International Journal of Hydrogen Energy 70 (2024) 29–38

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

journal homepage: www.elsevier.com/locate/he

The future European hydrogen market: Market design and policy recommendations to support market development and commodity trading

Sarah A. Steinbach [a,b,*], Nikolas Bunk [c]

[a] Chair of Management Accounting, Technical University of Munich, Arcisstraße 21, Munich, 80333, Germany
[b] Energy Research Institute (ERI@N), School of Electrical & Electronic Engineering, Nanyang Technological University, 50 Nanyang Ave, Singapore, 639798, Singapore
[c] TUM School of Management, Technical University of Munich, Arcisstraße 21, Munich, 80333, Germany

ARTICLE INFO

Keywords:
Hydrogen
Green hydrogen
Market design
Energy regulation
Commodity trading

ABSTRACT

A key building block of the European Green Deal is the development of a hydrogen commodity market, which requires a suitable hydrogen market design and the timely introduction of related policy measures. Using exploratory interviews with five expert groups, we contribute to this novel research field by outlining the core market design criteria and proposing suitable regulations for the future European hydrogen market. We identify detailed recommendations along three core market design focus areas: Market development policy measures, infrastructure regulations, as well as hydrogen and certificate trading. Our findings provide an across-industry view of current policy-related key challenges in the hydrogen commodity market development and mitigation approaches. We, therefore, support policymakers within the EU in the ongoing detailing of their regulatory hydrogen and green energy packages. Further, we promote hydrogen market development by assisting current and future industry players in finding a common understanding of the future hydrogen market design.

1. Introduction

Hydrogen will play a key role in Europe's transition to green energy, aiming for net-zero carbon emissions by 2050 [1,2]. Enabled by the rapid cost decline of renewable energy and continued technological development, the EU aims to promote the employment of green hydrogen in multiple emission-intensive sectors and complement the electrification of fossil-fuel-based processes [1]. Of highest priority is the industrial sector, where green hydrogen can play an essential role in decarbonizing steel and cement production, as well as in replacing grey hydrogen in refineries and the chemical industry [3–6]. In the transport sector, hydrogen-based fuels could be employed in road transport, such as trucks and buses, and additionally in rail, shipping, and aviation [4,7–9]. Green hydrogen is further explored as a clean energy carrier for heating buildings as well as for electricity storage [4,7,8,10,11]. Due to these promising applications, almost all EU member states see immense potential in green hydrogen and include the sustainable energy carrier in their national energy and climate plans [1]: By 2024, the EU aims to install at least 6 Gigawatt (GW) of renewable hydrogen electrolyzers. By 2030, 40 GW are planned. Europe is at the forefront of anticipated hydrogen investments up to 2030, along with leading in the number of announced hydrogen projects across the value chain [12,13]. Hence, in 2020, the European Commission published a hydrogen strategy with the long-term goal of implementing a liquid market with commodity-based hydrogen trading: "By 2030, the EU will aim at completing an open and competitive EU hydrogen market, with unhindered cross-border trade and efficient allocation of hydrogen supply among sectors". [1]. They emphasize the high added value of a hydrogen commodity trading market, as it enables transparent and efficient hydrogen distribution, allows investment decisions based on price signals, and facilitates the entry of new hydrogen producers. However, how the European hydrogen market has to be designed to establish efficient hydrogen commodity trading still remains relatively unclear. This poses a challenge to players within the hydrogen market, who call for regulatory certainty and robust international standards and certification schemes [14–16]. As existing hydrogen certification schemes are found to be unsuitable for cross-border trade, international collaboration on these measures requires more work, as outlined by IRENA and the WTO [17,18]. Institutes urge policymakers to create regulatory certainty, lay the foundations of a hydrogen market design, create a target model, and establish a hydrogen trading system [14,15,19–21].

Although a large amount of literature has been published about hydrogen, most research focuses on the technical feasibility, the production cost or future hydrogen market sizes and resource flows [22–

* Corresponding author at: Chair of Management Accounting, Technical University of Munich, Arcisstraße 21, Munich, 80333, Germany.
E-mail address: sarah.steinbach@tum.de (S.A. Steinbach).

https://doi.org/10.1016/j.ijhydene.2024.05.107
Received 7 March 2024; Received in revised form 2 May 2024; Accepted 8 May 2024
Available online 17 May 2024

26]. Policy aspects for hydrogen have only been covered by a limited number of recent articles, which have put their focus on financial support of hydrogen applications and the state of hydrogen infrastructure regulation proposals [4,27]. Many researchers agree that hydrogen market design and regulation are currently under-researched and call for further exploration [10,14,23,24,28]. This call for research is also of increased urgency, as current regulatory uncertainties are found to significantly hold back hydrogen investments and endanger the ambitious EU 2030 decarbonization objectives [16].

We aim to contribute to the still sparse literature in this upcoming research field by outlining the core design criteria and attached regulation of the future European hydrogen market to establish efficient commodity trading by 2030. By drawing on analogies from the gas market, we evaluate which infrastructure regulations are appropriate for the hydrogen market, analyze potential market development policy measures, and investigate hydrogen and certificate trading setups. As the hydrogen market is required to develop fast and will primarily be driven by policy interventions, gas market regulation cannot simply be replicated, and hydrogen market design choices can be complex. Hence, we employ the Grounded Theory Method, which is considered appropriate for new and under-researched topics, such as the hydrogen market design [29,30]. We incorporate input from 16 across-industry expert interviews with future hydrogen market players, research institutes, and regulators to ensure a holistic perspective. Our findings support policymakers in setting the guardrails to advance hydrogen market development, market design, and infrastructure regulation. Further, we assist hydrogen market players, such as hydrogen producers, consumers, infrastructure providers, and exchanges, in gaining a common understanding of which potential future hydrogen regulation they can advocate for.

Our work is structured as follows. In Section 2, existing literature on the future hydrogen market design, proposed related regulation, and its analogies to the natural gas market is laid out. Section 3 details the methodology employed and describes our interview process. Section 4 outlines our results, which are discussed in Section 5, while Section 6 concludes.

2. Theoretical background

Literature suggests that more mature European energy markets should be analyzed to develop a suitable hydrogen market design. The natural gas market is often suggested to be used as an analogy, mainly due to the physical similarities of both gases and the potential of using retrofitted natural gas pipelines for hydrogen transport in order to save infrastructure cost [4,19,21,23,31–34]. Hence, we first provide an overview of key market design aspects within the energy sector and the European natural gas market. Next, we review the current state of the hydrogen market literature to derive the research gap addressed.

2.1. Energy market design and the case of natural gas

For many energy markets, policymakers step into the role of market designers. This can include redesigning the rules that guide market transactions as well as the infrastructure that enables those transactions, addressing a broad range of market failures [35,36]. Such market failures are, for example, information asymmetry, hold-up of investments because of high uncertainty, or economies of scale when one player dominates a high fixed cost market [23,37]. In the area of energy market designs, the objective is to create a regulatory framework in which market participants' behavior supports the achievement of energy policy targets [38]. There is often no one-size-fits-all market design solution, but choices regarding the impacts of several costs and benefits need to be explored [36].

When detailing the market design and attached regulations for a heavily used energy carrier with multiple applications, such as natural gas and hydrogen, in the future, there are several key aspects to consider. One key aspect is transmission infrastructure regulation and access [36,37]. The transmission infrastructure is often at some point opened to third parties, the so-called third-party access (TPA), to foster competition, as for example in the First Gas Directive [39]. Transmission infrastructure can either be owned by integrated energy producers or unbundled, meaning that the infrastructure operator is separated from the producer [36,39]. Unbundling ensures transparent and non-discriminatory access for all potential suppliers within the market.

A second key aspect of market design is the trading setup. The natural gas market represents an example of a commodity trading in Europe. Commodities are unrefined or refined raw materials like agricultural products, metals, or energy carriers like natural gas or crude oil [40,41]. Within the energy sector, a commodity is a tradable unit of energy within a physical network during a specific period [20]. A perfectly competitive and thus liquid commodity market is characterized by a high trading volume and many suppliers and buyers, and full transparency is given [23,42]. Easily accessible infrastructure for communication and exchange of goods is required [32,37]. In the case of natural gas, it is typically traded Over-the-Counter (OTC) or on energy exchanges like the EEX [43]. In Europe, the OTC market is significantly larger [44,45]. In contrast, exchanges work with standardized contracts, eliminate credit risk, and are preferred for derivative products like futures [43].

