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Research Paper

Stakeholder perspectives on the scale-up of green hydrogen and electrolyzers

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ABSTRACT

Green hydrogen is a promising alternative to fossil fuels. However, current production capacities for electrolyzers and green hydrogen are not in line with national political goals and projected demand. Considering these issues, we conducted semi-structured interviews to determine the narratives of different stakeholders during this transformation as well as challenges and opportunities for the green hydrogen value chain. We interviewed eight experts with different roles along the green hydrogen value chain, ranging from producers and consumers of green hydrogen to electrolyzer manufacturers and consultants as well as experts from the political sphere. Most experts see the government as necessary for scale-up, by setting national capacity targets, policy support and providing subsidies. However, the experts also accuse the governments of delaying development through overregulation and long implementation times for regulations. The main challenges that were identified are the current lack of renewable electricity and demand for green hydrogen. Demand for green hydrogen is influenced by supply costs, which partly depend on prices for electrolyzers. However, one key takeaway of the interviews is the skeptical assessments by the experts on the currently discussed estimates for price reduction potential of electrolyzers. While demand, supply, and prices are all factors that influence each other, they result in feedback loops in investment decisions for the energy and manufacturing industries. A second key takeaway is, that according to the experts, current investment decisions in new production capacities are not solely dependent on short-term financial gains, but also based on expected first mover advantages. These include experience and market share which are seen as factors for opportunities for future financial gains.

Summarized, the results present several challenges and opportunities for green hydrogen and electrolyzers, and how to address them effectively. These insights contribute to a deeper understanding of the dynamics of the emerging green hydrogen value chain.

1. Introduction

1.1. Green hydrogen basics

Green hydrogen is defined as hydrogen produced via water electrolysis with electricity from renewable sources (Proost, 2020; Rabiee et al., 2021). This form of hydrogen is seen as a promising candidate for reducing greenhouse gas emissions (Oliveira et al., 2021) and achieving the climate goals of the Paris climate accord (Wappler et al., 2022). It is also now part of many energy system transformation strategies (Williams et al., 2021; Baker et al., 2021). This has led to interest in green hydrogen as a zero-emission fuel (Hartley and Au, 2020). Green hydrogen and its derivatives are particularly well-suited to eliminating emissions from sectors that cannot easily be electrified directly, for example the steel industry or the chemical industry (Griffiths et al., 2021; Luo et al., 2021). In addition, the projection of inexpensive excess energy from renewables has also led to the promise of a hydrogen industry based primarily on hydrogen from electrolysis (Fonseca et al., 2019; Maggio et al., 2019). At the same time, green hydrogen has the potential to be a storage solution for the intermittent nature of

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renewables (Razi and Dincer, 2022). A literature review by Khalilpour et al. shows how an increased interest in green hydrogen is reflected by a rise in scientific publications (Khalilpour et al., 2020). At the same time, there has been an increase in policy initiatives that support the development of green hydrogen production technologies (Zhang and Zhang, 2021; Liimatainen, 2021). Some researchers expect that global demand for hydrogen will exceed 500 million tons per year by 2070 (Nnabuife et al., 2022). However, estimates for global demand vary greatly (e.g. 67 million tons (IRENA, 2019) to 650 million tons (Hydrogen Council, 2017) in 2050).

1.2. Current state of the green hydrogen industry

Renewable sources may be the preferred choice to produce hydrogen with the least emissions, but in the short term, fossil fuels may play an important role (Moliner et al., 2016) to pave the way for large-scale hydrogen usage. At present, 85% of hydrogen is produced locally in refineries (Van de Graaf et al., 2020), while 95% of hydrogen is produced by fossil fuels (Trattner et al., 2022). However, compared to the huge demand that is projected, current production of low-emission hydrogen only accounted for around 0.6 Mt in 2021 (IEA, 2022a). The green hydrogen value chain currently remains a niche industry. While there are plans to grow the industry, there is still a gap between the installed capacities of electrolyzers that have been announced and the capacities that are needed (IEA, 2022a).

1.3. Literature review

The impact of the green hydrogen value chain and its growth are the subject of intensive study. For the remainder of our paper, we define the "green hydrogen value chain" as the entire field of industries relating to green hydrogen. This includes the value chain of the electrolyzer (e.g., suppliers or electrolyzer manufacturers) as well as the producers of green hydrogen and green electricity. One area of research is the possible techno-economical potential of green hydrogen in different countries, for example Germany (Husarek et al., 2021; Bhandari and Shah, 2021; Neuwirth et al., 2022; Kumar et al., 2020), China, or Canada (Razi and Dincer, 2022). Most of these works are of a purely techno-economic nature. Methods of this type tend to examine technical factors or costs, modeling their development based on simplified rational actions (Turnheim and Nykvist, 2019) and ignoring the multitude of stakeholders involved. In comparison, socio-technical work on transformation processes focuses on a wider range of social factors, including economical and technical factors from stakeholder perspectives (Hirt et al., 2020). This approach is used, for example, to analyze pathways for the transition of the electricity sector (Verbong and Geels, 2010) or the decarbonization of the refinery sector (Nurdiawati and Urban, 2022). Using different scenarios, Damman et al (Damman et al., 2021). investigate what role hydrogen can play in the Norwegian industry. For the socio-technical analysis of the paper, stakeholder interviews were conducted to determine the history and current status of the industry with regard to hydrogen production and consumption, and to validate the results of techno-economic analyses. An analysis of stakeholder perspectives involving interviews by Asna Ashari et al (Asna Ashari et al., 2023). explores possible pathways for a hydrogen industry in Germany and South Korea. Schlund et al (Schlund et al., 2022). use semi-structured interviews to conduct a stakeholder network analysis of the German hydrogen industry. Andreasen and Sovacool (Peter Andreasen and Sovacool, 2014) have done a stakeholder network analysis for Denmark. Chantre et al (Chantre et al., 2022). used stakeholder interviews in their paper to create long-term visions for a hydrogen industry in Brazil. Upham et al (Upham et al., 2020). use stakeholder interviews to investigate the perspective for green hydrogen, but with a focus on fuel cell applications. Blohm and Dettner (Blohm and Dettner, 2023) use an interview-based analysis to identify aspects for the sustainable production of green hydrogen.

As shown, previous work has used the stakeholder concept in combination with interviews in the context of the hydrogen industry. The research questions vary from analysis of barriers and challenges for market introduction to network analysis of the relevant stakeholders. In many papers, the question of electrolyzer availability is neglected, as the focus is often on individual sectors (e.g., electricity or hydrogen production). To the best of the authors' knowledge, there is no literature that performs a stakeholder analysis with a specific view on electrolyzer production, policies, and their influence investment decisions. This paper aims to contribute to the current research and discussion on the market ramp-up of hydrogen and electrolyzers by analyzing the key stakeholders' experience including their opportunities, risks, and relationships. Whereby special interest is given to the impact of policy. The focus is on Germany and the Netherlands and the period of market ramp-up.

1.4. Scope and focus of the study

By focusing on the electrolyzer manufacturer and their product in Germany and the Netherlands, we aim to analyze the scale-up of the entire green hydrogen value chain. By including industry stakeholders, we can leverage up-to-date, first-hand experience. These help to enhance the scientific view on the current challenges and opportunities facing the industry. By focusing on a socio-technical analysis, we are not solely limited to economic decision-making. This paper is therefore focused on the following research questions: What are the actor-by-actor narratives as the green hydrogen value chain scales up? What are the key challenges for the green hydrogen value chain and what influences the investment decisions of the different stakeholders? What is the role of the government and how can it influence the growth of the green hydrogen value chain? For this purpose, we conduct semi-structured interviews to complete the findings with a thematic analysis in order to cluster the results into themes and concepts in relation to our research questions.

We focus on Germany and the Netherlands in our study for three reasons. In short, because these countries have large energy-intensive industries that may need hydrogen in the future, both countries have ambitious targets for the development of electrolyzers, and lastly because they already have a large demand for hydrogen today. In more detail, Germany, and the Netherlands both have large energy-intensive industries, which are often not easily electrified, making hydrogen a possible option for reducing greenhouse gas emissions. Fig. 1 shows the share of CO_2 emissions from energy-intensive industries in the EU.

