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AUTHOR

David Schlund

Simon Schulte

Tobias Sprenger

EWI Working Paper, No 21/02

February 2021

Institute of Energy Economics at the University of Cologne (EWI)
www.ewi.uni-koeln.de

Institute of Energy Economics
at the University of Cologne (EWI)

Alte Wagenfabrik
Vogelsanger Str. 321a
50827 Köln
Germany

Tel.: +49 (0)221 277 29-100
Fax: +49 (0)221 277 29-400
www.ewi.uni-koeln.de

CORRESPONDING AUTHOR

David Schlund

Institute of Energy Economics at the University of Cologne (EWI)
david.schlund@ewi.uni-koeln.de

ISSN: 1862-3808

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David Schlund*, Simon Schulte, Tobias Sprenger

Institute of Energy Economics at the University of Cologne (EWI)
Vogelsanger Str. 321a, 50827 Cologne, Germany

Abstract

The interest in low-carbon hydrogen technologies is growing fast in politics and the economy. The ramp-up of a hydrogen market is a critical phase, which requires the engagement and coordination of many heterogeneous stakeholders. A better understanding of who these stakeholders are and what relationships, chances, and risks they perceive is crucial to guide a hydrogen market ramp-up. This paper conducts a stakeholder analysis for Germany with a focus on the market ramp-up period. Interviews with 36 hydrogen experts, literature, and stakeholders from 78 real-world hydrogen research and demonstration projects are analysed with qualitative content analysis and social network analysis. In total, 49 stakeholder groups are identified and defined accordingly. Our results indicate that established stakeholders' roles will significantly change in a future hydrogen market. Risks range from economic and supply chain risks to impacts on international policy. Chances are found along economic, ecological, and political dimensions. Political intervention during the market ramp-up should mostly focus on the economic gap between low-carbon hydrogen and fossil alternatives and on prioritising the allocation of scarce hydrogen supply on heterogeneous demand. Simultaneously, a long-term strategy should be envisaged to guarantee a competitive and non-discriminatory hydrogen market in the future.

Keywords: Hydrogen market, Hydrogen economy, Stakeholder analysis

JEL classification: L52, L94, L95, M21, Q40, Q42.

1. Introduction

In recent times the interest in hydrogen as a clean technology to support global decarbonisation gained increased awareness. Numerous governments, institutions, and private companies published hydrogen strategies in order to initiate a market ramp-up (for instance, Japan, South Korea, the EU, Germany)

*Corresponding author
Email address: david.schlund@ewi.uni-koeln.de (David Schlund)

(Albrecht et al., 2020). The utilisation of pure hydrogen in burners or fuel cells does not emit carbon dioxide. When hydrogen is produced with low-carbon or carbon-free production technologies[1] the total emission balance can be significantly reduced to combat climate change (Nikolaidis and Poullikkas, 2016).

Hydrogen is a versatile energy carrier that can be used for several end-use applications. It can be used as feedstock in the process industry, for low and high-temperature heating in industry, fuel for the mobility sector, space heating, and power generation. Additionally, the possibility of storing hydrogen over long periods, for instance, in underground caverns, increases its attractiveness for integrating volatile RES (Abdin et al., 2020; Ball and Weeda, 2015).

Today, hydrogen is mostly used in the petrochemical and the chemical industry as a feedstock (Abdin et al., 2020). Its trade usually takes place through bilateral contracts between producers and consumers, globally only 5% of the produced hydrogen is traded (FfE, 2019). Therefore, a roll-out of hydrogen into other end-use sectors and production technologies will profoundly reorganise the current hydrogen market. Ultimately, this leads to the ramp-up of a new hydrogen market. The integration of hydrogen into the energy system and the according ramp-up of a market could have a disrupting effect on established stakeholders. Existing business models and stakeholders' roles are questioned, and new stakeholders will enter the market, creating new forms of cooperation and business models but also causing new conflicts. The uncertainty among potential stakeholders of a future hydrogen market is currently high and market roles are not yet determined. However, stakeholder engagement and consensus will play a crucial role when ramping-up a hydrogen market to avoid resistance.

This paper aims at contributing to the current research and discussion on a hydrogen market ramp-up by methodologically assessing potential hydrogen market stakeholders and analysing their chances, risks, and relations. The stakeholder analysis results are subsequently interpreted by deriving three hypotheses and their implications for a market ramp-up's political guidance. The focus is set on Germany and the period of a market ramp-up. We use a multi-method approach by reviewing literature and current hydrogen research and demonstration project. Further information is added from semi-structured interviews and focus groups with hydrogen experts. The data is analysed using Qualitative Content Analysis (QCA) and Social Network Analysis (SNA). We identify and define 49 stakeholder groups, of which electricity utilities,

[1] Hydrogen emission intensity depends on the primary energy source used: hydrocarbon reforming methods and pyrolysis often use natural gas as an energy source. When CO_2 emissions are being captured and stored/utilised (CCS/U), the emission intensity is substantially reduced. Pyrolysis produces solid carbon produced instead of gaseous CO_2. Water electrolysis uses electricity to split water into hydrogen and oxygen and uses electricity as an energy input. Therefore, the emission intensity depends on the electricity generation technology. When using renewable energy sources (RES) or nuclear power, no direct CO_2 is emitted. Hydrogen from biomass does not emit *additional* CO_2, as emissions were removed from the atmosphere (Nikolaidis and Poullikkas, 2016; Abdin et al., 2020). We use the term *low-carbon* hydrogen for all production technologies (RES-based and fossil-fuel-based) emitting none or only a few emissions.

public companies, research and development (R&D) and hydrogen technology providers appear to be most relevant in current hydrogen projects. Whereas few conflicts between stakeholders are currently expected, uncertainties, risks, and different views on hydrogen technologies could ultimately lead to new conflicts in the upcoming years. Our work aims to support further projects and decision making processes by revealing a comprehensive view on hydrogen stakeholders.

Stakeholder analysis is a powerful tool to systematically understand stakeholders, particularly those who substantially impact a decision-making process or a phenomenon (Reed et al., 2009; Brugha and Varvasovszky, 2000). By determining the stakeholders' perspectives on the phenomenon of interest, the findings can support to achieve strategic objectives of organisations, firms, or governments, for instance, by revealing potentials for cooperation, conflicts, and opportunities (Varvasovszky and Brugha, 2000). The stakeholder concept originally stems from management literature and refers to individuals that are mandatory for an organisation's existence and therefore includes, e.g. shareholder, employees, customers, suppliers, lenders, and society (Freeman, 2010).

Regarding a hydrogen market, few publications systematically determine and analyse stakeholders. Hugh et al. (2007) use Key Changes and Actor Mapping (KCAM) to analyse hydrogen transition pathways with a rigour methodology qualitatively. They state that many hydrogen roadmapping activities lack a methodological approach when using qualitative information (in contrast to quantitative data). As a part of their applied methodology, actor groups are mapped with hydrogen supply chain designs to identify central actors. The KCAM methodology is further applied by Seymour et al. (2008) to determine European stakeholder perceptions on significant challenges of a hydrogen market ramp-up. Actor groups within the KCAM methodology are identified by expert elicitation and stakeholder workshops. As a result, the authors present a consensus on a hydrogen market's key challenges and recommendations to overcome barriers. Focusing on Poland Murray et al. (2008) discuss stakeholders' perceived challenges for a Polish hydrogen economy using expert workshops for data collection. Results conclude mostly technical challenges to develop a hydrogen economy as well as opportunities for hydrogen production and utilisation pathways.

Andreasen and Sovacool (2014a) and Andreasen and Sovacool (2014b) perform a stakeholder analysis for hydrogen research stakeholders in Denmark. Their stakeholder analysis builds upon interviews with members of the Danish hydrogen and fuel cell network, consisting of private companies, network organisations, industry associations, research, and public institutions. The analysis is limited to those stakeholders that significantly influence the development of a hydrogen economy. For each type of stakeholder, objectives and their influence are shown. Enevoldsen et al. (2014) use critical stakeholder analysis to assess stakeholders of a Danish hydrogen electrolysis industry. Stakeholders are identified with interviews and subsequently defined along the categories objectives, type of stakeholder, interest, and power. The analysis is limited to hydrogen stakeholders within the electricity industry. For each stakeholder group, strategic actions are suggested to support electrolysis diffusion in the energy system. Schmidt and Donsbach (2016) focus on hydrogen acceptance and assess communication strategies of media and hydrogen stakeholders. They define acceptance determinants using surveys and subsequently analyse documents discussing the pros and cons of hydrogen technologies. Their work aims to improve stakeholders' communication strategies through aligning anticipated stakeholder public communication with observable public acceptance criteria and public perception of hydrogen technologies.

Previous work already used the stakeholder concept in the context of hydrogen markets, mostly to analyse barriers and challenges during a market ramp-up. The scope is often limited to single sectors (e.g. electricity industry) or to serve a specific purpose (e.g. roadmapping, communication). However, no literature was found that systematically conducts a stakeholder analysis with a comprehensive view on potential stakeholders of a hydrogen market and analysing their relationships, chances, and risks. We aim at filling this gap by conducting a stakeholder analysis of a hydrogen market ramp-up in Germany without an ex-ante limitation of the considered stakeholders.

The remainder of this paper is structured as follows: in Section 2 we define the scope of our research, introduce our methodology, and the data collection and analysis methods. Results are presented in Section 3 and interpreted in Section 4 by deriving and discussing three hypotheses on the market ramp-up. Section 5 summarises the paper and closes with an outlook for future research.

2. Methodology

The analysis aims at generating new knowledge in the applied context of hydrogen market stakeholders; hence, we use existing theories and methodologies from stakeholder literature which we align with our research question. The stakeholder analysis methodology follows Reed et al. (2009) and Enevoldsen et al. (2014) and is adjusted for this work. It consists of the steps (i) identification and (ii) classification of stakeholders and (iii) analysis of relationships, chances, and risks.