For gas or power markets, it is also integral to define how commodity trading is connected to infrastructure limitations [36]. A point-to-point model, zone model or postage stamp model are possible [46–48]. In the point-to-point model, every trading transaction is based on a specific source–drain connection [46]. Substantial transaction costs occur due to high amounts of complex contracts and insufficient competition [47]. The access model with the highest trading flexibility is the postage-stamp model, further detailed in [47]. In this model, market participants can freely inject or withdraw an energy carrier, such as natural gas, within the network and distances are irrelevant. Nevertheless, as infrastructure and puffer reserves are not unlimited, this model is complex to implement. As a compromise, the zone model reflects capacity restrictions [47]. The market is separated into zones in which the postage stamp model is applied. In each zone, balancing group managers and market zone coordinators ensure a supply and demand balance [49]. Hence, technical feasibility is given, injection and withdrawal contracts can be booked separately via the Virtual Trading Point (VTP), and trading is flexible across zones [47]. The natural gas market uses the entry-exit model, an example of a zone model, where the market zones roughly align with the national markets of an EU member state [47,50].

Similarly to electricity generation, hydrogen further requires regulation on the certification of green house gas (GHG) emissions of the hydrogen produced [17,19,20]. Such certification could be introduced as a mass balance system or as a book and claim system similar to the electricity sector [19,51–53]. Furthermore, due to the current high uncertainty in future hydrogen market development, political support measures, including direct financial support, are required [14–16,27].

2.2. Hydrogen market development phases and suggested approaches for related regulation

Currently, hydrogen is mainly produced directly at its application locations, which are concentrated in Germany and the Netherlands [6,20,54,55]. Therefore, the hydrogen infrastructure in Europe is still limited today and based on long-term bilateral contracts [8]. Although researchers do not all agree on the expected time horizons, they agree on core hydrogen market developments, which can be summarized in three stages. Furthermore, the literature provides first suggestions on hydrogen market regulation.

In the first stage, from now until around 2025, the main objective of the emerging hydrogen economy is to showcase its scalability and facilitate the decarbonization of the existing hydrogen production [1,19]. The EU plans for at least 6 GW of installed green hydrogen electrolyzer capacity and to produce up to one million tons of clean hydrogen yearly by 2024 [1]. Isolated hydrogen islands are expected to emerge, including local hydrogen production, transportation, and consumption [20,31,32]. The hydrogen demand is driven by refineries, the chemical industry, and steel producers [1,3–5]. Bilateral and long-term contracts will dominate in these localized markets [31]. The literature recommends introducing a hydrogen certification scheme to provide GHG emissions transparency [1,17,19,20,23,45,53]. The specific decision regarding whether to implement a mass balance system, as outlined in Article 30 of the second Renewable Energy Directive (RED II), or to adopt a book and claim system similar to the electricity sector, remains subjects of ongoing deliberation [19,51–53]. Additionally, the geographic scope of the certificates is yet to be defined. Diverse opinions are expressed concerning the market access model. While the European Hydrogen Strategy argues for a point-to-point access model to be adopted initially, other institutes advocate for introducing a small entry-exit system from the beginning [1,20].

During the second phase, spanning approximately from 2025 to 2030, the European Hydrogen Strategy sees hydrogen as an integral component of an interconnected energy system, aiming for renewable hydrogen electrolyzer capacities of at least 40 GW and the production of up to ten million tons of green hydrogen by 2030 [1]. It is expected that green hydrogen will achieve cost competitiveness with fossil fuel alternatives [1]. A hydrogen pipeline network, consisting mainly of reassigned natural gas pipelines connecting member states, emerges [1,5,56–58]. Consequently, EU-wide standards for transportation and regulations for cross-border trade will be imperative [5,59]. Beyond industrial applications, hydrogen is predicted to see increased utilization in the transportation sector, electricity generation and heating [1,4]. Although the literature does not agree on a specific timeline, there is consensus regarding the necessity of regulations concerning access to transportation assets to achieve economies of scale [1,4,5,19,20,23,31,45,59,60]. The current regulatory proposal by the Council of the European Union suggests unbundling as the default model while allowing independent transmission system operators under certain conditions [61].

In the third phase, from around 2030 onwards, hydrogen will be utilized in all relevant hard-to-decarbonize sectors [1,4,5]. A mature European hydrogen backbone is envisaged to connect hydrogen ecosystems and transport hydrogen cross-border by 2040 [5,56,57]. Market consolidation will push the hydrogen market to be transparent and liquid, with prices driven by global supply and demand in the long term [19,20,31].

2.3. Review of hydrogen market design research and need for action

A multitude of literature has been published about hydrogen, covering several research fields [22,24]. Hydrogen market researchers, however, find that research focuses mainly on the technical feasibility and the production cost [23,24]. More recent studies also cover developing estimations for the future global hydrogen market sizes and resource flows as well as modeling hydrogen trading (e.g., [25,26,62–65]). Many studies about the expected development phases of the hydrogen market were published, which discuss first approaches for related regulation and deduct that hydrogen commodity trading might play a role from the year 2030 onwards (Section 2.2). However, even if production is efficient and hydrogen is socially beneficial, developing an efficient hydrogen market requires a suitable design and trading system [14–16]. Current regulatory uncertainties impede hydrogen market investments and put the ambitious EU 2030 decarbonization objectives at risk [16]. There is a consensus that market design issues for hydrogen are currently under-researched and require further exploration [10,14,23,24,28]. Only a few recent articles cover hydrogen market design and policy aspects. [27] performed a multidisciplinary literature review covering policy design for green hydrogen. However, they focus their analysis on the cost-competitiveness of hydrogen applications and related policy financial support. [4] are covering the state of hydrogen infrastructure regulation proposals and analogies to the gas market. They call for more precise infrastructure regulation, especially for higher hydrogen shares within the grid.

To contribute to the under-researched field of hydrogen market design and regulation, we investigate how the European hydrogen market should be designed based on learnings from the natural gas market as laid out in Section 2.1. Specifically, we analyze which infrastructure regulations are necessary for the hydrogen market and if they can be translated from the natural gas market. Additionally, we explore suitable market development policy measures as well as hydrogen and certificate trading setups. For the market design decisions, one needs to consider that the hydrogen market is just emerging and its fast market development will be strongly driven by EU regulation and sustainability targets. In contrast, the natural gas market mainly developed organically over decades, and regulations were introduced in hindsight. Hence, transferring learnings from the natural gas market can be complex.

3. Methods

We aim to identify core market design choices for a well-working future European hydrogen market and efficient commodity trading. As the literature on this topic is sparse, we employ the Grounded Theory Method (GTM). GTM, introduced by Glaser and Strauss in 1967, represents an adequate research method to analyze new and emerging topics, such as the hydrogen market design [29,30]. The GTM is especially suitable for studies based on qualitative data, which can come from various sources, with interviews representing a standard data collection procedure [29,66]. Based on the GTM, [67] successfully developed a holistic approach for inductive concept development that fulfills the demand of developing concepts from qualitative data inductively and simultaneously exhibits a high standard for rigor. Their approach consists of four core steps and represents a suitable research method for our inductive analysis in combination with the tools of the GTM of [29]. The first step of their methodology is the research design, including a well-defined research question. In the second step, the data collection, [67] suggest conducting semi-structured interviews. The third step is analyzing the collected data to create a data structure, representing emerging concepts and their relationships. In the fourth and last step, the generated and analyzed data is transformed into a theory grounded in the data. The following subsections are derived from the steps of the above-stated inductive methodology of [67], including key elements of [29], and provide detailed explanations of our research approach and its implementation.