Germany has a high share in the European steel, minerals, petroleum, and chemical industries, and the Netherlands has a high share in the European petroleum and chemical industries. Both countries combined make up a significant share of total CO_2 emissions from energy-intensive industries in the EU. Secondly, these countries have ambitious targets regarding hydrogen. The Dutch government aims to scale up electrolysis capacities to 500 MW in 2025 and 4 GW of installed electrolyzer capacity by 2030, which represents 10% of the total EU target for that year (Rijksoverheid, 2020). Fig. 2 shows the electrolyzer expansion to date and the targets for Germany and the Netherlands.

The figure shows that for Germany and the Netherlands, an increase in capacity by two and three orders of magnitude, respectively, is required to meet the 2030 targets. By setting these targets, both countries aim to be major players in green hydrogen. Thirdly, Germany and the Netherlands are already the two largest hydrogen consumers in the EU today (Rijksoverheid, 2020). For these reasons, we have chosen experts from these countries.

In summary, the following research questions can be identified for our investigations:

- Who are the individual stakeholders and how do their actions influence each other?

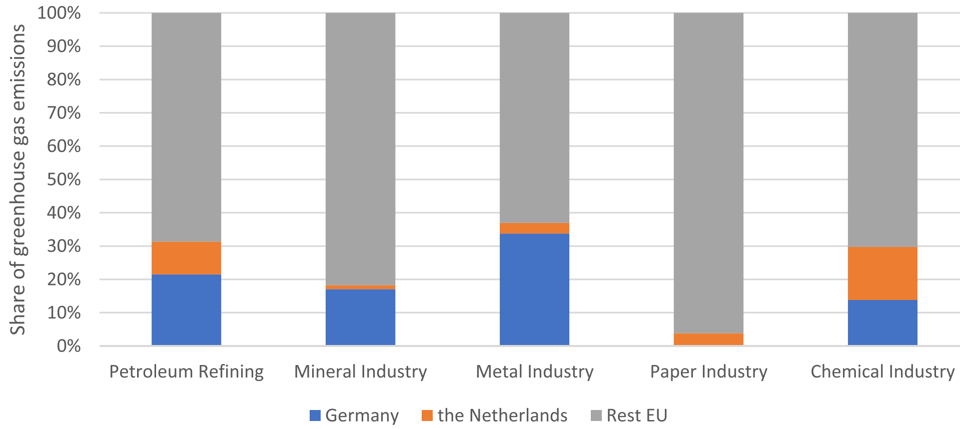

Fig. 1. Greenhouse gas emissions of energy intensive industries by country for 2020 – EU-27 (Eurostat, 2022).

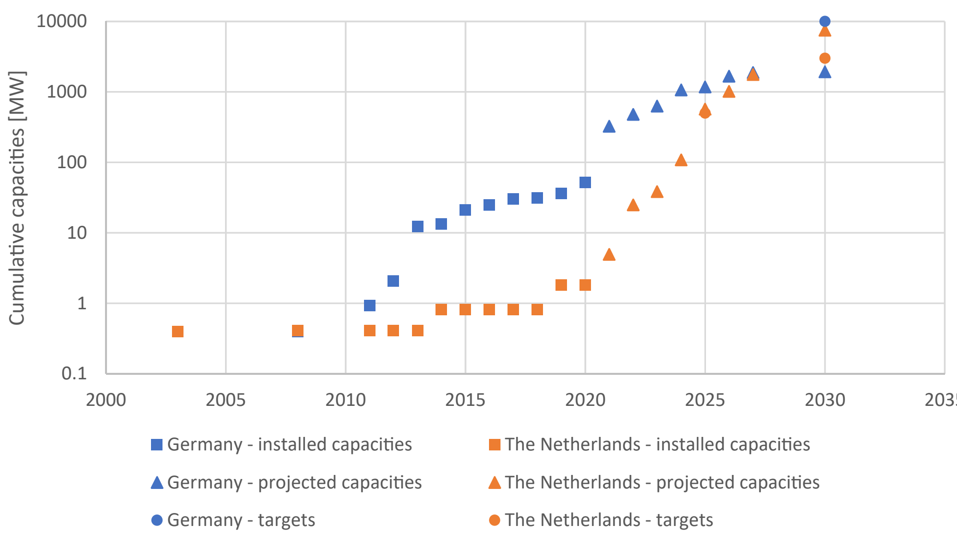

Fig. 2. Completed and planned electrolyzer projects (based on (Thema et al., 2019; Wulf et al., 2020) and policy targets (based on (Rijksoverheid, 2020; Bmwk, 2023).

- What are the current challenges and opportunities for the green hydrogen economy from the perspective of the stakeholders involved?
- What realistic future is seen for the industry?
- What are realistic price developments in the industry?
- What role do governments play in the development of the industry?
- What are reasons for current investments into the industry?

This paper aims to fill the research gap of these questions from a socio-technical perspective. The novelty is to answer them by considering the perspective of participating stakeholders rather than an academic view based on a techno-economic optimum.

The methods used are semi-structured interviews and a thematic analysis. The semi-structured form of the interviews allows us on the one hand to think through all our questions and on the other hand it allows deeper questioning and discussion based on given answers. The thematic analysis organizes the given answers and creates an overview of the different opinions on specific topics.

The remainder of this paper is structured as follows: In Section 2 the methodology, the data collection and the analysis methods are defined. Results are presented in Section 3 and interpreted. Section 4 summarizes the paper and closes with an outlook for future research.

2. Method

2.1. Semi-structured interviews: procedure and interview guide

2.1.1. Interviews

We conducted semi-structured interviews with industry experts to gain further in-depth knowledge in early 2022. An interview guide was developed and contained questions that explored: 1) the biggest challenge for the green hydrogen value chain; 2) the influential stakeholder; 3) possible challenges and opportunities; 4) the role of the government, and 5) the technological potential of electrolyzers. The interviews were conducted using this interview guide. The interviews were held in a semi-structured format and were partly influenced by the discussions, which sometimes led to follow-up questions where appropriate. The duration of the interviews was 1–1.5 h, and they were conducted online. All interviews were recorded with the consent of the participants and were transcribed verbatim from the audio recordings. The completed transcripts were reviewed to ensure that complete anonymity was retained. After each interview, the interview guide was revised to leverage the knowledge obtained by sharpening questions and reduce confusion for a better discussion. The modifications were only minor and should not affect the comparability of the interviews. The interview guide can be found in the supplementary data. Fig. 3 shows a comprehensive overview of the main stakeholders in the green hydrogen value

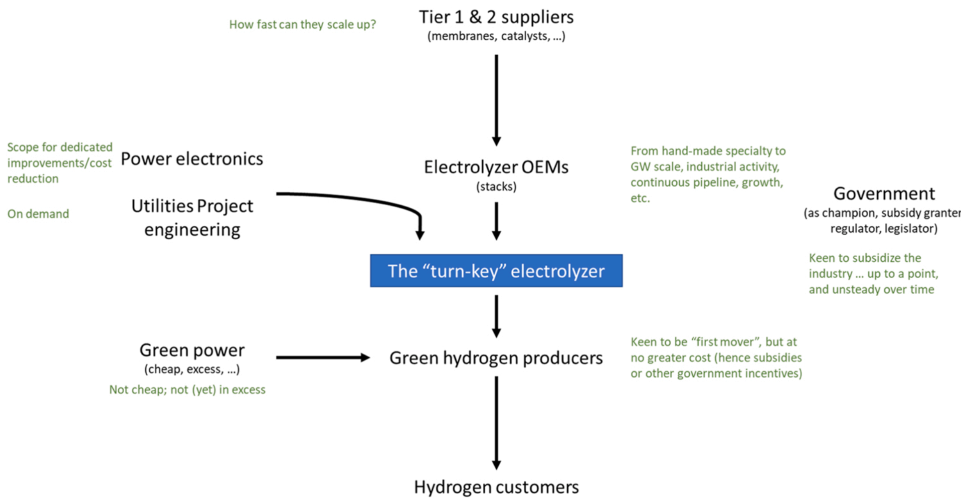

Fig. 3. Overview of stakeholders of the green hydrogen value chain.

chain. The overview as shown in Fig. 3 was used in the interviews as a visual guide and discussion point. We used public data to map the stakeholder network, their motivations, and their goals.