Stakeholder analysis is not a single methodology, but in-fact consists of several sub-methodologies (Crosby, 1992). Each part of our stakeholder analysis is covered by at least one sub-methodological step (see Figure 1). Our research design ensures that, first, each step of the stakeholder analysis is covered by methodological approaches to avoid ad-hoc determination of stakeholders, which often neglects marginal groups (Reed et al., 2009). Secondly, due to the overlaps of each qualitative research method, results are validated and reviewed during the research process.

For the data collection (Section 2.1), we use primary and secondary data sources to cover various information available on hydrogen stakeholders. The data analysis (Section 2.2) structures and evaluates the gathered information. The stakeholder analysis results are then interpreted by deriving hypotheses, which are subsequently discussed with regard to policy implications during the market ramp-up.

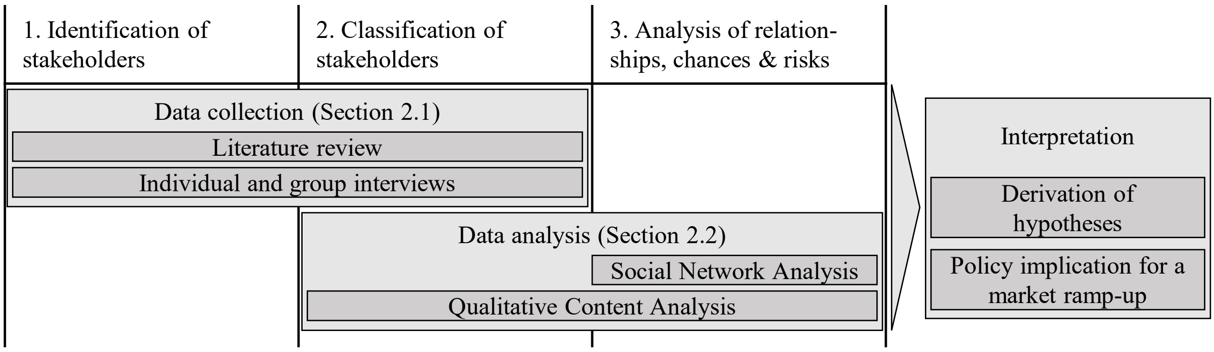

Figure 1: Methodology outline

The following system boundaries are drawn for our stakeholder analysis: (i) the *geographical scope* is defined as to Germany, whereby international stakeholders strongly affecting a German hydrogen market are not explicitly excluded. (ii) The *temporal scope* is set to the period of a hydrogen market ramp-up. And (iii) we use a broad definition of stakeholders and consider all groups and individuals that are affected by or can affect a hydrogen market (Freeman, 2010; Reed et al., 2009). This definition includes stakeholders of a hydrogen value chain and those having no active role during the value creation but with passive influence on a market ramp-up, e.g. Non-Govermental Organisations (NGOs) or associations (Seymour et al., 2008).

2.1. Data collection

Initial literature research is conducted to gather information on hydrogen market stakeholders. For the literature review, academic (peer-reviewed journals, working papers, etc.) and grey literature (reports, websites, news articles, etc.) on the topic of hydrogen stakeholders are considered.

Furthermore, stakeholders are obtained from a self-assessed hydrogen project database. For this purpose, German hydrogen-related power-to-gas demonstration and research projects are listed, and all stakeholders involved in these projects are documented. The final hydrogen project database contains 78 German hydrogen-related projects with over 380 stakeholders. This database includes completed, ongoing, and planned projects. Only projects with verifiable project websites or official announcements of involved stakeholders are considered[2].

To gather additional information and deeper insights into stakeholders' motives, we use semi-structured interviews as the primary data collection method. The identified stakeholders from the literature review and project evaluation serve as a basis for selecting interview partners (Reed et al., 2009; Kaiser, 2014). For the interviews, an interview guide was developed covering the topics of (i) potential stakeholders of a hydrogen market and (ii) chances & risks of a potential hydrogen market.[3] With snowball sampling, new stakeholders identified in the interviews were considered in the subsequent interview invitations (Reed et al., 2009; Andreasen and Sovacool, 2014b).

Interviews and focus groups were carried out as online meetings.[4] In total, 36 individuals participated in the interview sessions, which were carried out either as individual interviews or as focus group sessions with 3-5 participants. Interviews lasted 38.5 minutes in mean with a minimum and maximum duration of 19 and 55 minutes, respectively. The focus groups used the same guiding question as the interviews, but discussions between participants were allowed. Information on interview duration and interviewed individuals[5] are summarised in Table C.6 in Appendix C. Each interview was recorded, fully transcribed, and evaluated using QCA.

2.2. Data analysis

The literature review and the evaluation of the hydrogen project database serve as initial identification and categorisation of stakeholders. We then use QCA to structure and evaluate the diverse information from the interviews. QCA aims at analysing and interpreting qualitative, mainly textual, information with a rule-based methodology to ensure validity and reduce subjective interpretation of qualitative data (Mayring (2004); Mayring (2010)). The results of the QCA cover the categorisation of stakeholders, the analysis of their relationships—particularly conflicts—and their perceived chances and risks.

Its stakeholders significantly influence the development of a future hydrogen market. Collaboration, communication, and knowledge exchange or spillover between stakeholders could facilitate and accelerate the market ramp-up. For the analysis of these interactions, a SNA is conducted. In general, SNA are mainly applied in the field of sociology but can also be applied in many other fields like geography, information

[2]The complete list is attached in Table A.4 in the Appendix A. The database has no claim to cover all existing projects.
[3]The full interview guide is attached in the Appendix C.
[4]Due to the ongoing COVID-19 pandemic during the time the analysis was conducted interviews could only be organised as online meetings.
[5]For the reason of privacy and data protection, names of companies, organisations and persons are anonymously published.

science or economics (Otte and Rousseau, 2002). In the SNA the relationship between stakeholders, instead of individual characteristics and interests, are in focus.

A SNA allows the graphical illustration of connections, or collaborative ties, between the respective stakeholders. In this paper, the SNA is applied to German real-life hydrogen projects. Every stakeholder from the project evaluation is matched with the identified stakeholder groups.[6] In the resulting social network, each stakeholder group is represented as a node. For visualisation of the social network and calculation of the indicators, the open-source tool *Social Network Visualizer (SocNetV)* (Kalamaras, 2020) is used. The indicators allow to quantitatively assess the degree of a stakeholders' influence in the network. For our analysis, we choose the metric *density*, and the *centrality* indicators degree and betweenness, which are considered as the most important indicators (Otte and Rousseau, 2002; Lienert et al., 2013; Zedan and Miller, 2017).

Density is a general indicator for the level of connectedness of the graph. For example, in a complete network, each node is connected directly to every other node and the density would be equal to one. If only half of all possible connections are observed, the density would equal 0.5. (Scott, 1988; Otte and Rousseau, 2002). The indicator centrality can be subdivided into the indicators *betweenness* and *degree*. The betweenness of centrality gives the total number of times a node needs a certain node to reach another node on its shortest path. A higher value indicates that the respective stakeholder group facilitates the flow of information in the network as it represents the shortest path between otherwise disconnected stakeholder groups. Nodes connecting many other nodes with their shortest paths have higher values (Otte and Rousseau, 2002). The degree of centrality is the total number of ties the respective node has. In terms of stakeholder groups, the degree of centrality is equal to the number of connections to other groups (Freeman, 1978; Otte and Rousseau, 2002).

3. Stakeholder analysis results

The following section presents the results of the stakeholder analysis. First, the stakeholder identification and categorisation based on the interviews and the project data analysis are summarised. Second, relationships between stakeholders are shown, and third, clustered chances and risks, which interviewed stakeholders stated, are explained.

[6]In some cases, a stakeholder's exact role within a project and its stakeholder group did not become entirely clear. For instance, a company producing electricity and offering energy-related services would match more than one stakeholder category. As an assumption, the stakeholder's major activity was used to determine its stakeholder group. Since some stakeholders did not have an identifiable major activity but several business areas, such as a gas and electricity grid operator, in some cases, multiple stakeholder groups were assigned.

3.1. Stakeholder identification and categorisation

The stakeholder identification and categorisation is derived from analysing the interview transcripts with QCA, from reviewing literature, and from hydrogen demonstration and research projects. Hydrogen stakeholders, based on interviews and workshops as primary data source, were found in van de Kerkhof et al. (2009), Eames and McDowall (2010), Andreasen and Sovacool (2014a), Andreasen and Sovacool (2014b), Enevoldsen et al. (2014), and Glanz and Schönauer (2021). Hugh et al. (2007) and Murray et al. (2008) used expert elicitation within one project as data source. Decourt (2019) used a database of European power-to-x projects as primary data source and Schmidt and Donsbach (2016) applied surveys and a document analysis. The remaining publications either derived stakeholder groups from existing literature or did not specify their data sources (Seymour et al., 2008; Robinius et al., 2015; Haghi et al., 2018; Dawood et al., 2020). For the SNA, hydrogen-related project databases and overviews were merged and supplemented by further research on German projects. The hydrogen project data was retrieved from Federal Ministry for Economic Affairs and Energy (2020a), Deutscher Verein des Gas- und Wasserfaches e.V (DVGW) (2020), International Energy Agency (IEA) (2020), and OGE (2020) and critically reviewed.

In total, 49 stakeholder categories and subcategories are derived from the primary and secondary data sources. All categories and the corresponding definitions are shown in Tables 1 and 2. Categories with subcategories such as *industrial sector* are explicitly listed as a separate category since some general mentions in interviews and focus groups could not be directly assigned to a subcategory. Subcategories are introduced to prevent loss of information and guarantee a detailed overview of the rather general categories: building sector, natural gas industry, industrial sector, petroleum industry, and transport sector. Further, it must be noted that stakeholder categories are not necessarily MECE ("mutually exclusive and collectively exhaustive"). That means, real-world companies might match more than one stakeholder category (e.g. an electricity utility with a trading department, RES generation and gas storage assets would match with *Electricity utilities, Storage operators* as well as *RES plant operators*). Since stakeholders of a hydrogen market ramp-up are highly diverse, an unambiguous definition of stakeholder categories seems hardly feasible while keeping the number of stakeholder categories tractable.