3.1. Data collection

For our identified research topic of hydrogen market design, we next need to generate data through semi-structured interviews. We employ the theoretical sampling approach to select adequate interview partners, resulting in five expert groups [29,68]: utility companies (Utility), industrial companies of high-priority hydrogen applications (Industry), commodity energy exchanges (Exchange), government, political and research institutes (Institutes), and the energy sector focus of consulting companies (Consulting). These expert groups represent future hydrogen producers, transmitters, traders, certifiers, buyers, policymakers and regulators. This approach is in line with GTM, which suggests that the primary criterion for selecting comparison groups is their relevance for advancing emerging categories [29]. The selected expert groups were further recently confirmed as the most relevant stakeholders by [69], who performed a stakeholder analysis for the German hydrogen market, which was published after our interviews. The interviewed experts were selected and prioritized on the following

Table 1
Characterization of the research sample.

Category	Characteristic	Number	in %
Organization	Industry (ID)	5	31
	Institute (IS)	4	19
	Utility (U)	3	19
	Consulting (C)	3	25
	Exchange (E)	1	6
Gender	Male (M)	15	94
	Female (F)	1	6

interview recruiting criteria: having valuable expertise in the hydrogen market, market regulation and/or commodity trading, contributing to variation in future hydrogen market roles, contributing to variation in organization types, contributing to gender balance and contributing to generation balance.

Based on these interview recruiting criteria, own research, and contacting relevant organizations through industry collaboration partners, we identified 46 potential interviewees in these highly specialized fields. We focus our interviewees on German organizations, as Germany represents the largest European country in hydrogen demand today and will become even more relevant on a global scale until 2030 as well as 2050 [5,6,70]. Furthermore, many of the interviewed organizations represent large leading players in European or even global markets. After prioritizing 33 particularly suitable candidates, we and our industry collaboration partners reached out via e-mail and LinkedIn.

In total, we conducted 16 expert interviews. Most of the interviewed experts were heading the hydrogen, trading and/or regulatory departments of their respective organizations. The suitability of these experts for answering our research questions was additionally supported during the introductory stage of our interviews. All interviewees stated that their organizations perceive hydrogen as an essential strategic topic and expect significant market developments within the following years. Therefore, their organizations already started with organizational structuring measures (e.g., creating hydrogen departments) and operative preparation (e.g., conducting pilot projects) to perform well in the future hydrogen market. As shown in Table 1, we conducted the most interviews with experts from the industry sector, including one certification service provider. The reason is that the industry sector is quite diverse, representing future hydrogen producers, certifiers, and buyers. More concentrated sectors, such as exchanges and utilities, are hence represented with fewer interviewees. Moreover, the distribution between 15 male interviewees (94%) and one female interviewee (6%) seems uneven. However, this number closely correlates with the three women identified within the 46 potential interviewees and is driven by the low share of women in senior management positions in the energy sector of below 14% [71].

As we promised anonymity to the interview partners, we used codes for each interviewee to put quotes in Section 4 into context. The first letters represent the organization type, and the numbers represent the interview order.

For the GTM, the interview type should allow flexibility as the objective is to create a theory [30]. As mentioned by the authors, it is advantageous to maintain consistency over the covered concepts in the interviews. Hence, we chose semi-structured interviews for our approach, as they allow for consistency without limiting additional topics or the necessity to follow a specific sequence [30]. This approach aligns with [68], who recommends semi-structured interviews for researchers who require flexibility, comparability, and a relatively simple interview form.

Literature provides differing opinions on conducting a literature review before the interviews. While Glaser represents the original opinion from 1967 that literature review increases bias, other researchers, including Strauss, argue that, especially for semi-structured interviews, consulting literature without judging its conclusion helps broaden the mind and discover new insights [29,30,67,72]. As the topics analyzed in this work are rather complex, we conducted a literature review before the interviews.

We divided the semi-structured interview guideline into an intro, four main question sections, and an outro. The main part covers the topics of commodity trading, analogies to the gas market design, trading system, and model hydrogen market design. Following [68], the semi-structured interview guideline was tested and adjusted before interviewing the first experts. The interviews were conducted between January 19th and March 1st 2022 using the video conference tool Zoom. The interview language was German. More than 11 h of audio material was produced, with an average interview duration of 43 min (ranging from 33 to 56 min). Following the GTM, we modified the semi-structured interview guideline several times during the interview process [67]. Additionally, we adjusted the interview guideline to the expected focus of expertise of the interview partner, for example expanding the discussion on infrastructure regulation with the Utility expert group and analyzing the future trading setup in detail with the Exchange expert group. A version of the final general interview guide is attached in Section A of the Appendix.

Following [67], we anonymized all interviews for privacy protection and reduction of potential biases. To further encourage interview partners to share their perspectives openly, we granted full confidentiality at the beginning of the interview and gave an overview of the research project beforehand. Furthermore, interviewees could skip questions if they did not feel in the position to answer them.

3.2. Data analysis approach

As typical for the GTM, we use an iterative approach. Data collection and analysis are ongoing parallel processes to create concepts, categories, and core categories until theoretical saturation is reached and the theory can be articulated [66]. Following the suggestions and transcription rules of [73], we transcribed the conducted interviews completely. We used standard orthography, did not transcribe filler words, non-verbal expressions, pauses, or repetitions without specific purpose, and marked incomprehensive parts with brackets.

Coding represents the fundamental analytics process of the GTM, which is differentiated into three steps [66]. Open coding, also called first-order analysis by [67], aims to break down the data analytically. While constantly comparing observations, conceptual labels are assigned to text segments [66,67]. Within the next step, the second-order analysis, categories are connected and hypothetical patterns emerge, which are verified against incoming data [66]. The last step, selective coding, aims to distill and aggregate the emergent categories even further. This results in core categories representing central phenomena [66,67]. We used the qualitative data analysis software MAXQDA to apply the described coding approach. In total, 17 categories and four core categories emerged, which are outlined in Section B of the Appendix. Section 4 presents the four core categories and the associated categories in detail.

Regarding the proper number of interviews for the GTM, [30] suggest that primary saturation is reached when no new concepts are emerging. As shown in Fig. 1, the number of new concepts decreased significantly after the sixth interview, with only a few new concepts emerging in the last interviews. This observation aligns with [74], who explored that elements for main themes are found already during the first six interviews, and saturation is usually reached within twelve interviews.

4. Results

Four core categories emerged throughout the qualitative data analysis of the 16 conducted interviews: Hydrogen Market Development, Hydrogen Value Chain, Hydrogen Market Regulations, and Hydrogen

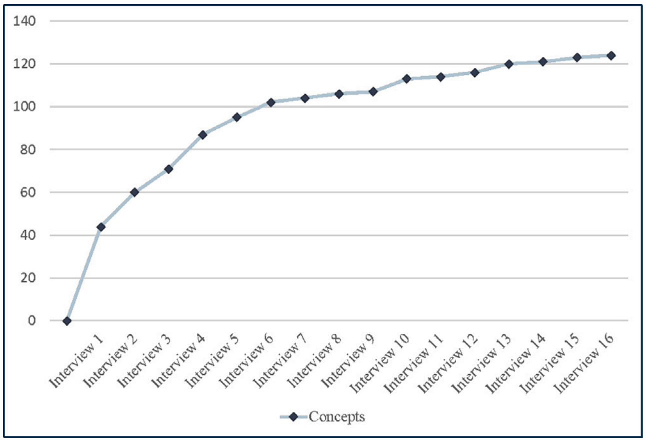

Fig. 1. Saturation of concepts distilled from the interviews.

Commodity Trading. The included concepts occurred in various interviews to ensure representativity. The first two core categories were covered to put our main findings into context. Hence, related results can be found in Section C of the Appendix. Further, additional highly relevant quotes are included in Section C.3.

4.1. Hydrogen market design and regulation

First, we focus on the design of future hydrogen regulation and point out the parallels to the natural gas market. We cover infrastructure regulations, appropriate market development policy interventions, and associated risks.