At the heart of our analysis is the electrolyzer, which is strongly connected to the hydrogen producer as a user and the electrolyzer manufacturer as a producer. Surrounding them are the participating stakeholders and their influences. Above and, therefore, "in front" of the electrolyzer in the value chain is the electrolyzer manufacturer, which is supplied with membranes and other parts by the tier 1 and tier 2 suppliers and assembles the individual parts into an electrolyzer stack. The electrolyzer manufacturers are currently still working on an individual unit production basis but must switch to GW scales and automation and, consequently, take decisions to invest in new production facilities. Today electrolyzer manufacturer are currently dominated by China and Europe, which represent around 66% of global capacities (IEA, 2023). Current electrolyzer OEMs in Germany and the Netherlands need to be active to secure their position. They are keen to be first mover to maintain or expand their share in the electrolyzer market, by investing into new and bigger manufacturing capacities. At the same time, suppliers may need to grow with them, to ensure the production of electrolyzers is not interrupted. It is unclear if they could be a potential bottleneck. The stacks produced by the electrolyzer manufacturers are combined with power electronics and other utilities cooperating over project engineering to form the "turnkey" electrolyzer. To streamline the complex process of planning and building the "turnkey" electrolyzer for the green hydrogen producer often EPC (Engineering, procurement, construction) contracts are used. This approach simplifies the process by having a single entity responsible for all aspects of the project. These electrolyzers will then be used by hydrogen producers to produce green hydrogen from renewable electricity on an industrial scale. However, there are still questions regarding the availability and costs of renewable electricity. The green hydrogen will then be used to either replace gray hydrogen or to be used in a new process by hydrogen customers. This could include applications like steel production, chemical manufacturing, or other industrial uses. Yet, the exact demand and willingness to pay are still unclear. Finally, the government has a special position in this process of building a green hydrogen value chain. They are not part of the green hydrogen value chain but try to influence its growth in various ways. This can include regulatory frameworks, incentives, funding, and policies that encourage the transition to green hydrogen production.

To ensure the objectivity of the interviews, multiple researchers of the team participate in the interviews. Furthermore, in addition to the interview guide, the corresponding author participated in all interviews to ensure consistency and comparability of the conducted interviews. Unfortunately, we do not have permission to publish the transcripts of the interviews.

2.1.2. *Interviewees*

For the selection of the experts, we made sure to integrate all important levels of the value chain and independent opinions. This methodological approach made it possible to ensure comprehensive representation of all essential perspectives. Given the specific focus on the production and availability of electrolyzers, opinions were sought from different electrolyzer manufacturers. The aim was to interview a larger number of manufacturers, but unfortunately many manufacturers did not agree to participate in our interviews. However, we were able to interview two manufactures of different types of electrolyzers, which allows for different opinions and outlooks. Between February and March 2022, eight stakeholders from Germany and the Netherlands were interviewed. The interviewees were a mixture of experts from consulting, industry, and the government. Table 1 shows the background and country of origin of the interviewees.

The industry experts interviewed can be categorized into green hydrogen producers, hydrogen consumers, electrolyzer manufacturer, and consultants. We deliberately selected participants with different perspectives along the green hydrogen value chain.

2.2. *Thematic analysis: coding and theme generation*

For the thematic analysis, we followed the six-step approach outlined by Braun and Clarke (Braun and Clarke, 2006). The transcripts of the

Table 1
Overview of interviewees.

Expert	Type	Position	Country
Expert A	Hydrogen producer	Innovation Technologist	Netherlands
Expert B	Consultant (for-profit org.)	Senior Manager Energy Strategy	Netherlands
Expert C	Consultant (non-profit org.)	Senior Consultant Energy Transition	Netherlands
Expert D	Electrolyzer manufacturer	Head of Public Affairs	Germany
Expert E	Electrolyzer manufacturer	Chief Executive Officer	Germany
Expert F	Hydrogen producer	Senior Manager Technology and R&D	Germany
Expert G	Fuel cell manufacturer	Director of Sales and Marketing	Germany
Expert H	Government	Policy Officer	Germany

interviews were coded and used to discuss general ideas in the data. The specific coding for this paper was developed and discussed in the research team. We subsequently went through the interviews and identified segments that were relevant to the research questions. Through multiple discussions, the codes were grouped into larger themes. The research team subsequently reviewed the themes discovered and discussed the final interpretations of the data.

The thematic analysis of interviews from stakeholders across the value chain allows us to identify common and differing stakeholder perspectives and understand the current developments and dynamics at play in the value chain, and hence answer the research questions posed in the previous section.

3. Results and discussion

Results are presented in relation to the following key themes: a) overview of the industry and b) challenges and opportunities for the green hydrogen value chain.

3.1. Overview

3.1.1. Industry stakeholders

The potential paths for the development of the green hydrogen value chain depend on many factors, such as market conditions, regulations, technical risks, and infrastructure (Hanley et al., 2015). For the industry to grow rapidly, many different stakeholders need to coordinate, with the most important stakeholders being the hydrogen and electrolyzer manufacturer and hydrogen customers as well as the electricity producers and the government. As mentioned above, Fig. 3 was used as the starting point for the discussion in the interviews. Most experts found it to be an accurate picture, but they suggested it was not always possible to separate the different roles. This is already the case with Siemens and STEAG, where a large electrolyzer manufacturer cooperates with an electricity provider to build and run a 17 MW electrolyzer (STEAG, 2019). Expert B mentioned, that especially in the early stages of scale-up, producers of hydrogen, electricity, and electrolyzers come together to form a consortium to better share the risks and the costs involved. This allows the realization of more or larger projects than if a single stakeholder had to bear all the costs and risks, which should help the scale-up. Further options can be that hydrogen producers generate their own electricity to guarantee the supply of green electricity. This is an attractive proposition, especially in the context of policies that require proof of the electricity's origin. In addition, it can be assumed that green hydrogen customers might produce green hydrogen themselves on site and thus become consumers and producers at the same time, since storage and transport can cause significant costs, as Expert C mentioned. Another possible explanation could be the scarcity of green hydrogen. Generating green hydrogen in-house ensures a more reliable supply compared to relying on external suppliers. However, this approach also entails that a single company shoulders the full burden of costs and risks. Such initiatives make sense, particularly during the industry's scaling-up phase, when the supply and demand for green hydrogen remain uncertain and limited. In practice, hydrogen and electricity consumers and producers are not always completely distinct. This happens to either disseminating financial burdens and risks through consortium formations or by ensuring a dependable supply of electricity or hydrogen. Both approaches can serve as determining factors leading to the approval of more projects, thereby facilitating the growth of the industry. However, it is reasonable to anticipate that specialization will emerge as the green hydrogen value chain evolves, as companies typically gravitate toward activities that optimize their profitability (Tsakanikas et al., 2022). In addition to the main stakeholders mentioned above, there are several other stakeholders that directly or indirectly influence the green hydrogen value chain. Among others, Expert A mentioned the financial sector as a stakeholder involved, as electrolyzer and hydrogen producers are likely to need debt capital for the investment. Furthermore, Expert H mentioned infrastructure operators, since the transport and storage of hydrogen adds significant costs. The green hydrogen produced can be used to produce carbon-based chemicals like methanol or other chemicals like ammonia (Capurso et al., 2022). Initial project plans are already being developed, such as the Rhyme Bavaria project, which plans to use green hydrogen to produce 15,000 t/a of methanol (Wacker, 2022). However, Expert D found the provision of water for electrolysis and CO_2 to be less important for the overall growth of the industry, since they see investment in new electrolyzers as a bigger challenge.

For this reason, we will subsequently focus on the following stakeholders: Hydrogen customers, hydrogen producers, electrolyzer manufacturers, electricity producers, and the government.