From a quantitative perspective, stakeholder groups from the energy demand sectors *Transport* and *Industry*, particularly the *Steel industry* and the *Chemical industry* as well as the *Heavy-duty transport*, have the highest number of mentions with more than 70% over all interviewed stakeholders. In this case, the chemical industry appears as an incumbent stakeholder group, as one interviewee notes[7] that "after

[7]As interviews were held in German, the following quotations were translated by the authors.

all, we have a hydrogen market [today], that is, the chemical industry"(Interview no. 19). The transport and steel industry instead appear as new stakeholder groups, as one interviewee expects "mobility will play a major role as a consumer of hydrogen. Personally, I would expect that in 2035, heavy-duty mobility will increase and, gradually, passenger cars as well. Regarding steel and industry, i.e. the manufacturing sector, there will certainly be several, if not many, companies that use hydrogen on a large scale" (Interview no. 20). Furthermore, *Hydrogen technology providers* are considered as an essential stakeholder category by interviewees with 71% of mentions, for instance, "on the generation side, I see the electrolyser manufacturers as the main stakeholders. There are already a number of them that [...] are gradually building up capacity. If I had to name names, I would say that the major players in the electrolyser industry are Nel ASA, ITM, Hydrogenics, Siemens, Thyssen-Krupp, McPhy, H-Tec and Sunfire" (Interview no 9). Natural gas TSOs/DSOs—interviewees barely made a distinction—and electricity utilities both are mentioned in more than 60% of interviews as important stakeholder groups of a hydrogen market, for instance: "on the supply side, the current utilities will play a big role in developing the [hydrogen] market (Interview no. 22)". The remaining stakeholder groups were mentioned each in less than 60% of the interviews.

3.2. Analysis of stakeholder relationships

In the following, the relationships between stakeholders during the market ramp-up are analysed from two perspectives. First, with the SNA we focus on cooperation between the identified stakeholder groups and determine the most and least essential groups in the current project landscape. The SNA is conducted based on the developed project list. Second, the interviews and focus groups provide additional information on existing or potential conflicts between groups as perceived by stakeholders.

Most of the projects analysed in the SNA are research and demonstration projects addressing technology scalings or exploration of new application areas. Therefore only the current market ramp-up phase is reflected. It is not possible to directly conclude from this static view to a fully developed hydrogen market in the future. As described in Section 2.2, the stakeholder groups are connected according to the observed project partnerships. Each stakeholder group is represented as a node. Figure 2 depicts the respective network. In this network, 42 out of the identified 49 stakeholder groups are represented. The remaining seven stakeholder groups are not involved in any of the projects analysed.

Table 1: Stakeholder categorisation and definition (1/2)

Stakeholder category	Stakeholder subcategory	Stakeholder definition
Agriculture & Forestry		Use of agricultural and forestry wastes for the production of hydrogen but also agricultural and forestry as competitor for the use of water
Associations		Associations in the field of industry and trade, representing the interests of their members and pursuing economic interests
Building sector		Residential and non-residential buildings with regard to heat and electricity demand
	Districts	Hydrogen use in districts with regard to heat and electricity demand
	Heating system manufacturers	Heating system manufacturers for the building sector. Mainly engaged in the hydrogen readiness of systems or pure hydrogen consumption systems
Citizens' initiatives		Citizens' initiatives interested in the hydrogen market (or ramp-up), both as potential supporters and as possible opponents
Consultants		Scientific, political, technical, and economic consulting as a service
Electricity DSOs		Regulated electricity distribution system operators (DSOs)
Electricity TSOs		Regulated electricity transmission system operators (TSOs)
Electricity utilities		Utilities along the electricity value chain with different focuses of activity along the electricity value chain (excluding municipal utilities)
Energy cooperatives		Cooperatives such as civil wind farms and (civil) energy cooperatives
ESCOs		Energy service companies (ESCOs) provide a wide range of energy solutions, for instance, planning or engineering of power generation and energy supply. ESCOs are not part of the value chain
Hydrogen exchange		Hydrogen exchange, possibly also integrated into existing energy exchanges
Hydrogen technology providers		Manufacturers and provider of special equipment for hydrogen technologies. Independent of the value chain (e.g. fuel cells, electrolysers, storage tanks, pipelines, compressors, liquefaction plants). Not included/listed separately: Heating system manufacturers, vehicle manufacturers and vehicle parts supplier
ICT industry		Companies in the information and communication technology (ICT) sector, e.g. as service providers or data center operators
Industrial sector		Mentions of the industrial sector in general, especially as hydrogen consumer with no further specification
	Cement industry	Companies in the cement industry, especially for provision of heat
	Chemical industry	Chemical industry as a consumer and supplier of hydrogen and as a user of by-products (heat, oxygen, carbon dioxide). Includes chemical parks as infrastructure providers
	Industrial gas companies	Manufacturer and supplier of industrial gas and industrial gas equipment
	Steel industry	Iron and steel industry (primary and secondary steel)
Institutional investors		Institutional investors such as pension funds, insurance companies, and credit institutions. Accordingly, private investors are excluded
Municipal utilities		Municipal utilities as stakeholders with multiple roles in the field of utilities and beyond (e.g. public transport or waste disposal)
Natural gas industry		Natural gas industry in the broad sense, e.g. gas exploration, extraction, import, and trading
	Gas DSOs	Regulated natural gas distribution system operators (DSOs)
	Gas TSOs	Regulated natural gas transmission system operators (TSOs)
NGOs		Non-governmental organizations (NGOs) as representatives of ecological and social interests, e.g. environmental, climate, or consumer protection

Table 2: Stakeholder categorisation and definition (2/2)

Stakeholder category	Stakeholder subcategory	Stakeholder definition
Petroleum industry		Exploration, extraction, import, processing, and distribution of petroleum products
	Refineries	Refineries as part of the transformation sector
Politics		European/ Federal/ State / Local politics. Also includes targeted policies (e.g. climate policy, regulation, and development policy)
Project developers		Project developers as service providers (e.g. developers of renewable energy projects)
Public companies		Public companies are companies in full or majority state ownership. The purpose of public enterprises is often a regional promotion of social or economic areas
RES plant operators		Operators of renewable energy plants such as photovoltaic, wind, hydro, and biomass
Research & Development (R&D)		Private (e.g. Fraunhofer) and public research institutions (e.g. universities)
Society		Civil society in a broad sense. Refers to the entire society in Germany as a whole, but also to local communities (e.g. municipalities)
Storage operators		Storage operators, e.g. natural gas underground storages or new hydrogen storage facilities
Transport sector		General mention of transport or mobility as a stakeholder, without limitation to specific applications
	Airport operators	Airport operators as infrastructure providers
	Aviation	Passenger and freight air transport. Refers to both airlines and aviation manufacturers
	Buses	Buses in local public transport and long-distance traffic
	Heavy-duty transport	Use of hydrogen in heavy-duty traffic
	Individual transport	Use of hydrogen in passenger cars
	Intra logistics	Use of hydrogen in plant logistics (e.g. forklift trucks or industrial trucks)
	Other commercial vehicles	Other commercial vehicles such as garbage trucks, street cleaning, and construction vehicles
	Rail transport	Use of hydrogen in passenger and freight rail transport
	Refilling station operators	Existing refilling station operators and new hydrogen refilling station operators
	Seaports	Seaport operators as infrastructure providers
	Shipping	Shipping in the role of user and transporter of hydrogen
	Vehicle manufacturers & OEMs	Vehicle manufacturers and original equipment manufacturers (OEMs) of the road transport sector (passenger cars, light commercial vehicles, trucks)
Water resource management		The water resource management sector includes, above all, waterworks for the production of drinking water and wastewater treatment plants for the management of wastewater

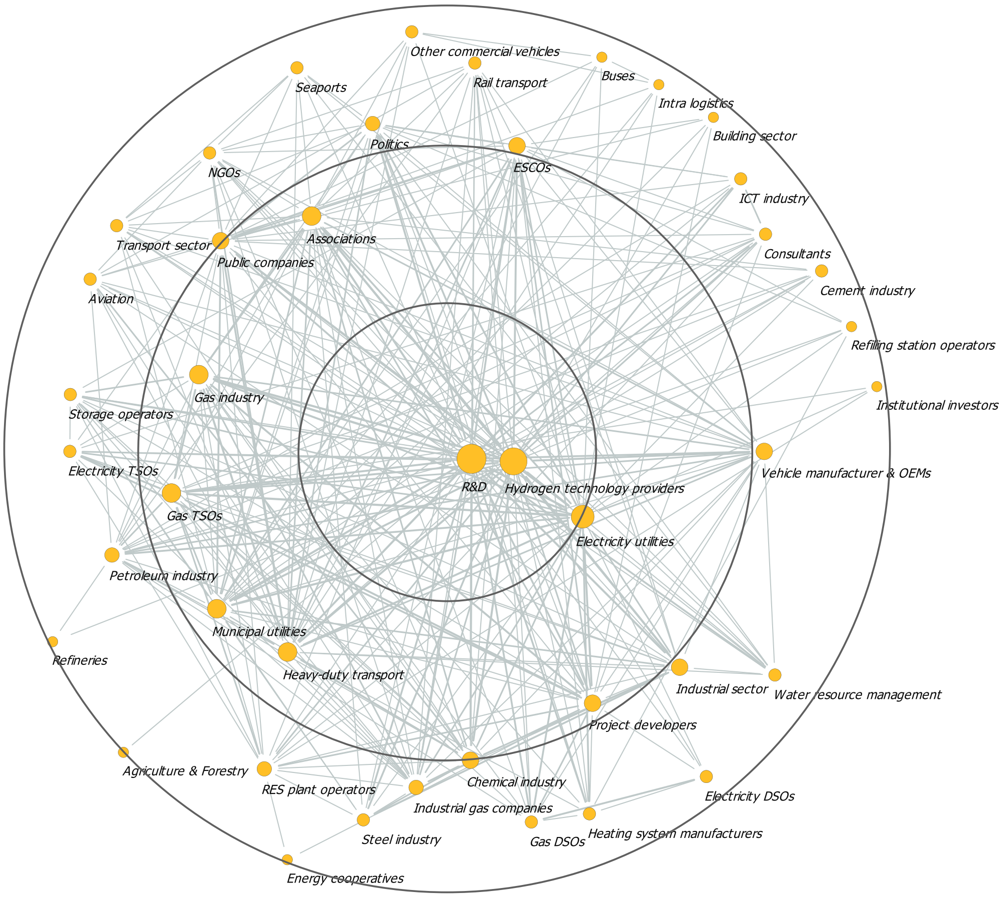

Figure 2: Network of stakeholder groups in German hydrogen related research and demonstration projects
Note: The graph was created in SocNetV, Version 2.5

The network shown in Figure 2 is drawn with a prominence-based placement in a radial form. A central position and a larger circle, for instance, R&D or electricity utilities, indicates a higher degree of centrality and thus higher importance in the network. In the following, essential indicators introduced in Section 2.2 are presented.

