary concerns arising from this sparsity is the occurrence of "informational bottlenecks," where the restricted flow of information through limited connections may slow down or distort the dissemination process. To combat this issue, the network needs to focus on enhancing its connectivity, creating multiple paths for the flow of information. This would ensure stakeholders stay informed and connected, enabling them to make evidence-driven decisions.

The network's sparsity also risks isolating certain stakeholders who only have a few connections or, in extreme cases, none at all. To ensure all stakeholders can contribute to the network effectively, it's necessary to proactively seek and establish more connections, fostering a diverse and inclusive network where every member can influence and contribute to the projects. Additionally, the network's sparse structure makes it vulnerable to the loss of key stakeholders. To mitigate this risk, the network could adopt redundancy measures such as creating multiple links between nodes, to ensure the information and resources can continue to flow if a hub is lost. The network's sparse nature also obscures the identification of communities or patterns within the network. It is therefore crucial to use sophisticated network analysis tools and methodologies to detect and leverage these communities for the betterment of hydrogen projects.

A notable observation from the study is the distinct communities within the network, indicated by a modularity value of 0.5930. These communities are characterized by stronger internal ties compared to those between different communities, suggesting specialized roles or clusters of interests. However, this structure presents a challenge for inter-community collaboration. It is essential, therefore, to foster cross-community connections, enabling the sharing of ideas, knowledge, and resources across the entire network. Furthermore, these distinct communities need to address the fair distribution of benefits, reducing the risk of imbalances and conflicts within the network. An understanding of these distinct communities and their specific interests can guide the development of strategies for equitable benefit sharing.

In conclusion, the combination of the identified challenges and the opportunities stemming from our in-depth, quantifiable analysis of the network provides critical insights into the stakeholder dynamics within the Dutch decentralized hydrogen infrastructure network. This understanding forms a robust foundation for effective network management, paving the way for the successful implementation of hydrogen projects.

5 Conclusion

In conclusion, this study bridges a vital knowledge gap by offering a methodical stakeholder network analysis during the foundational phase of distributed hydrogen infrastructure development in the Netherlands. By identifying the key stakeholder categories, their respective roles, and their influence in this development, we are able to provide crucial insights into potential risks and barriers, which can inform better coordination and collaboration strategies in these early stages.

Our analysis revealed several challenges and corresponding strategies. The low network density was observed to potentially lead to "informational bottlenecks." To overcome this, enhancing connectivity and developing multiple information paths could facilitate data-driven decision-making. Sparse connections within the network could potentially isolate stakeholders, thus proactive measures to foster a diverse network are necessary. This ensures that each stakeholder can meaningfully contribute to the projects. In terms of network resilience, the potential loss of key stakeholders presents a risk. This fragility can be mitigated by implementing redundancy measures such as creating multiple links between nodes. The presence of distinct communities within the network suggests specialized roles or clusters of interest. Therefore, fostering connections between these communities becomes essential for effective knowledge and resource sharing across the network. Understanding these communities also aids in devising strategies for equitable benefit distribution.

Lastly, the research underscores the essential role of engaging a diverse group of stakeholders in overcoming challenges, particularly those related to innovation, investment, and policy support. Our findings also highlight the urgency of adopting inclusive design processes like participatory design and scenario building. These approaches can help address coordination challenges in decentralized hydrogen infrastructure projects by fostering stakeholder inclusivity and alignment, thereby facilitating a successful hydrogen infrastructure rollout.

This study acknowledges several limitations in terms of methodology and scope that should be considered when interpreting the findings.

First, the use of SNA as a primary method to uncover hidden dynamics between stakeholders is valuable; however, it represents a snapshot of a continually evolving and dynamic ecosystem. As such, longitudinal approaches that capture changes over time may provide a more comprehensive understanding of the interactions and relationships within the distributed hydrogen infrastructure network.

Second, the study's representation of relationships is simplified, treating them as binary, single-dimensional, undirected, and weightless. This approach may not fully capture the complex, multidimensional, and context-specific nature of stakeholder interactions in the real world. To better understand and address the intricacies of stakeholder relationships, future research could employ more in-depth qualitative methods, such as interviews, and focus groups, to gather richer data and context-specific insights.

Furthermore, the scope of this study is limited to the distributed hydrogen infrastructure in the built environments in the Netherlands, which may not be generalizable to other regions or countries. Comparative studies involving multiple countries or regions with diverse energy systems could provide valuable insights into the factors that enable or hinder the development and deployment of distributed hydrogen infrastructures in different settings. Future research should aim to address these limitations and explore additional dimensions of stakeholder relationships and interactions, ultimately contributing to more effective strategies and interventions for advancing the energy transition toward a more sustainable and resilient future.

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