3.1.2. Role of the government

Companies have a direct influence on the development of the green hydrogen value chain, mainly through their investment decisions, while governments have a more indirect influence. However, governments can influence the value chain at different points. For example, they can influence the cost-competitiveness of green hydrogen through incentive policies (e.g. subsidies, cf (European Commission, 2022). or a CO_2 tax, cf (European Union, 2018).). They can also bring about a certain demand for green hydrogen through mandates, which to date has only happened in several places (IEA, 2022b). Governments can also encourage investment in new renewables (cf (Bundesregierung Deutschland, 2017).). Finally, governments can directly reduce the cost of electrolyzers through subsidies on hydrogen or electrolyzers (cf (European Commission, 2022).). The experts interviewed agreed that governments will play an important role, but there were two different opinions on what the role of the government will be. On the one hand, the government can provide planning security through regulations and targets. In particular, the EU renewable energy directive RED II (Wilson, 2022) was highlighted by most experts (Expert A, C, E, H) as a key driver of demand for green hydrogen. The EU's strategy sets specific targets for 2024 and 2030 (European Commission, 2020). Certification and standardization are regarded by the industry as a significant means of how governments could support the growth of the green hydrogen value chain (DNV, 2022). Some notable instances of beneficial policy measures encompass financial support allocated to hydrogen technology and systems through Important Project of Common European Interest (IPCEI) initiatives (cf (European Commission, 2022).). According to Expert A, subsidies play a pivotal role for companies within the industry, given the scarcity of equity in these companies for independent execution of such projects. Another instance of favorably seen policies involves the promotion of hydrogen refueling stations in Germany, (cf (BmDV, 2023).), which will help to stimulate the demand for green hydrogen. As noted by Expert B, particularly on the demand side, the carbon pricing policy stands as a driving force for industry, ensuring that products derived from green hydrogen become competitiveness. However, policies need to be in place to prevent the industry from relocation. In this regard, Expert B mentioned the Carbon Border Adjustment Mechanism (CBAM) of the EU (cf (European Commission, 2023).) as a safety net. Expert H concurs, emphasizing the necessity for local policymakers to intervene to retain employment opportunities within the region.

However, politics can also effectively hinder the scale-up of the industry. The RED II directive was cited by the experts as a negative example. It has not yet been clarified and thus delays investment decisions. Furthermore, the industry sees uncertainties regarding the certification of green hydrogen as a risk (GroenvermogenNL, 2022). The experts share this view and consider the prerequisites for certification to be another possible bottleneck. In addition, Expert E warned that the government should be wary of overregulation and should facilitate the rapid growth of the green hydrogen economy by imposing fewer requirements, or at least to not hinder its growth by being too strict. The requirements for the certification of green hydrogen are seen as a potential bottleneck by the interviewees. One example that was often mentioned is the rumored plan as part of RED II to only certify green hydrogen produced by electricity sourced from dedicated newly built green energy projects.[1] Similar concerns that RED II could hinder green hydrogen production in Europe have also been expressed by industry in the press (Graham, 2022). Since the interviews, the question has remained as to what kind of electricity to use to produce certified green hydrogen. In the meantime, there is a dispute in the European Union about low-carbon hydrogen, with France demanding that such hydrogen produced by electrolysis using electricity from nuclear power plants should also be certifiable (Jack, 2023). As reported, countries such as Romania, Bulgaria, Slovenia, Croatia, Slovakia, and Hungary argue that this could accelerate the scale-up of the hydrogen industry (Abnett, 2023). Other potential pitfalls include questions of responsibility between different ministries, as Expert E criticized. Furthermore, Expert G felt that existing regulations should be revised to ensure that there are no false financial incentives and that there is a fair playing field for technologies using hydrogen. They mentioned, for example, that buses with overhead lines would receive more funding than fuel cell buses. Another instance of biased favoritism towards alternative technologies over hydrogen is exemplified by the pilot project involving overhead lines on German highways, which primarily promotes direct electrification for long-distance transportation (cf (Autobahn GmbH, 2023).). Expert G disapproves of the prevalent trend of offering subsidies exclusively for projects for technological development, contending that these subsidies primarily yield prototypes and do not significantly contribute to the scale-up of the industry via mass production. In contrast, Expert A holds a differing viewpoint, asserting that such regulations are essential to prevent stagnation in technological advancement. Due to the continuous potential for innovation in electrolyzer technology, Expert A maintains that these regulations are crucial in promoting advancements.

3.2. Challenges and opportunities

3.2.1. Biggest challenges

While governments can attempt to influence the development of the green hydrogen value chain through directives and incentives, growth will be determined by investment from producers of green hydrogen, renewable electricity, and electrolyzers. The existence or expectation of unmet demand is usually a condition for investment in new production facilities, whether it is demand for green hydrogen or for electrolyzers. Most experts (Expert B, D, E, G) interviewed agreed that the lack of demand for green hydrogen is currently one of the biggest obstacles. Industry sees targets set by governments as an important tool to create long-term demand, which would create more security for investments (Hydrogen Council, 2022). While scientific analyses usually predict huge demand for green hydrogen (Pathak et al., 2022), and governments have set targets (cf (Rijksoverheid, 2020; European Commission, 2020; Bmwi, 2020; METI, 2019; Diis, 2019).) to stimulate demand for hydrogen, key stakeholders see a "chicken or egg" dilemma. In simple terms, this means that investment in large-scale green hydrogen production is limited by uncertain demand, while the commitment to use green hydrogen is hindered by the high costs of green hydrogen. However, the costs of green hydrogen can be reduced through large-scale investment in green hydrogen production. In addition, demand for green hydrogen depends on whether the price of green hydrogen can compete with hydrogen from other sources. In other words, there would need to be a coordinated investment dynamic of different industries without a coordinating body, such as governments.

The cost of green hydrogen is strongly dependent on the price and availability of renewable electricity (Martínez de León et al., 2022). Dutch industry says that for the Netherlands, operational expenses (OPEX) and, in particular, electricity costs are the dominant cost driver of green hydrogen production (GroenvermogenNL, 2022). The cost of electricity from renewable sources has decreased immensely in the last few years. For PV rooftop systems, the costs decreased by 92% over a period of 30 years in Germany (Philipps, 2022). Meanwhile, for onshore wind power, the levelized cost of energy decreased by 35% between 2008 and 10 and 2014–16 in Germany (Duffy et al., 2020). Internationally, the levelized cost of electricity for PV fell by 88%, for onshore wind by 68%, and offshore wind by 60% between 2010 and 2021 (IRENA, 2022). In addition, the installed capacity of renewables increased from 97.7 GW in 2015 to 138.6 GW in 2021 in Germany (BNetzA, 2022) and from 4.3 GW in 2015–15.4 GW in the Netherlands (ENTSO-E, 2023). It is sometimes assumed that to produce hydrogen from electrolysis, renewable electricity is mainly used or electricity from renewable sources that cannot be used in any other way (Bareiß et al., 2019; Giocoli et al., 2023). Although this was considered by some experts (Expert B, D, E, H) to be unrealistic and a huge obstacle for the rapid adaptation of green hydrogen, there are two main reasons for this assumption. On the one hand, it makes sense to use renewable electricity first to replace electricity from fossil sources and to not use it to produce green hydrogen. In fact, the production of hydrogen from electricity from fossil sources produces more CO_2 emissions than the direct production of hydrogen from fossil sources (Ji and Wang, 2021). The second reason is the cost of producing hydrogen. The cost of producing hydrogen from electrolysis is primarily influenced by the cost of electricity (Pivovar et al., 2018). High electricity costs, such as the variable costs of electricity from fossil sources, ensure that hydrogen from electrolysis is more expensive than production methods for hydrogen with fossil fuels (Ji and Wang, 2021). However, the availability of excess renewable electricity remains low. During 2022, there were only 20 h in Germany when electricity production from renewables was greater than the demand (BNetzA, 2023a, 2023b). One obstacle mentioned for the rapid expansion of renewables is the long approval procedure and the project length of renewables. In Germany, the average approval period is 23 months and the time taken from approval to commission is 25.9 months according to industry data (Wind, 2022). Long approval times for permits and grants for green hydrogen plants are cited in industry reports as a bottleneck for the growth of green hydrogen (Deloitte, 2022). Investments are therefore not undertaken, as the possible utilization of electrolyzers is too little with the current amount of low-cost renewable electricity. This is another reason why the price of green hydrogen remains high, as the capital costs (CAPEX) must be distributed to cover the fact that less hydrogen is produced due to low operating hours based on available low-cost electricity. According to industry sources, electrolyzers need at least 4000 h to operate profitably (GroenvermogenNL, 2022). The same issue was raised in the interviews. It was commented that a major obstacle to producing green hydrogen is the availability of green electricity. The slow deployment of renewables is also stated as a big problem faced by the industry (DNV, 2022). The idea of using only excess green electricity was criticized and, in light of the lack of low-cost green electricity, it was asked whether it makes sense to solely fixate on green electricity to achieve the necessary growth of the green hydrogen value chain in the time frame envisioned. These criticisms can also be found in politics and industry. As mentioned above, some countries in the European Union are pushing to recognize nuclear power as an additional legitimate power source for green hydrogen. Meanwhile, some industry actors have proposed subsidizing hydrogen on the basis of lifecycle CO_2 emissions instead of its production type (Deloitte, 2022). This should allow for more mixed forms of production, thus helping to achieve the necessary production hours for electrolyzers as well as cost competitiveness, while also allowing for an incremental transition.