Regarding the feasibility of transferring regulation from the natural gas to the hydrogen market, U10 says that "(. . .) the gas market works well and you start by taking as much of it as feasible " (U10: 15). C01, IS05, and IS13 go even further and propose merging the natural gas and hydrogen market regulations to exploit synergies. However, the interviewees also observed some differences and advise profiting from the lessons learned in deregulating the natural gas market. U12 questions whether all regulations applied in a developed market such as natural gas are feasible in the ramp up phase. IS05 adds that the hydrogen regulation can already start at a very high development level. Another difference is the market scope that, according to our experts, will become global much earlier on than the natural gas market. Because of blending opportunities, defining feed-in regulations for hydrogen into the natural gas networks is of high importance. Those measures should mainly focus on an EU-wide maximum feed-in hydrogen concentration (e.g., 10%) and rules on who is authorized to feed in which volumes. For the next years, however, there is consensus among the interviewees that blending of natural gas and hydrogen is infeasible on a large scale as the industry asks for pure hydrogen.

While the interviewees largely agree on the regulation of the hydrogen transportation system in its target state, recommendations for the ramp-up phase are less clear. U12 states: "I am not sure whether we should have something like a virtual trading point right from the start or whether we should use point-to-point transports at the beginning." (U12: 29). U10 agrees and but argues to implement an entry-exit model in the long run. The interviewees advocate TPA and non-discriminatory infrastructure access. Another central infrastructure regulation aspect is unbundling. Our experts generally support the approach of vertical unbundling without a clear consensus about the regulation's introduction time. Some interviewees, like U10, suggest applying unbundling in the early stages and transferring the regulation from the natural gas market. U12 supports this proposition and stresses that the current players in natural gas, who might also provide the hydrogen infrastructure, are already unbundled. Others fear that unbundling might discourage the development of the required hydrogen infrastructure and production, as companies who develop infrastructure assets might end up with stranded investments. To address this fear, C01 and IS13 can picture "(. . .) a time window of 5 to 10 years in which we allow transmission system operators to deviate from these unbundling regulations and also become hydrogen producers or hydrogen users. But it is clear from the onset that these parts of the company will be sold to other market players after this limited period." (IS13: 19). With this approach, the companies can still calculate an overall business case for a number of years. C03 and IS05 explain that pipeline fees might become a challenge during the market ramp-up phase while volumes are low. IS05 criticizes the too-small cross-subsidization planned in the new gas directive and suggests that a unit of capacity in natural gas should be priced the same as a hydrogen unit. IS13 agrees that cross-subsidization is a fair solution. He explains that in the beginning, natural gas consumers could subsidize the hydrogen transport costs and later receive a subsidy through hydrogen transport costs.

The interviewed experts support that policy measures will play an integral role in ensuring a timely hydrogen market ramp-up, as hydrogen will be "(. . .) a politically organized ramp-up and market." (IS15: 5). When asked about suitable policy measures to support the hydrogen market development, our interviewees recommended the instruments of direct industry subsidies, a CO_2-price increase, carbon contracts for difference (CCfD), adjusted green electricity taxation and hydrogen usage quotas for selected applications. These instruments do, however, not always work in an additive way, as "(. . .) there are reciprocal relationships between the instruments. This does not necessarily contribute to efficiency and clarity about the individual instruments. I would always prefer few instruments, (...) but then please implement them effectively and with full also political support." (IS05: 27). Policymakers can make the supply and usage of hydrogen more attractive by improving their business case through direct industry subsidies. Despite knowing that operational expenditure (OPEX) will be high, the interviewees strongly recommend focusing on capital expenditure (CAPEX) subsidies. C01 advises avoiding repeating the mistake of long-term financial subsidy support as occurred through Germany's Renewable Energy Sources Act. IS13 supports this statement and adds: "Suppose a project cannot cover its running costs despite the change in the government-induced price and a CAPEX subsidy. Then, frankly, I think the project is so bad that it should be left alone." (IS13: 15). Additionally, the interviewed agree on a CO_2 price increase to close the cost gap between hydrogen and fossil fuels. However, a CO_2 price increase alone might not suffice and might disadvantage German and European companies on a global scale. C01 sees a challenge to European companies in global competition, as an imminent agreement on a minimum global CO_2 price is unlikely. Therefore, a possible additional or alternative instrument is using temporary CCfD for products such as steel or green methanol to compensate price difference on global markets. Those CCfD could be lifted once other regions decarbonize. Another measure with which policymakers can influence green hydrogen prices is reducing related taxation. Especially tax reduction on renewable electricity could have a strong effect as the electricity procurement costs are a critical cost driver. ID06 adds that hydrogen should "(. . .) preferably not be burdened by any tax, government levy, or similar." (ID06: 11). Another measure that creates pressure for future hydrogen applying industries is based on the introduction of quotas, e.g. for green steel production. The experts suggest extending existing quotas, for example, in the refinery industry. IS05 mentions that introducing such quotas, however, has to be linked to hydrogen availability.

Our experts share associated reservations and potential risks regarding the future design and implementation of policy measures. They fear the current hydrogen regulatory uncertainty might persist and slow down the market development and infrastructure buildup. U14 underlines that "we need perspective, reliability, and stability. You can live with many regulations, good or bad. You have to rely on the fact that they will last when we make investment decisions." (U14: 35). U10 shares this assessment and argues that the sooner regulatory certainty is given, the faster the hydrogen market can develop. Furthermore, C03 and IS15 worry that subsidies might be mainly invested into a few, potentially infeasible business models for hydrogen applications. They highlight that such inefficient business models could emerge through long-running funding (e.g., OPEX subsidies).

Another emerging topic is the perceived risks that too strict regulation might carry. Firstly, to mitigate potential market development challenges, the interviewees advocate for a step-wise approach in introducing some regulation. C01 even suggests that "(...) in the beginning, monopoly positions in quotation marks, or closed ecosystems will probably be necessary to reach a certain maturity of the technology and the application because I just have a closed business case." (C01: 25). At the same time, many interviewees emphasize that competition is crucial for a decrease of hydrogen prices and that competition should be ensured by market concentration and monopoly control. IS05 raises the concern that very strict European hydrogen standards could lead suppliers to transport their hydrogen to other regions with lower requirements. E04 emphasizes that other hydrogen colors than green can help support the market ramp-up. However, a lock-in effect into using blue hydrogen needs to be avoided. Another substantial aspect for which many of our experts are convinced that the regulations are too strict is the delegated act of the RED II. While they agree that electricity for hydrogen production should be of renewable origin, the interviewees are certain that the regulatory guidance of geographical correlation, especially temporal correlation, and the element of additionality will harm the green hydrogen market ramp-up. IS13 criticizes the additionality rule, which leads to missing out on using the RES capacity during high electricity generation and low electricity demand periods. U14 agrees with this criticism and alludes to the lengthy planning and installation period for new RES of seven to eight years.

4.2. Hydrogen commodity trading

The following presents the advantages and the prerequisites for hydrogen commodity trading. Moreover, the development of hydrogen trading and the trading system are addressed.

Our interviewees agree that hydrogen trading will increase hydrogen market efficiency. The interviewees believe that exchange-based commodity trading ensures market access, price transparency and liquidity. These exchanges also allow to hedge risks, which is especially beneficial in a young market. In agreement with many other interviewees, ID02 defines the prerequisites for hydrogen commodity trading as the following three aspects: "That a supply and demand market develops, that it can be transported, and that there (...) is clear labeling for the quality." (ID02: 23). Our experts predict that hydrogen will become a tradable commodity, for which trading will be established between 2030 and 2035. However, this development will take time and higher available volumes, as the hydrogen market will be characterized by bilateral agreements in the next years. E04 suggests that a more transparent hydrogen pricing estimation could be achieved by creating a hydrogen price index based on bilateral contracts. C01 also sees advantages in such indices, as these enable hydrogen proxy trading on the index. Further, "(...) exchange trading plays an important role right from the start in creating price transparency and (...) also developing the market. And liquidity then builds up as a result. That can happen right now. As I said, actively accompanying the market ramp-up." (E04: 5). C01 is sure that as soon as hydrogen "(...) has arrived in the real economy, there will be a market, and it will automatically find its way to the exchange. In Europe, we have at least three large energy exchanges that are also looking for new business models with the EEX, Nordpool, and ICE (...)." (C01: 27).