The density of the graph is 0.37. This value indicates that over a third of all possible connections between stakeholder groups are present. This is clarified by Figure 2, as only some peripheral stakeholder groups have few or only a single connection to other groups. To determine the most important stakeholder groups we calculate two centrality indicators. These indicators are listed in Table 3 each sorted in descending order[8]. Only standardised indices with values between 0 and 1 are shown.

[8]A complete list of all centrality indicators can be found in Table B.5 in the Appendix B.

Table 3: Ten highest and lowest BC' and DC' values (BC'=Betweenness centrality, DC'=Degree centrality)

No.	Stakeholder group	BC'	No.	Stakeholder group	DC'
1	R&D	0.1147	1	R&D	0.8293
2	Hydrogen technology providers	0.0997	2	Hydrogen technology providers	0.8293
3	Electricity utilities	0.0875	3	Electricity utilities	0.7317
4	Public companies	0.0494	4	Heavy-duty transport	0.6585
5	Municipal utilities	0.0466	5	Municipal utilities	0.6585
...	...	...	...	...	...
38	Intra logistics	0	38	Building sector	0.1220
39	Building sector	0	39	Institutional investors	0.0732
40	Cement industry	0	40	Energy cooperatives	0.0488
41	Refilling station operators	0	41	Refineries	0.0488
42	Institutional investors	0	42	Agriculture & Forestry	0.0244

The betweenness of centrality indicates the flow of information in the network. R&D is the most critical stakeholder group which connects many otherwise unconnected groups. Since the database represents only the current status of a hydrogen market ramp-up, it is not surprising that R&D represents the most important bridge. Hydrogen technology providers and electricity utilities occupy places two and three with slightly lower values. Other stakeholder groups follow with significantly lower values. Overall, 11 out of 42 stakeholder groups have no relevance in terms of betweenness. This means that, for example, the building sector participates in several projects but does not connect other stakeholder groups as the shortest link in any of these projects.

Another important indicator is the degree of centrality. The degree of centrality indicates the absolute number of ties each stakeholder group has. For R&D the value of 0.8293 indicates that about 83% of all possible ties, 34 in absolute numbers, are present. Multiple ties stemming from several joint projects are not considered. Again, R&D, hydrogen technology providers, and electricity utilities take the most prominent places. In contrast, the least important stakeholder groups are connected to 5 (building sector) or even down to 1 other stakeholder groups (agriculture & forestry). These stakeholder groups have considerably less contact with other stakeholder groups. A higher number of connections is attributed to a greater extent of information exchange. Thus, fewer connections and a resulting lower density of the overall network could inhibit the flow of information (Fritsch and Kauffeld-Monz, 2010).

The SNA shows that few central stakeholder groups participate in many different hydrogen-related projects. Since many business and application areas are currently researched and developed, it is not surprising that R&D is the most central group. When comparing the network to the value chain, we see that the supply side is represented by a few central groups (mostly hydrogen technology providers and electricity utilities). Several interviewees confirm this observation, who note, for instance, "I can already imagine a big role from the electricity utilities, even bigger than we have" (Interview no. 13) or "electricity utilities, so to speak, as a driving force behind [a hydrogen market ramp-up]" (Interview no. 1). The demand side, on the contrary, is found in the peripheral area, though represented by numerous stakeholder groups without a clear focus on one type of consumer. One interviewee thinks that "in general, the demand is rather what runs up a little slower" (Interview no. 20). In many projects hydrogen technology providers and hydrogen production are essential roles to demonstrate and develop applications and business areas. Thus, these stakeholder groups are involved in many projects. Stakeholder groups of the demand side (e.g. refilling station operator) are less central and less connected.

In addition to a variety of cooperation, there are some potential conflicts in the market ramp-up. Since the SNA does not provide information on potential conflicts, in the following, we use findings from the interviews and focus groups. One source of conflict is seen in the hydrogen production technology, as one interview partner notes, "the central conflicts that I perceive is the question of the colour[9] of hydrogen" (Interview no. 10). Around 30% of interviewees expect the technology preference as a source of conflict among stakeholders.

The role of hydrogen in future energy systems is often controversially discussed. Stakeholders' perceptions reach from minimal utilisation, for instance, only in sectors where electrification is technically infeasible, to large utilisation scenarios in all end-use appliances. One stakeholder describes this situation as follows: "Hydrogen is always only the second-best solution. There is an apparent order. From my point of view, energy efficiency first, then direct electrification. When both have been exhausted, then one can consider converting surplus energy into hydrogen. Nevertheless, hydrogen never comes first, always third after efficiency and direct electrification" (Interview no. 9). This competition between hydrogen and other low-carbon energy sources can cause conflicts. Particularly in end-use appliances where both low-carbon hydrogen and electrification are feasible decarbonisation options. Around 50% of interviewed stakeholders perceived the issue of direct electrification versus hydrogen utilisation as a potential conflict.

Another highlighted area concerns distributional conflicts. Fifty per cent of interviewed stakeholders explicitly mention that hydrogen will be very scarce during the market ramp-up and distribution among end-use sectors will be a challenging issue, as the following citation exemplary describes: "I believe, another conflict is the relation between the demand sectors. I think this can already be seen in the current discussion

[9] Authors' note: The colour of hydrogen refers to the production technology, whereas mostly *green* hydrogen, which is produced by electrolysis and RES-based electricity, is compared with *blue* hydrogen, which originates from natural gas reforming with carbon capture and utilisation/storage.

that there should be a very targeted approach, that certain demand sectors should be stimulated to develop hydrogen demand for various reasons. [...] However, metaphorically speaking, some people have declared the champagne as mineral water and want to bring [hydrogen] into the heating sector. That is, of course, a conflict. I think it has to be resolved politically somehow by setting priorities" (Interview no. 22). Several interviews share the opinion of governmental intervention to prioritise end-use sectors. Therefore, many stakeholders expect competition for funding of specific sectors. Stakeholders are concerned about competitive disadvantages during the market ramp-up caused by a lack of subsidies and governmental support. However, one stakeholder also mentions that "this is a sign that a market is developing. [This] is a typical market ramp-up, where different stakeholders try to pitch each other's claims. In the end, this brings competition" (Interview no. 1).

3.3. Perceived chances and risks

Within the interviews and focus groups, stakeholders were explicitly asked to state perceived chances and risks of a hydrogen market ramp-up, which were extracted from the textual interview data using QCA. Chances and risks either apply to one specific stakeholder group or the German economy as a whole. Since many interviewees responded to the questions rather unspecific regarding to which stakeholder the chances and risks apply, they are not described for each single stakeholder group. Figure 3 shows an overview of stakeholders' perceived chances and risks, each clustered along three dimensions. The following section summarises the interviewed stakeholders' perspective on chances and risks. The relative frequency of each topic in the interviews is given[10].

3.3.1. Risks

The development of an entirely new branch in the energy sector requires massive investments evoking many *economic risks*. As low-carbon hydrogen has the potential to replace fossil fuels in a wide range of end-use applications, it could pose significant risks to all stakeholders that might suffer from a **loss of relevance of fossil fuels**. With 63% this is the most frequently mentioned risk by interviewed stakeholders, exemplary one stakeholder assigns the risk for, "first of all, those who have technologies that see hydrogen as competition. Clearly, the petroleum, natural gas, or the chemical industry." (Interview no 8). Besides business activities related to fossil fuel supply (e.g. production, transportation), this also includes a dependency on the utilisation of fossil fuels. The threat to each stakeholders' business activities might also depend on the policy targets, e.g. priorities for certain production technologies and end-use

[10] The frequencies must be carefully interpreted since interviewees had to respond spontaneously to the stated questions and did not receive a predefined list of possible chances and risks (also see interview guide in Appendix C).