3.2.2. Other potential bottlenecks

Besides the two aforementioned main issues, other smaller obstacles were brought up during the interviews. For example, the utilization of production facilities for electrolyzers is dependent on precious metals,

[1] This rule has been relaxed by the European Parliament since the conclusion of the interviews and the publishing of this article (Recharge, 2022).

among other things, as Expert E and Expert F noted.

However, other experts had different opinions as to whether the demand for rare metals could be neglected. Expert G did not see any bottlenecks among suppliers and considered the reduced need per electrolyzer and recycling to be adequate means of avoiding shortages.

Another challenge for the growth of the green hydrogen chain is the need for a trained workforce that can operate the new equipment. While these concerns were raised in the interviews, this problem should theoretically only be able to slow the growth and not stop the development of the industry. In theory, a shortage in workforce should lead to higher wages, which would attract more people. However, training these people would take time and thus delay the growth.

Regarding the financing of projects in the green hydrogen value chain, the discrepancy between governments and the financial sector was pointed out by Expert A. According to some interviewees, governments want to fund projects that drive innovation in the green hydrogen sector, while the financial sector would rather invest in proven technologies.

In addition to these potential obstacles, industry reports often cite safety concerns and risks regarding the transport, use, and storage of green hydrogen as possible bottlenecks for the expansion of green hydrogen (cf (DNV, 2022; GroenvermogenNL, 2022).).

3.2.3. First-mover advantage

When asked why, despite all these challenges, investments are being made in electrolyzers and production capacities for electrolyzers today, the participants responded with different but complementary arguments for a first-mover advantage. Firstly, Expert G explained that first movers in the green hydrogen industry can expect political support in the form of subsidies for early projects (European Commission, 2022).

The second possible reason cited for early investment in the green hydrogen industry was the experience gained. The collected experience is not only valuable for the electrolyzer manufacturers but – according to the experts (Expert A, E, F) – is also a reason for the operators to invest and help as references with new contracts. A lack of experience with large-scale electrolyzers could otherwise become another bottleneck for the growth of the green hydrogen value chain according to industry reports (DNV, 2022).

There are also strategic incentives to invest, which are dependent on the current market phase and are therefore indirectly linked to the amount of electrolyzers installed. Especially in the early phases, investors are willing to forgo an initial profit if higher profits can be achieved later. Electrolyzer manufacturers have made losses in recent years, yet continued to invest (cf (Nel, 2020, 2021, 2022).).

3.2.4. Technological development

The installed electrolyzers are a good indicator for their production costs. The economy of scale can reduce the costs of new technologies (Kim, 2021). Examples of energy technology cost trajectories are wind turbine and solar panel costs (Louwen and van Sark, 2020). In terms of the overall potential for reducing the cost of electrolyzers, the experts are of the same opinion. They assume that a realistic cost reduction potential is lower than the price potentials discussed in scientific literature. Academic literature currently indicates that the system costs are 620–1240 €/kW for polymer electrolyte membrane electrolyzers and 450–900 €/kW for alkaline electrolyzers, but they are projected to fall below 180 €/kW in the future (IRENA, 2020). According to some experts interviewed, this seems too optimistic. They consider estimates by the Institute for Sustainable Process Technology of 1400 €/kW for alkaline electrolyzers and 1800 €/kW for polymer electrolyte membrane electrolyzers to be more realistic (van't Noordende and Ripson, 2020; Krishnan et al., 2023). System cost estimates for 2030 are 730 €/kW and 830 €/kW for alkaline and polymer electrolyte membrane electrolyzers, respectively (van't Noordende and Ripson, 2022). Other industry sources project costs of 400–900 €/kW for polymer electrolyte membrane electrolyzers and 260–620 €/kW for alkaline electrolyzers by 2050 (DNV, 2022).

3.2.5. Investment decisions

Using the insights obtained from the interviews, we constructed a detailed overview of stakeholders, investment decisions, and influencing factors. Fig. 4 shows the updated version of the green hydrogen value chain.

The focus is still on the electrolyzer or the investment decision in new electrolyzers. New investments in electrolyzers are influenced by expenses and returns. In addition to these financial aspects, however, there is also a strategic influence, represented here by the market phase, since the strategic aspects of new investments decrease as the market develops. The income of the hydrogen producer depends on how much green hydrogen can be sold profitably. This quantity is limited either by lack of demand or by the lack of abundant renewable electricity for production. Demand can be affected during the scale up primarily by two possibilities. Firstly, the government can bring about the use of green hydrogen, and secondly, there will be further demand for green hydrogen if it is just as inexpensive as hydrogen from alternative sources. The government, of course, can also bring about the latter condition. Similar assumptions apply to electrolyzer manufacturer as they do for the hydrogen producer. They will invest in new electrolyzer manufacturer facilities if there is unmet demand or if there is a strategic advantage to be gained from the investment. In contrast, new investments in renewables will only be made when they make financial sense. This results in a negative feedback loop between abundant renewable electricity and investment in renewables. New plants increase the amount of abundant renewable electricity, but too much excess electricity prevents new investments unless governments step in and make them profitable anyway. A similar situation applies to investments in new production capacities for electrolyzers. These depend on whether there is an unmet demand for electrolyzers. If such demand exists, investments in new production facilities can be profitable. However, if these investments are made and the installed production capacity increases, the unmet demand will logically decrease. An example of a positive loop is that new investments in electrolyzers due to learning effects (represented by the market phase) can help to lower the cost of new electrolyzers. This in turn can lower the cost of green hydrogen and thus generate new demand that was previously met by hydrogen from fossil sources. This new demand again allows for investments in new electrolyzers and thus results in a positive reinforcement. Another example of a complex feedback loop is how greater investment in electrolyzers increases the learning effect of electrolyzer manufacturer to produce electrolyzers, which can lead to lower electrolyzer costs. Lower costs for electrolyzers can subsequently lead to more investment in electrolyzers. Overall, a complex picture emerges with different positive and negative feedback loops, showing how the interaction of the different stakeholders works and what is needed for the industry to grow.

4. Conclusion

In this paper, a socio-technical analysis was conducted for the green hydrogen value chain in Germany and the Netherlands. Germany and the Netherlands are in a special position because of their energy-intensive industries, their electricity mix, and their existing electrolyzer industry. The analysis uses semi-structured stakeholder interviews to shed light on the development, challenges, and opportunities of the green hydrogen value chain in Germany and the Netherlands. In addition, we provide a view of the dynamics of scale-up from a stakeholder perspective, thus improving the scientific understanding of this transformation process.