Strong analogies between the natural gas and hydrogen market regarding the trading system were explicitly pointed out by 13 of the 16 interviewees. C01 is "(...) sure there will be a similar structure as in the natural gas market where there are different time periods that are traded in the futures markets and then some spot market for short term balancing of supply and demand." (C01: 31). Next to trading on energy exchanges, OTC trading is expected to be established. Hydrogen derivatives also have to be considered as the hydrogen economy grows, as imports are mostly in the form of ammonia or methanol. For the hydrogen GHG emission-certification, two approaches were proposed. IS07 and IS13 advise the use of mass balancing to ensure that in addition to the production, GHG emissions caused by other factors, like transportation, could be considered. E04 counters, however, that "(...) out of a trading view, a market ramp-up can only work if there is trading with guarantees of origin [GO]. That means to trade product and origin separately." (E04: 21). The majority of the interviewees shares this suggestion which corresponds to the book and claim approach. This approach allows for simple balancing and straightforward tradability according to E04. Regarding the regional scope of the certificate system, the interviewees advise to establish an at least EU-wide system that is later extended to a global one.

5. Discussion

We conducted 16 semi-structured interviews with five different groups of potential hydrogen market stakeholders. Although the interviewees' backgrounds were heterogeneous, we identified a consensus on crucial market design topics among the interviewees. We found that recommendations for regulation and policy measures have strong interdependencies. Hence, developing a holistic understanding of the hydrogen market's functioning and development is necessary for creating a suitable market design with efficient hydrogen commodity trading. We identified three core areas to be covered in the European hydrogen market design and policy measures to support market development and establish efficient hydrogen commodity trading from 2030–2035 onwards. We illustrated the key results in Fig. 2.

In addition to the subsequent detailed discussion comparing our findings to the literature, Section D in the Appendix provides a further graphical comparison.

5.1. Market development policy measures

Our experts strongly recommend that policymakers quickly create planning certainty from the political side, as it is essential for market players to start executing investments and overcome challenges such as the chicken-and-egg problem in the market ramp-up. This finding aligns with current hydrogen literature, which supports that policymakers can significantly influence hydrogen market development and underline the urgency of setting a regulative framework and creating investment incentives [4,15,16,19,32,75].

To support market development, the hydrogen strategy of the European Commission mentions the option to provide direct industry funding support [76]. Our interviewees suggest focusing on providing direct industry support on CAPEX instead of OPEX. This recommendation contradicts multiple reports that state that subsidies should address CAPEX and OPEX [19,32,59]. However, our experts indicate that the prerequisite for financial support should be a solid operational business model.

Our interviewees stress that policymakers must ensure the operative feasibility of hydrogen production requirements. However, article 27 in the delegated act of RED II requires that the green electricity from RES and hydrogen production must correlate geographically and temporally, and only electricity from additionally built RES can be used starting in 2026 [51]. Such strict regulations might significantly aggravate hydrogen production capacities and delay market development. Hence, we recommend that policymakers revise this article and suspend such requirements until a more mature hydrogen market has emerged. This recommendation agrees with the plead of other associations to mitigate or drop those strict regulations [32,52]. A very recent analysis

Core market design and policy areas	Ramp-up and transition phase (until 2030/2035)	Commodity market phase (from 2030/2035)
Market development policy measures	• Support investments by reducing regulatory uncertainty • Allow other hydrogen colors apart from green • Focus direct industry support on CAPEX investments • Revisit strict green electricity criteria in RED II regarding correlation and additionally	• Support clear focus on green hydrogen • Repeal monopoly positions to support hydrogen production competition
	• Support business case of green hydrogen applications through CO2 price increases, CCfD, electricity taxation benefits and/or hydrogen usage quotas	
Infrastructure regulation	• Cross-subsidize hydrogen infrastructure through natural gas while pipelines below capacity	• Determine EU-wide feed-in regulations in natural gas infrastructure, including hydrogen concentration rules and injection authorization
	• Transfer key regulations from natural gas market, such as TPA, unbundling, and entry-exit system; either in early market phases or after an communicated transfer period before market liberalization	
Hydrogen and certificate trading	• Use hydrogen price indices as preliminary trade price orientation • Increase market efficiency through continued development of hydrogen exchange offering	• Trade hydrogen similar to natural gas on energy exchanges and OTC, including a spot market, derivatives and futures • Leverage hydrogen exchange for hedging opportunities, price transparency and liquidity
	• Launch an at least EU-wide GO scheme separate from physical hydrogen delivery through a book and claim system	

Fig. 2. Core hydrogen market design criteria and policy measures.

by [77] on the effects of this strict hourly simultaneity requirement also argue for its relaxation, as a more flexible definition can reduce hydrogen cost while not leading to increased power sector emissions. In their most recent amendment of RED II in October of 2023, the Council of the European Union agrees to evaluate the impact of this additionality and temporal and geographical correlation rule on the availability and affordability of hydrogen by July 2028 [78]. While the agreement to evaluate this issue is positive, given the long planning times of hydrogen projects, the persisting uncertainty of this regulation might still impede hydrogen market growth.

In line with the existing literature, we suggest CCfD in specific sectors with intense international competition, where the CO_2 price might be insufficient for the profitability of using hydrogen-based production methods instead of conventional production [8,19,21,76]. Our findings also match the literature suggesting introducing quotas for specific materials that can be produced using hydrogen, such as fuels, steel, or fertilizers [8,19,21,76]. Besides direct industry support, CCfD, and quotas, the European Commission declares it a critical action to explore additional support instruments [76]. Our analysis identified two supplementary measures to foster hydrogen market development. Firstly, introducing higher CO_2 prices increases green hydrogen applications' competitiveness over conventional production methods. Researchers and organizations agree with the significant effects of CO_2 pricing and emphasize the need for a more internationally consistent CO_2 pricing scheme [21,32]. Secondly, in line with related literature, we suggest repealing all taxes, levies, and duties on green electricity used to produce green hydrogen [8,19,32,59]. As green electricity represents one of the main cost drivers for green hydrogen production, this measure allows for more competitive hydrogen prices and faster market development.

5.2. Infrastructure regulation

Building upon literature that expects infrastructure regulation analogies to the natural gas market, we analyzed which regulations should be transferred to the hydrogen infrastructure market design [23,32,47]. As in previous studies, our interviewees confirm that hydrogen will mainly be transported by a pipeline network, for which also existing natural gas pipelines could be retrofitted [1,5,32,56,57]. We suggest cross-subsidies between hydrogen and natural gas infrastructure, which is controversially discussed in the literature [59,75,79,80]. Infrastructure cross-subsidization avoids high hydrogen pipeline fees during the early market stages and hence accelerates the market ramp-up. Hydrogen could again cross-subsidize gas infrastructure costs in the long run.

Our experts advocate for certain key regulations to be introduced analogous to the natural gas market. Requiring TPA ensures transparent and non-discriminatory access for all future hydrogen suppliers. Unbundling avoids monopolies throughout the hydrogen value chain, and the entry-exit system provides operational feasibility and trading flexibility for hydrogen transport. These recommendations can also be found in the literature [19,20,23,45,59,75]. We answer the open question about regulation introduction time in the literature with two options. Either regulation should be introduced from early on to maximize planning certainty or after a predetermined grace period for a liberal market development.

While our experts agree that blending hydrogen in the natural gas network is inefficient and hydrogen should be primarily used in its pure form in the following years, we find that EU-wide feed-in regulation should still be introduced in the long run [19,45,75]. As the literature suggests, policymakers should cover the permitted concentration of hydrogen within the natural gas grid. The latest proposal for a regulation on the internal markets for renewable and natural gases and for hydrogen suggests an upper limit for blending of 2% hydrogen [81]. Moreover, we recommend that regulation should clearly define which players are authorized to inject which amounts of hydrogen.

5.3. Hydrogen and certificate trading

Our experts confirm that the hydrogen commodity trading system should be designed analogous to the natural gas trading system, including OTC trading, energy exchanges, a spot market, and a future market [1,20,23,45]. Energy exchanges can actively accompany the hydrogen market development by providing hedging opportunities, liquidity, and transparency. Moreover, we find that a hydrogen price index launched by energy exchanges can play a significant role already in the early market stages, as recommended by [45]. Accurate price indices based on information from bilateral contracts can provide price transparency in the ramp-up phase of the market, thereby increasing trading volumes. The EEX supports this approach and launched the first market-based index for hydrogen, HYDRIX, in 2023 [82].