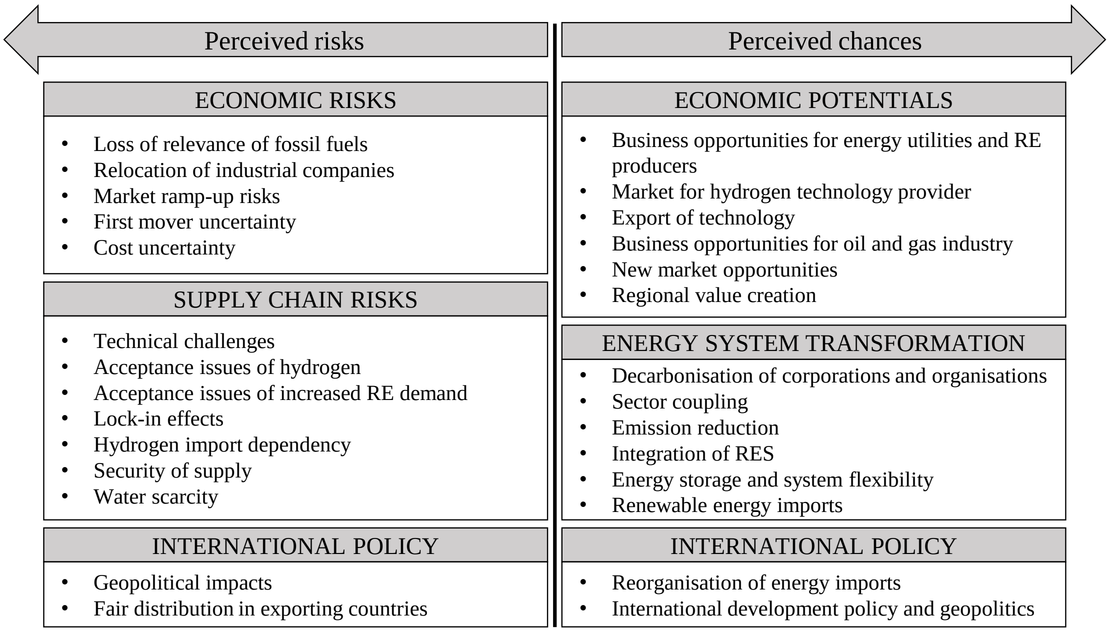

Figure 3: Stakeholders' perceived chances and risks of a hydrogen market

sectors. As global hydrogen production costs strongly differ among countries[11], the risk could emerge that **industrial companies are relocated** to locations with lower costs for RES-based hydrogen compared to Germany (42%). Especially industrial companies facing international competition would be at risk from this particular type of carbon leakage, e.g. the steel industry as "steel production is relocated to where there is also sun or offshore wind of some kind, which is not necessarily in the Ruhr[12] area [...]. And that is, of course, a risk." (Interview no. 16).

Particularly during the hydrogen market ramp-up, stakeholders could be faced with **market ramp-up risks**, such as slow market dynamics or lower learning curve and cost degression effects as expected, which was considered a risk by 25% of interviewees. One stakeholder focuses on the dynamic of a market ramp-up: "What I can say as someone who has been involved with hydrogen for almost twenty years is, of course, what you must not underestimate is the temporal ramp-up risk. It always comes slower than you think, at least it has been in the past [...], as we can see with solar PV, for example. Here, it also took a very long time until the first per cent coverage was achieved. From then on, it actually felt very fast. Nevertheless, it's no use at all if you have the best idea, but bring it to the market at the wrong time. And then the investors simply don't have the staying power to wait until it works. So that is certainly a big risk." (Interview no. 20). During the ramp-up, low-carbon hydrogen is expected to be very scarce and production costs to be high.

[11] See, for instance, a recent publication of Brändle et al. (2020).
[12] Authors' note: The Ruhr area is a region in Germany with many steel production and manufacturing plants.

Unless state support is granted or CO_2 prices are accordingly high, this could prevent stakeholders from investing in hydrogen consumption technologies. The market ramp-up of low-carbon hydrogen would require **first movers** which test and demonstrate hydrogen utilisation (25%). In the commercialisation phase, those first movers face investment risks due to a high level of uncertainty, for instance, regarding costs, demand volumes, regulation, and technical challenges, as one interviewee expresses "I would also like to add that there are risks for those who invest in the market first, especially when the hydrogen economy is being built up, i.e. during the ramp-up. Especially if the regulatory framework has not yet been established." (Interview no. 28). Furthermore, 54% of stakeholders note that the German government and economy as a whole need to bear the risk of a first-mover country with massive investments in R&D, facilities and infrastructure, which ultimately results in **cost uncertainty** or as one stakeholder describes "we have to invest the money as a society or as a state to build up a hydrogen market that we don't really know how big it can become." (Interview no. 11). Most presumably, these costs would be shared by the public and private sector to a certain extent. However, the uncertainty about the volume and optimal allocation of the additional costs is high, exposing several stakeholder groups to financial risks.

Along the *hydrogen supply chain* stakeholders perceive several risks. A lack of experience and technical expertise on several supply chain steps could pose a significant challenge. The large-scale production, transportation, and utilisation of hydrogen using innovative and immature technologies could cause **technical issues and risks**, which is mentioned by 58% of interviewees. Mostly, stakeholders refer to safety issues such as the following quotation shows: "we also must talk about technical risks. That is also something that I think is often overlooked. Yes, hydrogen can be produced, transported and used safely. There's no question about it, but it's also quite clear that you have to know what you're doing. [...] It does have potential danger. At the moment, there are not many reported accidents, simply because hydrogen is not as widespread everywhere as natural gas or other energy sources. So there will certainly be more [accidents] [...]. Of course, this is a risk for each individual" (Interview no. 20). Over time, these issues are assumed to be solved by increasing technology maturity, but technical insecurities could persist during the market ramp-up. These technological risks might also create additional challenges regarding the **acceptance of hydrogen**, particularly in the society, as 33% of interviewed stakeholders state. Hydrogen is—except for the (petro-)chemical industry—so far not widely used. The physical characteristics of hydrogen could evoke objections within the population and impede a wide application in end-use sectors, for instance, because of its explosion hazard or hydrogen infrastructure expansion. Some stakeholders described scenarios where mistrust of inexperienced technologies could put the entire hydrogen technology at stake. One stakeholder explains such objections as follows: "In any case, there is a general fear, uncertainty, and ignorance among the population that blocks innovation. And of course, this is also reflected in the press." (Interview no. 18). Additional obstacles from the society could emerge due to **acceptance issues related to increased RE demand**, as 33% of interviewees expect. The production of RES-based hydrogen[13] will increase demand for RES electricity significantly. However, this additional demand requires further expansion of RES and power grids, which might lead to additional acceptance issues. Hence, the market ramp-up would be slowed down by limited electricity from RES. Furthermore, during the market ramp-up, a range of fundamental decisions will be made by stakeholders. These decisions, such as choosing production or transportation technologies, end-use appliances, and market designs, could shape the hydrogen market for a long time. These long-term and fundamental decisions in technologies and infrastructure may result in **lock-in effects** and in the long run in stranded investments (29%), exemplary explained by one interviewee: "We are also in competition with other [countries], as we now risk to bring huge quantities and failed investments into the country if we rely on hydrogen and then realise: there was another way." (Interview no. 16). As described above, during the market ramp-up, hydrogen supply will most probably be very limited, as production and transportation capacities will expand gradually. Consequently, **security of supply** could be low in the beginning, reducing the acceptance of hydrogen as an energy carrier (17%). Additionally, Germany will most probably depend on hydrogen imports[14]. Thus, **dependence on energy imports** is probably barely reduced; instead, it would be shifted from oil, gas, and coal to hydrogen imports (21%). Also, 21% of interviewed stakeholders perceive the risk of **water scarcity** for electrolysis-based hydrogen, mostly concerning countries with high water stress (e.g. Middle East & North Africa (MENA) states).

From a global perspective, the market ramp-up of hydrogen could cause some risks in *international policy.* The risk of being vulnerable to exporting countries' power to use hydrogen as a policy instrument could persist, which would, in particular, be risky in the early phase of a global hydrogen market when supply diversification is low. As soon as consumers are committed to hydrogen, they would call for a stable and secure supply of hydrogen, which is in line with the demand requirements. Therefore, hydrogen trade potentially creates **geopolitical risks** (20%), as hydrogen imports to Germany could increase or cause new geopolitical conflicts, as one interviewee explains referring to the example of Russia: "I don't think one can say to Russia: We won't import anything from you anymore, we don't need any more natural gas. I

[13] The German government aims at only producing RES-based hydrogen within Germany and enable other types of hydrogen as imports (Federal Ministry for Economic Affairs and Energy, 2020b)

[14] See e.g. Schulte and Schlund (2020)

don't know what the relationship in Europe will be like then. Unfortunately, there are always other political things that play a role." (Interview no. 10).[15] Geopolitical risks could be particularly high when high import dependencies on few exporting countries exist. Within hydrogen exporting countries, economic opportunities are created; however, it should be ensured that threats and benefits are **fairly distributed in hydrogen exporting countries** among all local stakeholders and actors, as 33% of interviewed stakeholders think. This risk might be related to the economic effects of hydrogen production and other side effects, such as water scarcity, which could be a significant challenge for MENA-states. Another crucial aspect is the energy system's state in hydrogen exporting countries, as RES-based hydrogen exports from a country with high fossil fuel generation could counteract global greenhouse gas (GHG) mitigation. However, some stakeholders noted that the development of a clean hydrogen export industry and decarbonisation of the national energy system should go hand in hand, accompanied by the expertise of developed countries. A stakeholder suggests that "with compliance criteria, an involvement and added value for the local population can be ensured." (Interview no. 24).

3.3.2. Chances

The ramp-up of a national hydrogen market could offer wide *economic possibilities* for both private companies and the economy as a whole. Around 42% of interviewed stakeholders expect new business models for **Energy utilities and RES producers**, as "from the perspective of an electricity producer, of course, we see the opportunity to be able to market our renewable assets more flexibly." (Interview no. 28). Hence, positive portfolio effects of RES and hydrogen production plants are expected with an increase in RES operators' profits. Electricity utilities could further diversify their business portfolio by operating on the hydrogen market, e.g. as a hydrogen supplier. Furthermore, a new market for hydrogen equipment could develop for domestic and export products, which could open new business opportunities for **hydrogen technology providers**, as 42% of interviewees expect. As determined in the German hydrogen strategy, hydrogen **technology export** could be a pillar of industrial policy to generate long-term economic growth and establish an entirely new economic sector (Federal Ministry for Economic Affairs and Energy, 2020b) for "worldwide export opportunities once you have shown that it works" (Interview no. 13). Seventy per cent of interviewed stakeholders mention that **business opportunities for the oil and gas industry** could be created as a producer, supplier, or pipeline operator of low-carbon hydrogen. "For Gas TSOs [...] it's an opportunity to somehow continue to use their infrastructures" (Interview no. 22). Hence, by

[15] For more details on geopolitical impacts of global hydrogen trade, see e.g. Van de Graaf et al. (2020); Pflugmann and De Blasio (2020)

using existing assets and infrastructure, hydrogen supply chains could be quickly developed and costs could be reduced. Furthermore, many interviewees emphasise the relevance of enabling new business models for the oil and gas industry. Their cooperation and participation could become a crucial success factor of a German hydrogen market ramp-up. During the ongoing energy system decentralisation process, hydrogen could support **regional value creation** and improve regional economies. Within Germany, this might stimulate economic activities in structurally weak regions, e.g. those, that suffer from economic degradation by phasing out of lignite (8%).