The study reveals the specific views of the stakeholders of these industries in Germany and the Netherlands. According to the experts interviewed, the lack of demand for green hydrogen and the lack of abundant renewable electricity are the two major problems. The EU is

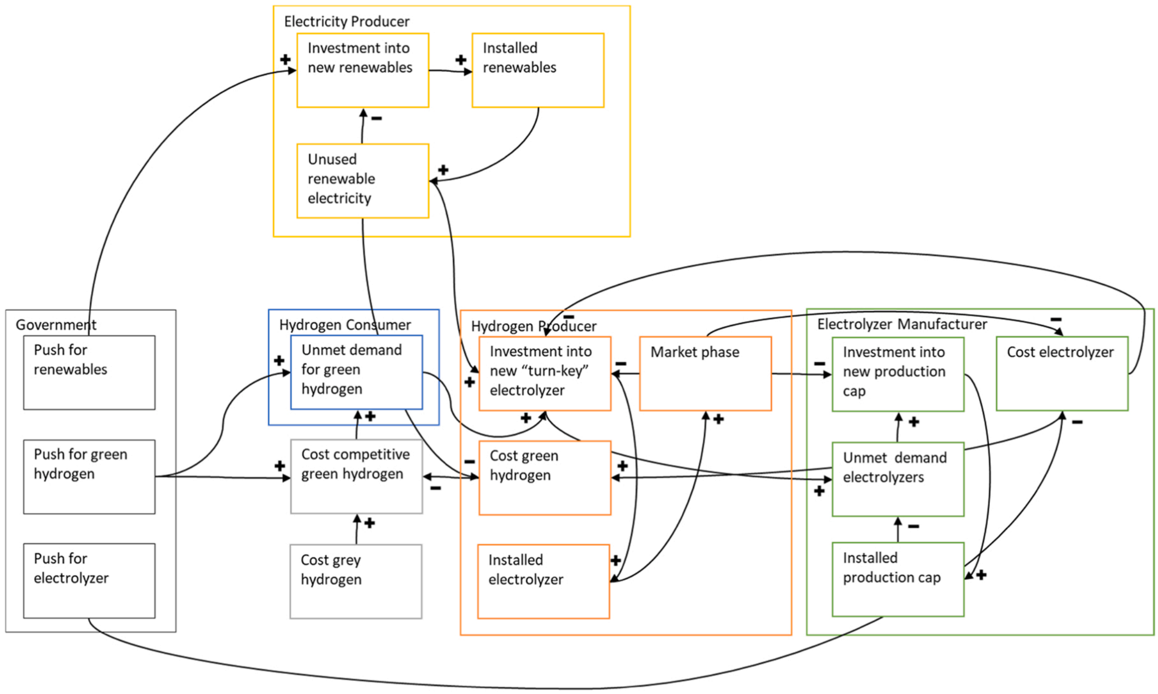

Fig. 4. Overview of stakeholders and investment decisions. The arrows in the diagram indicate the direction in which the factors influence each other. The plus and minus signs indicate whether it is a strengthening or weakening relation. The boxes represent the decisions and influencing factors of either the entire industry or of individual actors.

trying to stimulate the demand side through RED II and thus solve the "chicken or egg" dilemma. The availability of abundant renewable electricity is increased through various national regulations. The stakeholders interviewed see these interventions as positive, but also warn against overly complex rules. Many of the stakeholders' experiences are in line with similar work (cf (Damman et al., 2021).). Furthermore, the statements regarding the first-mover advantage and the strategic rationale behind investment decisions within the green hydrogen value chain provide insights into the current investments made in projects that may not yield immediate profits. The interviews provide an insight into how industry stakeholders are connected by investment decisions as well as the current state of the industry, supply, and demand for green electricity and electrolyzers. The positive feedback loop between the cost of electrolyzers and the demand for electrolyzers could be a potential point for stimulating the growth of the green hydrogen value chain. Governments only need to create an incentive once to catalyze the process, after which the industry should theoretically grow on its own based on the feedback loop.

Germany and the Netherlands have a substantial interest in fostering the green hydrogen industry, given their status as the largest hydrogen consumers within the EU today. However, these countries grapple with a relatively limited availability of electricity sourced from renewables, which could render regulatory provisions like RED II problematic. Experts interviewed from the industry express a desire for subsidies with more relaxed prerequisites to facilitate the initial scale-up.

Concerns in Germany also revolve around the distance requirements related to the origin of green power, as existing hydrogen customers are often situated far from optimal spots for renewable energy. This would result in additional transportation costs. The consensus among these experts emphasizes the importance of retaining hydrogen customers within their respective countries. Thus, mechanisms such as CBAM or regional subsidies for hydrogen products assume special significance. In addition, regional and national policymakers have a strong interest in preserving jobs, which should increase the focus on this type of regulation.

Furthermore, manufacturers of electrolyzers in Germany emphasize the importance of receiving support to remain competitive on the international stage. Failure to do so could result in the relocation of not only their operations but also those of their suppliers. Whether current policies should rather support technological developments or cost reductions through economy of scale is disputed among experts.

Further research should investigate how these insights could help to better understand and model the dynamics of the emerging green hydrogen value chain. New studies should include analyses of the most efficient ways that governments could stimulate the electrolyzer industry in Germany and the Netherlands and countries in a similar position.

CRediT authorship contribution statement

B.-J. Jesse: Investigation, Writing – Original Draft, Visualization. **G. J. Kramer:** Methodology, Conceptualization, Investigation, Writing – Review & Editing, Supervision. **V. Koning:** Investigation, Writing – review & editing. **S. Vögele:** Investigation, Writing – Review & Editing. **W. Kuckshinrichs:** Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.egyr.2023.11.046.

References

Abnett K. France leads push for EU to boost nuclear-produced hydrogen. Reuters, 2023.

Asna Ashari, P., Oh, H., Koch, C., 2023. Pathways to the hydrogen economy: a multidimensional analysis of the technological innovation systems of Germany and South Korea. Int J. Hydrog. Energy, S0360319923044798. https://doi.org/10.1016/j.ijhydene.2023.08.286.

Autobahn GmbH. The eHighway Future oriented technology, 2023. ⟨https://www.autobahn.de/fileadmin/user_upload/The_eHighway_Future_oriented_technology.pdf⟩.

Baker, E., Goldstein, A.P., Azevedo, I.M., 2021. A perspective on equity implications of net zero energy systems. Energy Clim. Change 2, 100047. https://doi.org/10.1016/j.egycc.2021.100047.

Bareiß, K., de la Rua, C., Möckl, M., Hamacher, T., 2019. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Appl. Energy 237, 862–872. https://doi.org/10.1016/j.apenergy.2019.01.001.

Bhandari, R., Shah, R.R., 2021. Hydrogen as energy carrier: techno-economic assessment of decentralized hydrogen production in Germany. Renew. Energy 177, 915–931. https://doi.org/10.1016/j.renene.2021.05.149.

Blohm, M., Dettner, F., 2023. Green hydrogen production: integrating environmental and social criteria to ensure sustainability. Smart Energy 11, 100112. https://doi.org/10.1016/j.segy.2023.100112.

BmDV. BMDV fördert Ausbau öffentlicher Wasserstofftankstellen für schwere Nutzfahrzeuge, 2023. ⟨https://bmdv.bund.de/SharedDocs/DE/Pressemitteilungen/2023/023-wissing-wasserstofftankstellen-fuer-lkw-und-busse.html⟩.

Bmwi. The National Hydrogen Strategy. Bundesministerium für Wirtschaft und Klimaschutz, 2020.

Bmwk, 2023. Fortschreibung der Nationalen Wasserstoffstrategie. Bundesministerium für Wirtschaft und Klimaschutz, Berlin.

BNetzA, 2022. BKartA. Monitoringbericht 2022. Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen; Bundeskartellamt, Bonn.

BNetzA. Electricity generation. SmardDe, 2023a. ⟨https://www.smard.de/en/downloadcenter/download-market-data/⟩.

BNetzA. Electricity consumption. SmardDe, 2023b. ⟨https://www.smard.de/en/downloadcenter/download-market-data/⟩.

Braun, V., Clarke, V., 2006. Using thematic analysis in psychology. Qual. Res Psychol. 3, 77–101. https://doi.org/10.1191/1478088706qp063oa.

Bundesregierung Deutschland Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare- Energien-Gesetz - EEG 2017), 2017.

Capurso, T., Stefanizzi, M., Torresi, M., Camporeale, S.M., 2022. Perspective of the role of hydrogen in the 21st century energy transition. Energy Convers. Manag. 251, 114898 https://doi.org/10.1016/j.enconman.2021.114898.

Chantre, C., Andrade Eliziário, S., Pradelle, F., Católico, A.C., Branquinho Das Dores, A. M., Torres Serra, E., et al., 2022. Hydrogen economy development in Brazil: an analysis of stakeholders' perception. Sustain Prod. Consum. 34, 26–41. https://doi.org/10.1016/j.spc.2022.08.028.