Our interviewees agree with the European Commission's suggestion of EU-wide certificates reflecting GHG emissions [76]. To support a global hydrogen market and significant expected imports, especially for the large future German hydrogen market, we suggest a certification scheme that is at least EU-wide and ensures international interoperability. Related literature discusses mass balancing or the book and claim system as potential tracking models for tracing renewable hydrogen along the value chain [52]. The European Commission suggests the mass balance system in RED II [51,52]. However, to allow for greater flexibility and efficient commodity trading, our analysis concludes that the physical hydrogen products and the certificates should not be linked. Instead, the book and claim system based on GOs should be introduced, similar to the case of renewable electricity. Several studies support the book and claim system as an adequate tracking model [19,20,23,59,75].

6. Conclusion

We investigate the core market design criteria and market development regulation for an efficient hydrogen commodity market in Europe. Based on an inductive approach of the GTM, we conducted 16 semi-structured interviews with different players along the hydrogen value chain to provide a holistic perspective. Other researchers could complement our findings by gaining insights from diverse European countries, such as hydrogen-export-focused countries, and non-European experts, or through quantitative methods such as surveys. As we aimed to provide a holistic perspective on key market design choices, future works could dive deeper into the implementation details of individual discussed regulatory measures, such as quantification of hydrogen goals, region-specific perspectives, quantification of subsidies, or specific infrastructure deliverables. We cover three core areas for the European hydrogen market design and policy measures to support market development and establish efficient hydrogen commodity trading from 2030–2035 onwards: Market development policy measures, necessary infrastructure regulations, and functioning hydrogen and certificate trading setup. Our main findings in these areas include:

1. Market development policy measures
   - 1.1 Policymakers need to urgently reduce regulatory uncertainty.
   - 1.2 Direct financial support through CAPEX subsidies should be provided.
   - 1.3 Policymakers need to push the profitability of hydrogen business models.
   - 1.4 Policymakers should avoid very strict green electricity regulations, such as in Article 27 of RED II.
2. Infrastructure regulations
   - 2.1 As for the natural gas market, fundamental regulations such as third-party access, unbundling, and the entry-exit system should be introduced early on or after a grace period to favor liberal market development.
   - 2.2 EU-wide feed-in regulations in natural gas infrastructure and infrastructure cross-subsidization should be explored.
3. Hydrogen and certificate trading
   - 3.1 Energy exchanges can play a fundamental role in the hydrogen market development by providing hedging opportunities, liquidity, and price transparency.
   - 3.2 The book and claim system on at least an EU scale should be used to for GHG certification.

Our findings are especially relevant for policymakers, as we provide guidance on appropriate measures to support hydrogen market development, market design as well as infrastructure regulation. The results further support gas and future hydrogen infrastructure providers in gaining a more detailed understanding of potential future infrastructure governance and regulation. Our analysis can accelerate market development for future hydrogen producers and consumers by giving clear recommendations on which regulation they can advocate and plan for. Energy exchanges can leverage our findings to define their offering in the emerging hydrogen market.

CRediT authorship contribution statement

Sarah A. Steinbach: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Nikolas Bunk:** Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – review & editing.

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.

Acknowledgments

The authors would like to thank the hydrogen market experts from Horváth & Partners for their contributions to this work.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.05.107.

References

[1] European Commission. Communication from the commission to the European parliament, the council, the European economic and social comittee and the comitee of the regions: A hydrogen strategy for a climate-neutral europe. 2020, URL https://energy.ec.europa.eu/system/files/2020-07/hydrogen_strategy_0.pdf,
[2] European Commission. European green deal. 2021, URL https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.
[3] Egerer J, Farhang-Damghani N, Grimm V, Runge P. The industry transformation from fossil fuels to hydrogen will reorganize value chains: Big picture and case studies for Germany. Appl Energy 2024;358:122485. http://dx.doi.org/10.1016/j.apenergy.2023.122485, URL https://www.sciencedirect.com/science/article/pii/S0306261923018494.
[4] van der Spek M, Banet C, Bauer C, Gabrielli P, Goldthorpe W, Mazzotti M, et al. Perspective on the hydrogen economy as a pathway to reach net-zero CO 2 emissions in europe. Energy Environ Sci 2022;15(3):1034–77. http://dx.doi.org/10.1039/D1EE02118D.
[5] Braun JF, Frischmuth F, Gerhardt N, Pfennig M, Schmitz R, Wietschel M. Clean hydrogen deployment in the europe-MENA region from 2030 to 2050: A technical and socio-economic assessment. 2023, http://dx.doi.org/10.24406/publica-1763,
[6] Hydrogen Europe. Clean hydrogen: Monitor 2021. 2021, URL https://hydrogeneurope.eu/wp-content/uploads/2021/11/HE_CleanH2Monitor_2021.pdf,
[7] International Renewable Energy Agency. Hydrogen from renewable power: Technology outlook for the energy transition. 2018, URL https://www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power,
[8] Sachverständigenrat für Umweltfragen. Wasserstoff im klimaschutz: Klasse statt masse. 2021, URL https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.html.
[9] International Energy Agency. Global hydrogen review 2021. 2021, URL https://www.iea.org/reports/global-hydrogen-review-2021,
[10] International Energy Agency. The future of hydrogen: Seizing today's opportunities. 2019, URL https://www.iea.org/reports/the-future-of-hydrogen.
[11] Zhao G, Nielsen ER, Troncoso E, Hyde K, Romeo JS, Diderich M. Life cycle cost analysis: A case study of hydrogen energy application on the orkney islands. Int J Hydrog Energy 2018;44(19):9517–28. http://dx.doi.org/10.1016/j.ijhydene.2018.08.015.
[12] Hydrogen Council, McKinsey Company. Hydrogen insights: A perspective on hydrogen investment, market development and cost competitiveness. 2021, URL https://hydrogencouncil.com/en/hydrogen-insights-2021/,
[13] Bundesministerium für Wirtschaft und Klimaschutz. IPCEI-standortkarte. 2021, URL https://www.bmwk.de/Redaktion/DE/Downloads/I/ipcei-standorte.html.
[14] Hydrogen Council, McKinsey & Company. Hydrogen insights 2022: An updated perspective on hydrogen market development and actions required to unlock hydrogen at scale. 2022, URL https://hydrogencouncil.com/wp-content/uploads/2022/09/Hydrogen-Insights-2022-2.pdf.
[15] Dawin F, Renelt S, Hecht S, Auer C, Pisula, Stefan: Pfemeter, Felix, Guth A-S, et al. Eine branchenübergreifende sicht auf den wasserstoffhochlauf in deutschland. 2023, URL https://www.psvdl-consulting.com/eine-branchenuebergreifende-sicht-auf-den-wasserstoffhochlauf-in-deutschland/,
[16] Lagioia G, Spinelli MP, Amicarelli V. Blue and green hydrogen energy to meet European union decarbonisation objectives. An overview of perspectives and the current state of affairs. Int J Hydrog Energy 2023;48(4):1304–22. http://dx.doi.org/10.1016/j.ijhydene.2022.10.044, URL https://www.sciencedirect.com/science/article/pii/S0360319922046675.
[17] International Renewable Energy Agency, RMI. Creating a global hydrogen market: Certification to enable trade. 2023, URL https://www.irena.org/Publications/2023/Jan/Creating-a-global-hydrogen-market-Certification-to-enable-trade.