Hydrogen could offer vast potentials for the *transformation of energy systems* and deep decarbonisation. Besides striving for profitability and economic success, many private companies and organisations aim at sustainability and CO_2 emission reduction as part of their long-term strategy - although the motivation for these objectives may be manifold (e.g. due to cost reduction potentials, political and societal pressure, or consumer preferences). Seventy-five per cent of interviewed stakeholder expect that hydrogen could offer new ways to achieve strategic goals of **decarbonising corporations and organisations** or as one interviewee summarises: "First of all, I believe it is an opportunity for those who have difficulties to decarbonise, mostly on the demand side" (Interview no. 11). Hence, hydrogen is of particular interest in end-use appliances, which can not, or only at very high costs, be decarbonised by RES-based electrification (e.g. high-temperature processes in the industry or hydrogen as feedstock in the (petro-)chemical industry). Over all end-use sectors, hydrogen could enable **sector coupling** as it is a versatile energy carrier than can be flexibly produced by a range of production technologies and used in a wide range of appliances (17%). Interviewed stakeholders expect the (petro-)chemical and steel industry, heavy-duty and utility vehicles, and aviation/shipping as prior end-use sectors. The lowest priority is seen in the heating and building sector by most interview partners. With a broader scope and referring to the economy as a whole, hydrogen could enable overall **emission reduction**, not only of CO_2 emissions but also of other unwanted effects, such as nitrogen oxides, particles, and noise. Fifty per cent of the interviewed stakeholders mention this as a chance. This opportunity is particularly of high relevance, as some emissions currently create costs (e.g. social, environmental, health) that are not paid by any polluter and therefore reduce the overall welfare, as explained by the following quotation: "the population benefits directly, leaving more money in its pocket [...]. [Hydrogen] has the advantage of noise and also particle emission or nitrogen oxides reduction." (Interview no. 18).

Remaining at the system level, hydrogen usage might **integrate RES**, increase **energy system flexibility and decentralisation** and provide **energy storage** (54%). The German power system currently suffers from a substantial imbalance of wind power generation in the north and consumption centres in the country's mid and southern regions. Due to grid congestion in some hours of the year, wind power needs to be curtailed and the energy is wasted, where hydrogen could "use green power surpluses" (Interview no. 14). Furthermore, some hours of the year experience negative electricity prices, partially due to an oversupply of electricity from RES. Several stakeholders anticipate using excess renewable electricity as a substantial chance for low-carbon hydrogen and as "a storage medium to decouple volatile generation from volatile consumption" (Interview no. 13). This use case might not only be meaningful for wind power generation but also distributed solar photovoltaic (PV) surpluses during peak production hours, which one stakeholder explains: "generate hydrogen on-site from solar PV, store it and then convert it back into electricity on-site, i.e. without the need for transport." (Interview no. 9). In an energy system with high penetration of renewable generation, hydrogen production and storage could provide flexibility in both electricity generation (e.g. fuel cells and hydrogen-fired gas turbines) and electricity consumption (e.g. water electrolysis) to decouple inflexible electricity demand and fluctuating supply. Energy communities and local microgrids which strive for energy autarky could be additional use cases, where hydrogen could provide energy storage and increase flexibility. However, Germany is expected to depend on energy imports in the long-term as indigenous energy demand exceeds energy supply potentials, particularly RES potentials. Hydrogen could foster the **import of renewable energy** (13%), as it may be produced abroad at lower costs and then used as an energy import medium to Germany, due to its beneficial transport and storage capabilities, compared to electricity, as the following stakeholder indicates: "And that is also a huge advantage of hydrogen but even more so, of course, of the synthetic fuels produced from hydrogen, which can be transported very well and can be produced in locations where wind turbines produce a factor of three times more energy than an onshore wind turbine in Germany. That makes transport almost negligible in comparison. Of course, I also have a considerable cost advantage because I need far fewer solar PV modules and fewer wind turbines than I do now with production in Germany." (Interview no. 14). Therefore, stakeholders hope "to be able to harvest the huge renewable [energy] potentials internationally." (Interview no. 3).

From a global perspective, hydrogen trade offers possibilities in *international policy.* Existing import dependencies could be reduced and new import partnerships could be established with the benefit of **reorganising energy imports** (13%). Unlike oil and gas, RES-based hydrogen is not limited to fossil resources; instead, its production is technically possible almost in every country. Therefore, hydrogen imports could potentially be more diversified. Another foreign policy aspect of hydrogen is its potentials in

international development policy and geopolitics, as one interviewee describes: "But I see the opportunities for value creation in countries that have not been so active industrially up to now [...], and also for ensuring that there are stable relationships among the countries which then trade with each other. So I see the advantages rather than the risks. But as with all things, the sustainability criteria are, of course, very important." (Interview no. 14). New options of international cooperation through hydrogen projects, especially regarding development policy (e.g. hydrogen imports from MENA-states or Ukraine) and geopolitics (e.g. continuing energy imports from Russia to maintain economic relations), could emerge. Around 21% of interviewees share this opinion.

4. Implications for the hydrogen market ramp-up

In the following section, three hypotheses are presented and discussed, derived from the stakeholder analysis by synthesising the most important findings from the stakeholder identification, the SNA, and the clustered chances and risks. The hypotheses aim at identifying essential implications for the market ramp-up in general and its stakeholders in particular. The topics (i) reorganisation of hydrogen market roles, (ii) distributional conflicts on the demand side of a hydrogen market, and (iii) the impact of a lack of stakeholder coordination and hydrogen competitiveness are addressed.

Hypothesis 1: The market ramp-up reorganises stakeholders along the supply chain

Today, hydrogen is predominantly used as a feedstock in the (petro-)chemical industry. Trading of hydrogen is limited (5% of global consumption (FfE, 2019)) and mostly takes place by vertically integrated companies, who own production and transportation infrastructure. With its potential for electricity storage and energy system integration, hydrogen is likely to transform from a feedstock to an energy carrier. As a consequence thereof, a fundamental reorganisation of the market and its participants will take place.

Our results indicate that this is most significant on the supply side of the developing hydrogen market. The (petro-)chemical industry, as the largest producer and consumer of conventional hydrogen in Germany today, as well as industrial gas producers, could relinquish their leading roles in production when conventional hydrogen is replaced with RES-based hydrogen. The SNA identifies electricity utilities as a central and well-connected player in the current landscape of hydrogen demonstration projects. This view is confirmed by the stakeholder interviews, where electricity utilities are seen as a major beneficiary of a hydrogen market ramp-up. Utilities could take a leading role in RES-based hydrogen production in Germany. With their RES portfolio and expertise in supply and trading, for instance, they have a competitive advantage.

To enable a competitive and liquid hydrogen market to emerge, physical and financial trade possibilities must be created. Different options for hydrogen transportation can be used to enable physical trade, e.g. blending hydrogen into natural gas grids, new hydrogen pipelines as well as conversion of natural gas to hydrogen pipelines, liquefied or compressed hydrogen transportation in trucks, tank wagons or ships, and as liquid organic hydrogen carriers (LOHC). In the short-term, hydrogen will mostly be generated close to consumption to avoid costly long-distance hydrogen transportation. In the medium and long term, the grid-based transport of hydrogen could become necessary when local clusters are connected and large volumes of hydrogen are imported. Transmission pipelines are generally the most economical transportation option to transport large volumes within Germany or Europe. Consequently, gas grid operators, in particular, will most probably play a central role in hydrogen infrastructure development, for instance, by converting existing natural gas pipelines for hydrogen. Alternative modes of transportation could involve other stakeholder groups, for instance, railway system operators, logistics, or shipping companies.

In the beginning, conventional hydrogen could be replaced with RES-based hydrogen, e.g. in the (petro-)chemical industry as a *no-regret* decarbonisation option. However, the characteristic of hydrogen as a medium for sector coupling implies that the use of hydrogen as a feedstock today will increasingly shift toward utilisation as an energy carrier in multiple new appliances, e.g. in the steel industry (as a feedstock), for the provision of high-temperature heat in the industry and the mobility sector. It is uncertain which consumers will first adopting hydrogen in new applications, but the demand side will most probably become increasingly heterogeneous. This potential source of conflict is further discussed in the following Hypothesis no. 2.

The ramp-up of a new market and the inherent reorganisation of the involved stakeholders might call for developing a comprehensive regulatory framework. A hydrogen market is embedded in a complex environment of stakeholders, markets, and systems and interconnects highly regulated infrastructure assets, i.e. the electricity and gas system. Given these peculiarities of a hydrogen market, policymakers should be aware of the effects on the entire spectrum of stakeholders when changing the regulation of energy systems for a hydrogen market ramp-up. Profound changes in the energy system regulation could be required in order to facilitate sustainable market development. Moreover, a German hydrogen market will most probably be part of a European market. Thus, integration with EU legislation should be considered from the very beginning.