Damman, S., Sandberg, E., Rosenberg, E., Pisciella, P., Graabak, I., 2021. A hybrid perspective on energy transition pathways: is hydrogen the key for Norway? Energy Res. Soc. Sci. 78, 102116 https://doi.org/10.1016/j.erss.2021.102116.

Deloitte. Hydrogen - Making it happen. Deloitte, 2022.

Diis. Australia's national hydrogen strategy. Canberra, A.C.T.: COAG Energy Council Hydrogen Working Group, 2019.

DNV, 2022. Hydrogen Forecast to 2050. DNV, Oslo. https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html.

Duffy, A., Hand, M., Wiser, R., Lantz, E., Dalla Riva, A., Berkhout, V., et al., 2020. Land-based wind energy cost trends in Germany, Denmark, Ireland, Norway, Sweden and the United States. Appl. Energy 277, 114777. https://doi.org/10.1016/j.apenergy.2020.114777.

ENTSO-E. Installed Capacity per Production Type, 2023. ⟨https://transparency.entsoe.eu/generation/r2/installedGenerationCapacityAggregation/show?name=&defaultValue=false&viewType=TABLE&areaType=BZN&atch=false&dateTime.dateTime=01.01.2015+00:00|UTC|YEAR&dateTime.endDateTime=01.01.2021+00:00|UTC|YEAR&area.values=CTY|10YNL-L!BZN|10YNL-L&productionType.values=B01&productionType.values=B02&productionType.values=B03&productionType.values=B04&productionType.values=B05&productionType.values=B06&productionType.values=B07&productionType.values=B08&productionType.values=B09&productionType.values=B10&productionType.values=B11&productionType.values=B12&productionType.values=B13&productionType.values=B14&productionType.values=B20&productionType.values=B15&productionType.values=B16&productionType.values=B17&productionType.values=B18&productionType.values=B19⟩.

European Commission, 2020. A hydrogen strategy for a climate-neutral Europe. Brussels. European Commission,.

European Commission. Carbon Border Adjustment Mechanism (CBAM) starts to apply in its transitional phase, 2023. ⟨https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4685⟩.

European Commission. State Aid: Commission approves up to €5.4 billion of public support by fifteen Member States for an Important Project of Common European Interest in the hydrogen technology value chain, 2022.

European Union. Directive (EU) 2018/410 of the European Parliament and of the Council of 14 March 2018 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814 (Text with EEA relevance), 2018.

Eurostat. Air emissions accounts for greenhouse gases by NACE Rev. 2 activity - quarterly data, 2022. ⟨https://ec.europa.eu/eurostat/de/web/products-datasets/product?code=ENV_AC_AIGG_Q⟩.

Fonseca, J.D., Camargo, M., Commenge, J.-M., Falk, L., Gil, I.D., 2019. Trends in design of distributed energy systems using hydrogen as energy vector: a systematic literature review. Int J. Hydrog. Energy 44, 9486–9504. https://doi.org/10.1016/j.ijhydene.2018.09.177.

Giocoli, A., Motola, V., Scarlat, N., Pierro, N., Dipinto, S., 2023. Techno-economic viability of renewable electricity surplus to green hydrogen and biomethane, for a future sustainable energy system: hints from Southern Italy. Renew. Sustain Energy Transit. 3, 100051 https://doi.org/10.1016/j.rset.2023.100051.

Graham R. EU's Move to Replace Gas With Hydrogen Held Up by Red Tape, 2022. ⟨https://www.bloomberg.com/news/articles/2022–09-09/eu-s-move-to-replace-gas-with-hydrogen-fraught-by-red-tape⟩.

Griffiths, S., Sovacool, B.K., Kim, J., Bazilian, M., Uratani, J.M., 2021. Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options. Energy Res. Soc. Sci. 80, 102208 https://doi.org/10.1016/j.erss.2021.102208.

GroenvermogenNL. Quickscan development green hydrogen value chain. GroenvermogenNL, 2022.

Hanley, E.S., Glowacki, B.A., Nuttall, W.J., Kazantzis, N., 2015. Natural gas – synergies with hydrogen. Proc. Inst. Civ. Eng. Energy 168, 47–60. https://doi.org/10.1680/ener.14.00018.

Hartley, P.G., Au, V., 2020. Towards a Large-Scale Hydrogen Industry for Australia. Engineering 6, 1346–1348. https://doi.org/10.1016/j.eng.2020.05.024.

Hirt, L.F., Schell, G., Sahakian, M., Trutnevyte, E., 2020. A review of linking models and socio-technical transitions theories for energy and climate solutions. Environ. Innov. Soc. Transit. 35, 162–179. https://doi.org/10.1016/j.eist.2020.03.002.

Husarek, D., Schmugge, J., Niessen, S., 2021. Hydrogen supply chain scenarios for the decarbonisation of a German multi-modal energy system. Int J. Hydrog. Energy 46, 38008–38025. https://doi.org/10.1016/j.ijhydene.2021.09.041.

Hydrogen Council. Hydrogen scaling up - A sustainable pathway for the global energy transition. Brussles: Hydrogen Council, 2017.

Hydrogen Council, McKinsey & Compancy. Hydrogen Insights 2022. Brussles: Hydrogen Council, 2022.

IEA, 2022a. Hydrogen Supply. IEA, Paris.

IEA, 2022a. World Energy Oultook 2022. International Energy Agency, Paris.

IEA, 2022b. Hydrogen. IEA, Paris.

IEA, 2023. Energy Technology Perspective 2023. International Energy Agency, Paris.

IRENA, 2019. Global energy transformation: A roadmap to 2050. International Renewable Energy Agency, Abu Dhabi.

IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal. International Renewable Energy Agency, Abu Dhabi.

IRENA, 2022. Renewable Power Generation Costs in 2021. International Renewable Energy Agency, Abu Dhabi.

Jack V. France mounts 'aggressive' nuclear push with eye on EU industrial plan. Politico, 2023.

Ji, M., Wang, J., 2021. Review and comparison of various hydrogen production methods based on costs and life cycle impact assessment indicators. Int J. Hydrog. Energy 46, 38612–38635. https://doi.org/10.1016/j.ijhydene.2021.09.142.

Khalilpour, K.R., Pace, R., Karimi, F., 2020. Retrospective and prospective of the hydrogen supply chain: a longitudinal techno-historical analysis. Int J. Hydrog. Energy 45, 34294–34315. https://doi.org/10.1016/j.ijhydene.2020.02.099.

Kim, D., 2021. Economies of scale and international business cycles. J. Int Econ. 131, 103459 https://doi.org/10.1016/j.jinteco.2021.103459.

Krishnan, S., Koning, V., Theodorus De Groot, M., De Groot, A., Mendoza, P.G., Junginger, M., et al., 2023. Present and future cost of alkaline and PEM electrolyser stacks. Int J. Hydrog. Energy 48, 32313–32330. https://doi.org/10.1016/j.ijhydene.2023.05.031.

Kumar, S., Loosen, M., Madlener, R., 2020. Assessing the potential of low-carbon technologies in the German energy system. J. Environ. Manag. 262, 110345 https://doi.org/10.1016/j.jenvman.2020.110345.

Liimatainen, H., 2021. Decarbonizing road freight transport. International Encyclopedia of Transportation. Elsevier, pp. 395–401. https://doi.org/10.1016/B978-0-08-102671-7.10277-5.

Louwen, A., van Sark, W., 2020. Photovoltaic solar energy. Technological Learning in the Transition to a Low-Carbon Energy. Elsevier,, pp. 65–86. https://doi.org/10.1016/B978-0-12-818762-3.00005-4.

Luo, Y., Wu, Y., Li, B., Mo, T., Li, Y., Feng, S.-P., et al., 2021. Development and application of fuel cells in the automobile industry. J. Energy Storage 42, 103124. https://doi.org/10.1016/j.est.2021.103124.

Maggio, G., Nicita, A., Squadrito, G., 2019. How the hydrogen production from RES could change energy and fuel markets: a review of recent literature. Int J. Hydrog. Energy 44, 11371–11384. https://doi.org/10.1016/j.ijhydene.2019.03.121.