[18] World Trade Organization, International Renewable Energy Agency. International trade and green hydrogen: Supporting the global transition to a low-carbon economy. 2023, URL https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net/-/media/Files/IRENA/Agency/Publication/2023/Dec/IRENA_WTO_International_trade_green_hydrogen_2023.pdf?rev=5478e0e6ebb141cdbd1b1c5a8f9395b1.
[19] Hydrogen Europe. Hydrogen act: Towards the creation of the European hydrogen economy. 2021, URL https://hydrogeneurope.eu/wp-content/uploads/2021/11/2021.04_HE_Hydrogen-Act_Final.pdf,
[20] Bundesverband der Energie- und Wasserwirtschaft. Wasserstoffmarkt – ein commodity handelssystem: Von den evolutionsschritten des erdgasmarktes zu einem zukünftigen wasserstoffmarktdesign. 2021, URL https://www.bdew.de/media/documents/2021-07-BDEW_Positionspapier_Wasserstoffmarkt-Commodity_Handelssystem.pdf.
[21] Deutsche Energie-Agentur. Dena-leitstudie: Aufbruch klimaneutralität: Eine gesamtgesellschaftliche aufgabe. 2021, URL https://www.dena.de/fileadmin/dena/Publikationen/PDFs/2021/Abschlussbericht_dena-Leitstudie_Aufbruch_Klimaneutralitaet.pdf,
[22] Blanco H, Nijs W, Ruf J, Faaij A. Potential for hydrogen and power-to-liquid in a low-carbon EU energy system using cost optimization. Appl Energy 2018;232:617–39. http://dx.doi.org/10.1016/j.apenergy.2018.09.216.
[23] Mulder M, Perey PL, Moraga JL. Outlook for a dutch hydrogen market: economic conditions and scenarios. 2019, p. 1–83, URL https://www.rug.nl/cenber/blog/ceer_policypaper_5_web.pdf.
[24] Blanco H, Leaver J, Dodds PE, Dickinson R, García-Gusano D, Iribarren D, et al. A taxonomy of models for investigating hydrogen energy systems. Renew Sustain Energy Rev 2022;167:112698. http://dx.doi.org/10.1016/j.rser.2022.112698, URL https://www.sciencedirect.com/science/article/pii/S1364032122005871.
[25] Ikonnikova SA, Scanlon BR, Berdysheva SA. A global energy system perspective on hydrogen trade: A framework for the market color and the size analysis. Appl Energy 2023;330:120267. http://dx.doi.org/10.1016/j.apenergy.2022.120267, URL https://www.sciencedirect.com/science/article/pii/S0306261922015240.
[26] Li Z, Zhao Y, Wu P. A coordinated green hydrogen and blue hydrogen trading strategy between virtual hydrogen plant and electro–hydrogen energy system. IET Generation, Transmission & Distribution 2024. http://dx.doi.org/10.1049/gtd2.13118.
[27] Farrell N. Policy design for green hydrogen. Renew Sustain Energy Rev 2023;178:113216. http://dx.doi.org/10.1016/j.rser.2023.113216, URL https://www.sciencedirect.com/science/article/pii/S1364032123000722.
[28] Deutsches Zentrum für Luft- und Raumfahrt. Wasserstoff als ein fundament der energiewende: Teil 2: Sektorenkopplung und wasserstoff: Zwei seiten der gleichen medaille. 2020, URL https://www.dlr.de/de/medien/publikationen/broschueren/2020/wasserstoffstudie-teil-2,
[29] Glaser BG, Strauss AL. The discovery of grounded theory: Strategies for qualitative research. New York: Aldine de Gruyter; 1967.
[30] Corbin JM, Strauss AL. Basics of qualitative research: Techniques and procedures for developing grounded theory. 4th ed. Los Angeles: SAGE; 2015.
[31] PWC. Development of the structure of the European hydrogen market and implications for energy traders. 2021, URL https://www.pwc.de/en/energy-sector.html.
[32] Neuhauser T, Schimek F, Heimann M, Corneille M, Kuhn J, Maier L, et al. Wasserstofferzeugung und märkte schleswig-holstein: Gutachten. 2020, URL https://www.schleswig-holstein.de/DE/fachinhalte/E/energiewende/Downloads/Wasserstoff-Gutachten.pdf?__blob=publicationFile&v=1.
[33] Adam P, Heunemann F, von dem Bussche C, Engelshove S, Thiemann T. Wasserstoffinfrastruktur - tragende säule der energiewende: Umstellung von ferngasnetzen auf wasserstoffbetrieb in der praxis. 2020, URL https://www.get-h2.de/wp-content/uploads/200915-whitepaper-h2-infrastruktur-DE.pdf.
[34] Cerniauskas S, Jose Chavez Junco A, Grube T, Robinius M, Stolten D. Options of natural gas pipeline reassignment for hydrogen: Cost assessment for a Germany case study. Int J Hydrog Energy 2020;45(21):12095–107. http://dx.doi.org/10.1016/j.ijhydene.2020.02.121.
[35] Roth AE. The art of designing markets. 2007, URL https://hbr.org/2007/10/the-art-of-designing-markets,
[36] Vazquez M, Hallack M. Interaction between gas and power market designs. Util Policy 2015;33:23–33. http://dx.doi.org/10.1016/j.jup.2014.04.001, URL https://www.sciencedirect.com/science/article/pii/S095717871400023X.
[37] Roth AE. Marketplaces, markets, and market design. Amer Econ Rev 2018;108(7):1609–58. http://dx.doi.org/10.1257/aer.108.7.1609.
[38] Ringler P, Keles D, Fichtner W. How to benefit from a common European electricity market design. Energy Policy 2017;101:629–43. http://dx.doi.org/10.1016/j.enpol.2016.11.011.
[39] Cronshaw I, Marstrand J, Pirovska M, Simmons D, Wempe J. Development of competitive gas trading in continental europe - how to achieve workable competition in European gas markets?. 2008, URL https://www.iea.org/reports/development-of-competitive-gas-trading-in-continental-europe.
[40] Büsch M. Praxishandbuch Strategischer Einkauf. Wiesbaden: Gabler Verlag; 2013, http://dx.doi.org/10.1007/978-3-8349-4567-9.
[41] Priolon J, editor. Financial Markets for Commodities. Innovation, entrepreneurship and management series, Hoboken, NJ: John Wiley and Sons Inc; 2019, http://dx.doi.org/10.1002/9781119579274, URL https://onlinelibrary.wiley.com/doi/book/10.1002/9781119579274.
[42] Peck J, Shell K. Liquid markets and competition. Games Econom Behav 1990;2(4):362–77. http://dx.doi.org/10.1016/0899-8256(90)90005-F, URL https://www.sciencedirect.com/science/article/pii/089982569090005F.
[43] Burger M. Managing energy risk: A practical guide for risk management in power, gas and other energy markets. 2nd ed. Chichester, West Sussex, United Kingdom: John Wiley & Sons Inc; 2014, http://dx.doi.org/10.1002/9781118618509.
[44] ACER. ACER report on the conditionalities stipulated in contracts for standard capacity products for firm capacity. 2019, URL https://documents.acer.europa.eu/Media/News/Pages/ACER-reports-on-gas-conditional-capacity-products-in-the-EU.aspx,
[45] Trinomics, LBST. Sector integration – regulatory framework for hydrogen. 2020, URL https://trinomics.eu/project/5110-sector-integration/.
[46] Schwintowski H-P. Handbuch Energiehandel. 3rd ed. Berlin: Erich Schmidt Verlag; 2014.
[47] Robinius M, Stolten D, Küster M. Power to gas: Netzzugangsmodelle und marktdesign. 2014, p. 1–13. http://dx.doi.org/10.13140/2.1.4147.7923.
[48] Robinius M. Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff: Dissertation. Schriften des Forschungszentrums Jülich Reihe Energie & Umwelt/energy & environment, 2015, URL https://publications.rwth-aachen.de/record/565873/files/565873.pdf.
[49] Haucap J, Kofler C, Nöcker T, Westerwelle, Angelika, Zimmer D. Energie 2011: Wettbewerbsentwicklung mit licht und schatten: Sondergutachten der monopolkommission gemäß S 62 abs. 1 enwg. 2011, URL https://www.monopolkommission.de/images/PDF/SG/s59_volltext.pdf,
[50] Chyong CK. European natural gas markets: Taking stock and looking forward. Rev Ind Organ 2019;55:89–109. http://dx.doi.org/10.1007/s11151-019-09697-3.
[51] Council of the European Union, European Parliamanent. Directive (EU) 2018/2001 of the European parliament and of the council. 2018, URL https://eur-lex.europa.eu/eli/dir/2018/2001/oj.
[52] Deutsche Energie-Agentur. Global harmonisation of hydrogen certification: Overview of global regulations and standards for renewable hydrogen. 2022, URL https://www.dena.de/newsroom/publikationsdetailansicht/pub/report-global-harmonisation-of-hydrogen-certification/,
[53] White LV, Fazeli R, Cheng W, Aisbett E, Beck FJ, Baldwin KG, et al. Towards emissions certification systems for international trade in hydrogen: The policy challenge of defining boundaries for emissions accounting. Energy 2021;215:1–6. http://dx.doi.org/10.1016/j.energy.2020.119139.
[54] Forschungsgesellschaft für Energiewirtschaft. Studie zur regionalisierung von ptg-leistungen für den szenariorahmen NEP gas 2020–2030. 2019, URL https://www.ffe.de/veroeffentlichungen/studie-zur-regionalisierung-von-ptg-leistungen-fuer-den-szenariorahmen-nep-gas-2020-2030/.
[55] European Commission. Questions and answers on the hydrogen and decarbonised gas package. 2021, URL https://ec.europa.eu/commission/presscorner/detail/en/QANDA_21_6685.
[56] Wang A, van der Leun K, Peters D, Buseman M. European hydrogen backbone: How a dedicated hydrogen infrastructure can be created. 2020, URL https://ehb.eu/files/downloads/2020_European-Hydrogen-Backbone_Report.pdf.
[57] Kotek P, Tóth BT, Selei A. Designing a future-proof gas and hydrogen infrastructure for europe – a modelling-based approach. Energy Policy 2023;180:113641. http://dx.doi.org/10.1016/j.enpol.2023.113641, URL https://www.sciencedirect.com/science/article/pii/S0301421523002264.
[58] Bundesnetzagentur. Regulierung von wasserstoffnetzen. 2024, URL https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Wasserstoff/start.html.
[59] Agora. Making renewable hydrogen cost-competitive: Policy instruments for supporting green h_2. 2021, URL https://static.agora-energiewende.de/fileadmin/Projekte/2020/2020_11_EU_H2-Instruments/A-EW_223_H2-Instruments_WEB.pdf,
[60] Bundesnetzagentur. Regulierung von wasserstoffnetzen: Bestandsaufnahme. 2020, URL https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/NetzentwicklungUndSmartGrid/Wasserstoff/Wasserstoffpapier.pdf?__blob=publicationFile&v=2.
[61] Council of the European Union. Proposal for a directive of the European parliament and of the council on common rules for the internal markets in renewable and natural gases and in hydrogen (recast) - general approach. 2023, URL https://www.consilium.europa.eu/en/press/press-releases/2023/03/28/gas-package-member-states-set-their-position-on-future-gas-and-hydrogen-market/.
[62] Liu W, Wan Y, Zhang Y, Liu Q. Design and implementation of China hydrogen price index system. Clean Energy 2023;7(1):148–56. http://dx.doi.org/10.1093/ce/zkad008, URL https://academic.oup.com/ce/article/7/1/148/7074350?login=false.
[63] Nuñez-Jimenez A, de Blasio N. MIGHTY: Model of international green hydrogen trade. Belfer Center for Science and International Affairs, Harvard Kennedy 2022. URL https://nrs.harvard.edu/URN-3:HUL.INSTREPOS:37373227.