Hypothesis 2: Distributional conflicts on the demand side requires political prioritisation during the market ramp-up

As previously explained, hydrogen is an ideal and versatile medium for sector coupling and it enables to decarbonise sectors, which are very difficult to be electrified. Currently, hydrogen is assessed in real-life projects by almost every final energy demand sector, as the SNA and the stakeholder interviews reveal. Our results particularly point toward the steel and chemical industry as well as heavy-duty transportation, aviation, and shipping as early hydrogen adopters on the demand side. Other demand uses, particularly household heating, power generation, and individual transportation, are considered only in the long-term. Particularly during the market ramp-up, when hydrogen trade partnerships with exporting countries and hydrogen import infrastructure are not established yet, RES-based hydrogen is expected to be very scarce. Hence, limited supply meets highly ambitious utilisation scenarios on the demand side. Distributional conflicts do not only occur between different final energy demand sectors but also within a sector (e.g. the steel industry versus the chemical industry). Hydrogen utilisation will also require investments in new technologies (e.g. new steel production plants, adjustments in heating equipment in buildings, fuel cell vehicles, hydrogen filling stations, etc.) that are not as mature and still inhere technical challenges. As a consequence, public support will be required to develop, demonstrate, and commercialise novel technologies. By determining governmental support for specific end-use applications, politics implicitly address the distributional conflict on the demand side.

In an ideal hydrogen market, price signals coordinate individual market participant's decisions and lead to a cost-efficient allocation of hydrogen. Furthermore, different energy taxes, CO_2 prices, and levies distort price signals from the beginning. Hence, it is justified to use political intervention to allocate scarce hydrogen supply during the market ramp-up.

In the end, an essential advantage of hydrogen is its ability to decarbonise energy utilisation. From an economic point of view, CO_2 abatement cost is a central metric to prioritise demand sectors. Policy measures, which steer scarce hydrogen resources during the market ramp-up, could be based on this metric to strengthen price signals. As RES-based hydrogen utilisation is not yet economical in end-use, such policy measures could be, for instance, quota obligations or capital expenditures (CAPEX) support in specific end-use sectors to accelerate and guide the market ramp-up towards the politically desired outcome. Additionally, policymakers may have further interest in a hydrogen market besides climate protection, such as industrial or international policy. Translating metrics like CO_2 abatement costs and other strategic targets into political support instruments is challenging and should be investigated by further research.

Simultaneously, technology-neutral hydrogen production (indigenous or as imports) could increase hydrogen supply to mitigate distributional conflicts on the demand side and improve the security of supply.

Hypothesis 3: The economic gap between conventional and RES-based hydrogen aggravates the three-sided chicken-and-egg problem

In the hydrogen market ramp-up, nothing less than a synchronised build-up of low-carbon hydrogen demand, supply, and infrastructure must be coordinated. In all three areas, there are still various uncertainties. This situation can be interpreted as a three-sided *"chicken-and-egg"* problem: without supply, there is no demand, without demand, there is no supply, and without a transportation infrastructure, a spatially distributed trade is not possible. This coordination problem is further complicated by the substantial economic gap between conventional and RES-based hydrogen. The high costs, particularly of RES-based hydrogen, is a significant obstacle for a wide diffusion in the end-use sectors. Like carbon leakage, high costs of low-carbon hydrogen could ultimately impede the market ramp-up and lead to a relocation of industries in international competition.

Currently, this issue is partly solved through publicly funded integrated demonstration projects where stakeholders along the supply chain (supply, transport, consumption) cooperate in closed and coordinated environments. In the medium term, policymakers should aim to gradually reduce the economic gap and strengthen the market, e.g. by direct production support for RES-based hydrogen through (Carbon) Contracts for Difference ((C)CfD), feed-in tariffs or tax exemptions. While closing the economic gap on the production side, competition on the demand side is held up. Since scarcity in RES-based hydrogen during the market ramp-up could result in prohibitive hydrogen prices, prioritisation on the demand side could be required as an additional measure (see Hypothesis no. 2). In the long-term, politics should aim for a non-discriminatory market, where price signals allocate resources and distorting effects of subsidies and taxes are gradually removed to avoid ongoing public support for hydrogen technologies. Hence, a target model for a competitive hydrogen market should be defined and pursued from the beginning of a market ramp-up.

5. Conclusion

In this paper, a comprehensive stakeholder analysis of a hydrogen market ramp-up in Germany is presented. The stakeholder identification, categorisation, and analysis of relationships use interviews as primary and literature as well as an assessment of real-life hydrogen demonstration and R&D projects as secondary data sources. The qualitative data is analysed using Qualitative Content Analysis (QCA) and

Social Network Analysis (SNA). The research design ought to ensure that information is systematically and methodologically analysed.

In total, 49 stakeholder groups are derived from the data and defined accordingly. The relationships between stakeholders are analysed on two levels: first, results on cooperation and centrality of stakeholder groups is presented by applying a SNA on the hydrogen project data. Second, potential conflicts between stakeholders are revealed by analysing stakeholder interviews employing QCA. Furthermore, stakeholder's perceived chances and risks of a hydrogen market for both individual stakeholder groups and the economy as a whole are shown.

Our results indicate that electricity utilities, R&D, hydrogen technology provider, and public companies are the most central stakeholders during the market ramp-up. Gas grid operators will most probably play a central role in hydrogen transportation. On the demand side, interviewees assumed the (petro-)chemical and steel industry, heavy-duty and utility vehicles, and aviation/ shipping as the most critical stakeholder groups. The household heating sector, the power sector and individual mobility were not seen as important stakeholder groups in the short-term. However, stakeholder groups from beyond the value chain could affect a market ramp-up, for instance, NGOs, Energy Service Companies (ESCO), public companies, or associations. Interestingly, most interviewed stakeholders did not expect substantial conflicts between stakeholder groups during the market ramp-up.

Significant risks emerge for the oil and gas industry and energy-intensive industries, as hydrogen could replace parts of fossil fuel supply and could substantially increase energy-related production costs. Though, simultaneously hydrogen offers opportunities for new business models. External effects, competitive constraints, and the economic gap of hydrogen are expected to be major obstacles to the market ramp-up. Stakeholders called for public support to overcome initial frictions. In the long-term, a hydrogen market is expected to allocate scarce resources accordingly. Risks along the value chain could occur during the market ramp-up, such as technical challenges, uncertainties regarding costs, low security of supply, and acceptance issues. The latter was assumed to come from the population or society as a whole. Transparent information and communication strategies play a crucial role to avoid acceptance issues. Germany will most probably import large volumes of hydrogen. Aspects of international policy should not be neglected. The German government must ensure that hydrogen production in exporting countries does not negatively affect the local population and beneficiaries are appropriately shared among all stakeholders. Furthermore, the geopolitical impacts of changing import dependencies must be carefully balanced.

For stakeholders and the economy as a whole, economic opportunities emerge through a hydrogen market ramp-up. Sustainable business models and a new market are to be created, for instance, for electricity utilities, RES operators, the oil and gas industry, hydrogen technology, and consumption equipment providers. The energy system can benefit from emission reduction, RES integration, enhanced flexibility, and resilience. On a global scale, the ramp-up of a hydrogen market increases the chance of reorganising energy import dependencies, as hydrogen can theoretically be produced in any country. Furthermore, an international hydrogen trade could positively influence geopolitics and development policy goals.

The analysis has shown that the market ramp-up will profoundly reorganise stakeholders' roles along the hydrogen value chain. The change is most significant on the supply side, where electricity utilities are expected to become the central player regarding the production of RES-based hydrogen, thus, partially replacing the chemical industry and industrial gas companies. During the market ramp-up, governmental intervention will need to solve distributional conflicts on the demand side to prioritise scarce RES-based hydrogen. Transparent and quantitative measures, such as CO_2 abatement cost, and technology-neutral hydrogen production should be used to lower the issue of scarce hydrogen resources during the ramp-up period. The three-sided "chicken-and-egg" problem and the economic gap call for governmental intervention as well in order to accelerate a politically desired market ramp-up. However, a long-term strategy including a hydrogen market target model should be defined to avoid continuing financial support for and political intervention in a hydrogen market.

Our work can be understood as a synthesis of hydrogen stakeholders' current landscape during the market ramp-up and their characteristics. Several new research questions emerged, which must be assessed in more detail, such as determining suitable supporting instruments for hydrogen technologies, in-depth analysis of relationships between stakeholders (particularly concerning conflicts), geopolitical impacts of global hydrogen trade, or the efficiency of immature hydrogen markets.

While aiming for a rigour research design, our analysis still has limitations that need to be considered. First, our collected data may not be exhaustive, as both hydrogen projects and stakeholder interviews could be extended. The latter, in particular, shows by nature a hardly avoidable influence of subjectivity of interviewed individuals. Second, the data analysis methods require interpretation and subjective evaluation to a certain extent. And third, our analysis is limited to Germany and the market ramp-up period.

Acknowledgements

Financial support for this research by the "Research Programme Hydrogen: The Role of Gas in the Energy Transition", an initiative of the Society of Benefactors to the EWI (Gesellschaft zur Förderung des EWI e.V) is gratefully acknowledged. We thank Marc Oliver Bettzüge, professor of energy economics and director of the Institute of Energy Economics at the University of Cologne (EWI) for his guidance and support. We also thank Samir Jeddi for his valuable feedback and all experts participating in the interviews and focus groups.