Martínez de León, C., Ríos, C., Brey, J.J., 2022. Cost of green hydrogen: limitations of production from a stand-alone photovoltaic system. Int J. Hydrog. Energy, S0360319922021280. https://doi.org/10.1016/j.ijhydene.2022.05.090.

METI. Strategic Roadmap for Hydrogen and Fuel Cells. Tokyo: Ministry of Economy, Trade and Industry, 2019.

Moliner, R., Lázaro, M.J., Suelves, I., 2016. Analysis of the strategies for bridging the gap towards the Hydrogen Economy. Int J. Hydrog. Energy 41, 19500–19508. https://doi.org/10.1016/j.ijhydene.2016.06.202.

Nel. Annual report 2019. Nel | ASA, 2020.

Nel. Annual report 2020. Nel | ASA, 2021.

Nel. Annual report 2021. Nel | ASA, 2022.

Neuwirth, M., Fleiter, T., Manz, P., Hofmann, R., 2022. The future potential hydrogen demand in energy-intensive industries - a site-specific approach applied to Germany. Energy Convers. Manag. 252, 115052 https://doi.org/10.1016/j.enconman.2021.115052.

Nnabuife, S.G., Ugbeh-Johnson, J., Okeke, N.E., Ogbonnaya, C., 2022. Present and projected developments in hydrogen production: a technological review. Carbon Capture Sci. Technol. 3, 100042 https://doi.org/10.1016/j.ccst.2022.100042.

Nurdiawati, A., Urban, F., 2022. Decarbonising the refinery sector: a socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden. Energy Res. Soc. Sci. 84, 102358 https://doi.org/10.1016/j.erss.2021.102358.

Oliveira, A.M., Beswick, R.R., Yan, Y., 2021. A green hydrogen economy for a renewable energy society. Curr. Opin. Chem. Eng. 33, 100701 https://doi.org/10.1016/j.coche.2021.100701.

Pathak, P.K., Yadav, A.K., Padmanaban, S., 2022. Transition toward emission-free energy systems by 2050: potential role of hydrogen. Int J. Hydrog. Energy, S0360319922057755. https://doi.org/10.1016/j.ijhydene.2022.12.058.

Peter Andreasen, K., Sovacool, B.K., 2014. Energy sustainability, stakeholder conflicts, and the future of hydrogen in Denmark. Renew. Sustain. Energy Rev. 39, 891–897. https://doi.org/10.1016/j.rser.2014.07.158.

Philipps S. PHOTOVOLTAICS REPORT. Fraunhofer ISE, 2022.

Pivovar, B., Rustagi, N., Satyapal, S., 2018. Hydrogen at scale (H_2 @Scale): key to a clean, economic, and sustainable energy system. Electrochem Soc. Interface 27, 47–52. https://doi.org/10.1149/2.F04181if.

Proost, J., 2020. Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen. Int J. Hydrog. Energy 45, 17067–17075. https://doi.org/10.1016/j.ijhydene.2020.04.259.

Rabiee, A., Keane, A., Soroudi, A., 2021. Green hydrogen: a new flexibility source for security constrained scheduling of power systems with renewable energies. Int J. Hydrog. Energy 46, 19270–19284. https://doi.org/10.1016/j.ijhydene.2021.03.080.

Razi, F., Dincer, I., 2022. Challenges, opportunities and future directions in hydrogen sector development in Canada. Int J. Hydrog. Energy 47, 9083–9102. https://doi.org/10.1016/j.ijhydene.2022.01.014.

Recharge. Scrapped|EU's controversial "additionality" rules for green hydrogen are history after European Parliament vote, 2022. ⟨https://www.rechargenews.com/energy-transition/scrapped-eus-controversial-additionality-rules-for-green-hydrogen-are-history-after-european-parliament-vote/2–1-1299195⟩.

Rijksoverheid. Government Strategy on Hydrogen. Government of the Netherlands, 2020.

Schlund, D., Schulte, S., Sprenger, T., 2022. The who's who of a hydrogen market ramp-up: a stakeholder analysis for Germany. Renew. Sustain. Energy Rev. 154, 111810 https://doi.org/10.1016/j.rser.2021.111810.

STEAG. HydroHub – mit Wasserstoff die Energiewende gestalten, 2019. ⟨https://www.steag.com/en/steag-news-ausgabe-4–2019/hydrohub-fenne-mit-wasserstoff-die-energiewende-gestalten⟩.

Thema, M., Bauer, F., Sterner, M., 2019. Power-to-gas: electrolysis and methanation status review. Renew. Sustain Energy Rev. 112, 775–787. https://doi.org/10.1016/j.rser.2019.06.030.

Trattner, A., Klell, M., Radner, F., 2022. Sustainable hydrogen society – vision, findings and development of a hydrogen economy using the example of Austria. Int J. Hydrog. Energy 47, 2059–2079. https://doi.org/10.1016/j.ijhydene.2021.10.166.

Tsakanikas, A., Caloghirou, Y., Dimas, P., Stamopoulos, D., 2022. Intangibles, innovation, and sector specialization in global value chains: a case study on the EU's and the UK's manufacturing industries. Technol. Forecast Soc. Change 177, 121488. https://doi.org/10.1016/j.techfore.2022.121488.

Turnheim, B., Nykvist, B., 2019. Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions. Res. Policy 48, 775–788. https://doi.org/10.1016/j.respol.2018.12.002.

Upham, P., Bögel, P., Dütschke, E., Burghard, U., Oltra, C., Sala, R., et al., 2020. The revolution is conditional? The conditionality of hydrogen fuel cell expectations in five European countries. Energy Res Soc. Sci. 70, 101722 https://doi.org/10.1016/j.erss.2020.101722.

Van de Graaf, T., Overland, I., Scholten, D., Westphal, K., 2020. The new oil? The geopolitics and international governance of hydrogen. Energy Res. Soc. Sci. 70, 101667 https://doi.org/10.1016/j.erss.2020.101667.

van't Noordende, H., Ripson, P., 2020. Baseline Design and Total Installed Costs of a GW Green Hydrogen Plant - State-of-the-art Design and Total Installed Capital Costs. Institute for Sustainable Process Technology, Amersfoort.

van't Noordende, H., Ripson, P., 2022. A One-GigaWatt Green-Hydrogen Plant - Advanced Design and Total Installed-Capital Costs. Institute for Sustainable Process Technology, Amersfoort.

Verbong, G.P.J., Geels, F.W., 2010. Exploring sustainability transitions in the electricity sector with socio-technical pathways. Technol. Forecast Soc. Change 77, 1214–1221. https://doi.org/10.1016/j.techfore.2010.04.008.

Wacker. Renewable HYdrogen and MEthanol Bavaria, 2022. ⟨https://www.wacker.com/cms/en-de/about-wacker/research-and-development/rhyme-bavaria/detail.html⟩.

Wappler, M., Unguder, D., Lu, X., Ohlmeyer, H., Teschke, H., Lueke, W., 2022. Building the green hydrogen market – current state and outlook on green hydrogen demand and electrolyzer manufacturing. Int J. Hydrog. Energy 47, 33551–33570. https://doi.org/10.1016/j.ijhydene.2022.07.253.

Williams, J.H., Jones, R.A., Torn, M.S., 2021. Observations on the transition to a net-zero energy system in the United States. Energy Clim. Change 2, 100050. https://doi.org/10.1016/j.egycc.2021.100050.

Wilson A. Revision of the Renewable Energy Directive: Fit for 55 package. European Parliamentary Research Service, 2022.

Wind, F.A., 2022. Analyse der Ausbausituation der Windenergie an Land im Herbst 2022. Fachagentur Windenergie an Land, Berlin.

Wulf, C., Zapp, P., Schreiber, A., 2020. Review of Power-to-X Demonstration Projects in Europe. Front Energy Res. 8, 191 https://doi.org/10.3389/fenrg.2020.00191.

Zhang, R., Zhang, J., 2021. Long-term pathways to deep decarbonization of the transport sector in the post-COVID world. Transp. Policy 110, 28–36. https://doi.org/10.1016/j.tranpol.2021.05.018.