[64] Zhang K, Zhou B, Chung CY, Bu S, Wang Q, Voropai N. A coordinated multi-energy trading framework for strategic hydrogen provider in electricity and hydrogen markets. IEEE Trans Smart Grid 2023;14(2):1403–17. http://dx.doi.org/10.1109/TSG.2022.3154611.

[65] Zhu J, Meng D, Dong X, Fu Z, Yuan Y. An integrated electricity - hydrogen market design for renewable-rich energy system considering mobile hydrogen storage. Renew Energy 2023;202:961–72. http://dx.doi.org/10.1016/j.renene.2022.12.015, URL https://www.sciencedirect.com/science/article/pii/S0960148122018006.

[66] Corbin JM, Strauss AL. Grounded theory research: Procedures, canons, and evaluative criteria. (13):1990, p. 3–21. http://dx.doi.org/10.1515/zfsoz-1990-0602.

[67] Gioia DA, Corley KG, Hamilton AL. Seeking qualitative rigor in inductive research. Organ Res Methods 2013;16(1):15–31. http://dx.doi.org/10.1177/1094428112452151.

[68] Rowley J. Conducting research interviews. Manag Res Rev 2012;35(3/4):260–71. http://dx.doi.org/10.1108/01409171211210154.

[69] Schlund D, Schulte S, Sprenger T. The who's who of a hydrogen market ramp-up: A stakeholder analysis for Germany. Renew Sustain Energy Rev 2022;154:111810. http://dx.doi.org/10.1016/j.rser.2021.111810, URL https://www.sciencedirect.com/science/article/pii/S1364032121010789.

[70] Hydrogen Council, McKinsey & Company. Global hydrogen flows: Hydrogen trade as a key enabler for efficient decarbonization. 2022, URL https://hydrogencouncil.com/wp-content/uploads/2022/10/Global-Hydrogen-Flows.pdf.

[71] International Energy Agency, editor. Women in senior management roles at energy firms remains stubbornly low, but efforts to improve gender diversity are moving apace. 2021, URL https://www.iea.org/commentaries/women-in-senior-management-roles-at-energy-firms-remains-stubbornly-low-but-efforts-to-improve-gender-diversity-are-moving-apace.

[72] Heath H, Cowley S. Developing a grounded theory approach: a comparison of glaser and strauss. Int J Nurs Stud 2004;41(2):141–50. http://dx.doi.org/10.1016/S0020-7489(03)00113-5.

[73] Gläser J, Laudel G. Experteninterviews und qualitative Inhaltsanalyse: als Instrumente rekonstruierender Untersuchungen, 3rd ed. Wiesbaden: VS Verlag für Sozialwissenschaften; 2009.

[74] Guest G, Bunce A, Johnson L. How many interviews are enough? Field Methods 2006;18:59–82. http://dx.doi.org/10.1177/1525822X05279903.

[75] Bundesnetzagentur. Regulierung von wasserstoffnetzen: Ergebnisse der marktkonsultation. 2020, URL https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/NetzentwicklungUndSmartGrid/Wasserstoff/Konsultationsbericht.pdf?_blob=publicationFile&v=1.

[76] European Commission. Hydrogen generation in Europe: Overview of costs and key benefits. 2020, http://dx.doi.org/10.2833/122757.

[77] Ruhnau O, Schiele J. Flexible green hydrogen: The effect of relaxing simultaneity requirements on project design, economics, and power sector emissions. Energy Policy 2023;182:113763. http://dx.doi.org/10.1016/j.enpol.2023.113763, URL https://www.sciencedirect.com/science/article/pii/S0301421523003488.

[78] Council of the European Union, European Parliamanent. Directive (EU) 2023/2413 of the European parliament and of the council of 18 october 2023 amending directive (EU) 2018/2001, regulation (EU) 2018/1999 and directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing council directive (EU) 2015/652. 2023, URL https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302413.

[79] Monopolkommission. Energie 2021: Wettbewerbschancen bei strombörsen, E-ladesäulen und wasserstoff nutzen. 2021, URL https://www.monopolkommission.de/images/PDF/SG/8sg_energie_volltext.pdf.

[80] Pielow JC. Rechtsgutachten zur vereinbarkeit gemeinsamer netzentgelte für erdgas und wasserstoff mit dem EU-recht. 2021, URL https://h2-news.eu/wp-content/uploads/2021/04/rechtsgutachten_zur_eu_konformitaet_gemeinsamer_netzentgelte_erdgas_h2_maerz_2021.pdf,

[81] Council of the European Union. Proposal for a regulation of the European parliament and of the council on the internal markets for renewable and natural gases and for hydrogen (recast) - general approach. 2023, URL https://www.consilium.europa.eu/en/press/press-releases/2023/03/28/gas-package-member-states-set-their-position-on-future-gas-and-hydrogen-market/.

[82] European Energy Exchange. EEX hydrogen index. 2023, URL https://www.eex-transparency.com/hydrogen.