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Appendix A. Hydrogen project data

Table A.4: Overview of considered German hydrogen related power-to-gas projects

Audi e-gas	Klimafreundliches Wohnen in Augsburg
bioCO2nvert	Klimaneutrales Stadtquartier - Neue Weststadt Esslingen
BioPower2Gas	Kopernikus-Projekt P2X
Carbon2Chem	Leuchtturmprojekt Power-to-Gas Baden-Württemberg
cec - clean energy conversion	Lingen BP Refinery
CO2RRECT	localHy
Direktmethanisierung von Biogas in Power-to-Gas-Anlage	lübesse@energie
E2Fuel	MefCO2
E-CO2MET Raffinerie Mitteldeutschland	MethFuel (MethQuest)
eFarm	Norddeutsches Reallabor
Ekolyser	P2G Ketzin
ElementEins	Power 2 Metal
Energie im Container	Power to X Allianz
Energiepark Pirmasens-Winzeln	PtG-Anlage Metelen
EnergieparkBL	Quarree100
Forschungsprojekt "Energiepark Mainz"	Reallabor Westküste100
Get H2 Nukleus	Referenzkraftwerk Lausitz
Green MeOH	REFHYNE
GreenHydroChem	RefLau
GreenPower2Jet (GP2J)	Regenerativer Energiepark Ostfalia
GrInHy2.0	RegEnKibo
H2 Mobility Joint Venture	RH2-Pripsleben/Tützpatz/Gültz project (RH2-PTG)
H2anau	RH2-WKA
H2BER	SALCOS (3.Baustein)
H2BrakeCO2	Smart Grid Solar
H2-Flex	SmartQuart
H2Herten	STORE&GO
H2-Modellregion Düsseldorf - Wuppertal - Rhein-Kreis Neus	Stromlückenfüller
H2Move	tkH2Steel
H2ORIZON	Versuchsanlage Reußenköge
H2-Projekt Ellhöft/Westre	Wasserstoffanlage am Wasserkraftwerk Wyhlen
HELMETH	Wasserstoffelektrolyse-Anlage
HPEM2Gas	wind2gas energy
Hybridge	WindGas Falkenhagen
Hybridkraftwerk Prenzlau	WindGas Hamburg
HydroHub Fenne	Windgas Haurup
HySynGas	WindH2 (2.Baustein)
Hyways for Future	Windstrom zu Methanol
HyWindBalance	
Kavernenanlage Etzel	

Appendix B. Social network analysis

Table B.5: Centrality indicators of stakeholder network (BC' = Betweenness of centrality ; DC' = Degree of centrality)

No.	Stakeholder group	BC'	No.	Stakeholder group	DC'
1	R&D	0.1147	1	R&D	0.8293
2	Hydrogen technolygy providers	0.0997	2	Hydrogen technolygy providers	0.8293
3	Electricity utilities	0.0875	3	Electricity utilities	0.7317
4	Public companies	0.0494	4	Heavy-duty transport	0.6585
5	Muncipal utilities	0.0466	5	Muncipal utilities	0.6585
6	Heavy-duty transport	0.0466	6	Associations	0.6341
7	Project developers	0.0465	7	Public companies	0.6098
8	RES plant operator	0.0313	8	ESCOs	0.5854
9	Associations	0.0295	9	Vehicle manufacturers & OEMs	0.5610
10	ESCOs	0.0268	10	Project developers	0.5610
11	Petroleum industry	0.0243	11	Industrial gas companies	0.5122
12	Gas TSOs	0.0204	12	Gas TSOs	0.5122
13	Vehicle manufacturers & OEMs	0.0147	13	Industrial sector	0.4878
14	Politics	0.0139	14	Chemical industry	0.4878
15	Industrial sector	0.0101	15	Petroleum industry	0.4878
16	Industrial gas companies	0.0086	16	Politics	0.4634
17	Chemical industry	0.0081	17	RES plant operator	0.4390
18	Gas industry	0.0059	18	Gas industry	0.4390
19	NGOs	0.0043	19	NGOs	0.3902
20	Heating system manufacturers	0.0030	20	Storage operators	0.3415
21	Consultants	0.0027	21	Rail transport	0.3171
22	Gas DSOs	0.0018	22	Consultants	0.3171
23	Storage operators	0.0013	23	Electricity TSOs	0.2927
24	Transport sector	0.0012	24	Aviation	0.2927
25	Electricity TSOs	0.0011	25	Transport sector	0.2927
26	Water resource management	0.0008	26	Water resource management	0.2683
27	Rail transport	0.0006	27	Heating system manufacturers	0.2683
28	Other commercial vehicles	0.0005	28	Gas DSOs	0.2683
29	Aviation	0.0003	29	Steel industry	0.2683
30	Steel industry	0.0002	30	Seaports	0.2195
31	ICT industry	0.0002	31	ICT industry	0.2195
32	Electricity DSOs	0	32	Cement industry	0.1951
33	Energy cooperatives	0	33	Other commercial vehicles	0.1707
34	Agriculture & Forestry	0	34	Electricity DSOs	0.1463
35	Refineries	0	35	Buses	0.1463
36	Seaports	0	36	Intra logistics	0.1463
37	Buses	0	37	Refilling station operators	0.1463
38	Intra logistics	0	38	Building sector	0.1220
39	Building sector	0	39	Institutional investors	0.0732
40	Cement industry	0	40	Energy cooperatives	0.0488
41	Refilling station operators	0	41	Refineries	0.0488
42	Institutional investors	0	42	Agriculture & Forestry	0.0244

Appendix C. Interview documentation

Appendix C.1. Interview guide

Introduction[16]

The coordination and involvement of potential stakeholders of a future hydrogen market in today's decision-making processes are of central importance for the success of a hydrogen market ramp-up. As a basis for this, a comprehensive stakeholder analysis can provide information about possible stakeholders to be involved and potential problems between them. The stakeholder analysis conducted by the EWI therefore aims to identify and categorise possible stakeholders of a future hydrogen market and to determine their potential interests and influence. Based on this, conflict and cooperation potentials are to be derived, which could be used as guidelines for future stakeholder processes by providing recommendations for action.

Introductory question

We are in the year 2030+ and nothing fundamental has changed in the political objectives of the energy transition. How is the hydrogen market structured in your view?

Assumption for following questions: A somehow structured hydrogen market exists.

Topic 1: Stakeholders of a hydrogen market in Germany

- In general, which stakeholders might be active on a hydrogen market?
  - In your opinion, what are the interests of the various stakeholders?
  - Could you think of stakeholders who have reservations or concerns about a hydrogen market?
  - What role could your company/organisation play on a hydrogen market?
- Which stakeholders could be influenced by a hydrogen market?
- What conflicts could arise between stakeholders during the market ramp-up?

Topic 2: Chances and risks of a hydrogen market

- For which stakeholders could the development of a hydrogen market pose risks?
  - In your opinion, what are these risks?
- For which stakeholders could the development of a hydrogen market offer an opportunity?
  - In your opinion, what are these chances?

[16] The interview guide used in the individual interviews and focus groups was originally written in German.

- Can you imagine new collaborations or partnerships between stakeholders?
- Do you see possible roles of a hydrogen market that are not currently populated by any stakeholder?
- Are there any other comments you would like to share with us for our analysis?

Appendix C.2. Interviews

Table C.6: Overview of interviews and focus groups

No	Type of stakeholder	Type of interview (individual/ focus group)	Duration [min.]
1	Electricity utilities/ electricity DSOs	individual	46
2	Natural gas industry	individual	44
3	Hydrogen technology providers	individual	55
4	Heating system manufacturers	individual	46
5	Municipal utilities	individual	39
6	Associations	individual	45
7	Consultants	individual	31
8	Hydrogen technology providers	individual	35
9	Heating system manufacturers	individual	37
10	NGOs	individual	38
11	Politics	individual	44
12	NGOs	individual	29
13	Rail transport	individual	30
14	Vehicle manufacturers & OEMs	individual	53
15	Petroleum industry	individual	31
16	NGOs	individual	39
17	Associations	individual	48
18	Public companies	individual	43
19	Chemical industry	individual	19
20	Industrial gas companies	individual	38
21	Vehicle manufacturers & OEMs	individual	34
22	Electricity TSOs	individual	23
23	Chemical industry	focus group	85
24	Municipal utilities	focus group	85
25	Electricity utilities	focus group	85
26	Associations	focus group	85
27	Gas TSOs	focus group	85
28	Electricity utilities	focus group	85
29	NGOs	focus group	78
30	Steel industry	focus group	78
31	Gas TSOs	focus group	78
32	Institutional investors	focus group	78

Table C.7: Relative frequency of stakeholder category mentions in the interviews

Stakeholder category	Relative frequency	Stakeholder category	Relative frequency
Steel industry	83%	Refilling station operators	29%
Transport sector	75%	Electricity TSOs/DSOs	25%
Chemical industry	71%	Institutional investors	25%
Heavy-duty transport	71%	Intra logistics	25%
Hydrogen technology providers	71%	Society	25%
Natural gas TSOs/DSOs	67%	Cement industry	21%
Electricity utilities	63%	Citizens' initiaitves	21%
Building sector	58%	Other commercial vehicles	21%
Industrial sector	58%	Shipping	21%
Aviation	42%	Heating system manufacturers	17%
NGOs	42%	Research and Development	17%
Petroleum industry	42%	Associations	13%
RES plant operators	42%	Districts	13%
Refineries	38%	Agriculture & Forestry	8%
Individual transport	33%	Consultants	8%
Natural gas industry	33%	Energy cooperatives	8%
Politics	33%	Hydrogen exchange	8%
Storage operators	33%	ICT industry	8%
Vehicle manufacturers and OEMs	33%	Project developers	8%
Buses	29%	Airport operators	4%
Industrial gas companies	29%	Water resource management	4%
Municipal utilities	29%	ESCOs	0%
Rail transport	29%	Public companies	0%

Table C.8: Relative frequency of interviewed stakeholders' perceived chances

Chances	Relative frequency
Decarbonisation of corporations and organisations	75%
Business opportunities for oil and gas	71%
Integration of RES	54%
Energy storage and system flexibility	54%
Emission reduction	50%
New market opportunities	46%
Business opportunities for energy utilities and RE producers	42%
Market for hydrogen technology provider	42%
Export of technology	29%
International development policy and geopolitics	21%
Sector coupling	17%
Reorganisation of energy imports	13%
Renewable energy imports	13%
Regional value creation	8%

Table C.9: Relative frequency of interviewed stakeholders' perceived risks

Risks	Relative frequency
Loss of relevance of fossil fuels	63%
Technical challenges	58%
Cost uncertainty	54%
Relocation of Industry	42%
Fair distribution in exporting countries	33%
Acceptance issues of hydrogen	33%
Acceptance issues of increased RE demand	33%
Lock-In effects	29%
Market ramp-up risks	25%
First Mover uncertainty	25%
Hydrogen import dependency	21%
Geopolitical impacts	21%
Water scarcity	21%
Security of supply	17%