Market Design Options for a Hydrogen Market

Niedrig, Nicolas; Giehl, Johannes; Jahnke, Philipp; Müller-Kirchenbauer, Joachim

CSEI Working Paper 2024-02

CBS DEPARTMENT OF ECONOMICS COPENHAGEN SCHOOL OF ENERGY INFRASTRUCTURE

WORKING PAPER

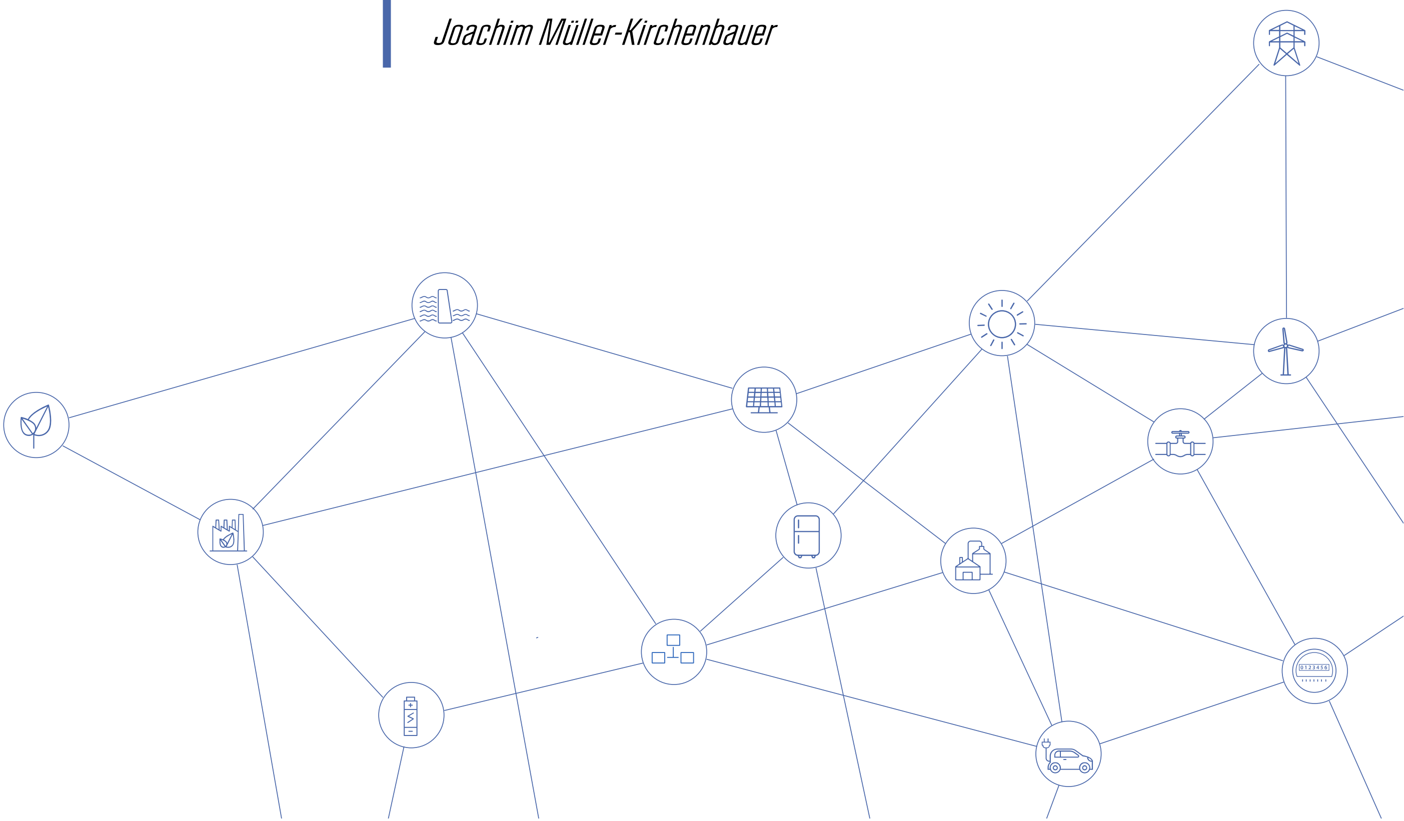
Market design options for a hydrogen market

Nicolas Niedrig

Johannes Giehl

Philipp Jahnke

Joachim Müller-Kirchenbauer



Copenhagen
Business School
HANDELSHØJSKOLEN

Department of Economics

Copenhagen Business School

Working paper 4-2024

Market design options for a hydrogen market

Nicolas Niedrig
Johannes Giehl
Philipp Jahnke
Joachim Müller-Kirchenbauer

Department of Economics – Porcelænshaven 16A, 1. DK-2000 Frederiksberg

Market design options for a hydrogen market

Nicolas Niedrig[1,2], Johannes Giehl[3,*], Philipp Jahnke[2], Joachim Müller-Kirchenbauer[1]

[1] Chair of Energy and Resource Management, Technische Universität Berlin, Germany

[2] BBH Consulting AG, Berlin, Germany

[3] Copenhagen School of Energy Infrastructure, Copenhagen Business School, Denmark

Version: January 2024

Abstract

Renewable hydrogen is a crucial element of the energy transition towards climate neutrality. A key aspect of the development of a hydrogen economy is a suitable market design. Public and science discuss aspects like generation, consumption sectors, and infrastructure in detail. However, the discussion of the design options for the hydrogen market is insufficient. The current discussion does not cover different possibilities of the final market states. Thus, this paper focuses on options for the future hydrogen market design.

The paper presents a two-step approach to identify market designs. First, a literature review and morphological analysis using the electricity and gas market as references provide the basic elements and values of the options. Second, three different infrastructure scenarios for Germany provide the basis for expert interviews to derive suitable market designs.

The analysis results in seven elements that are crucial for the future hydrogen market design. The market design should cover the elements marketplace, trading period, price formation, cost components, price orientation, prequalifications, and geographical coverage. The interviews show that over-the-counter trading and, with increasing regional coverage and more participants, stock exchange trading will be part of the market. The implementation of the stock market requires sufficient market liquidity of the seller's market dominated by potential generation costs. Further aspects of an exchange in combination with prequalifications would be higher transparency and access to information. These aspects could positively influence the development of the hydrogen economy.

Keywords: Renewable Hydrogen, Market Design, Hydrogen Economy, Energy Policy, Power-to-Gas

JEL Codes: K2, L1, L5, N54, N74, O24, O25, Q21, Q27, Q41, Q42

* Corresponding author, jfg.eco@cbs.dk.
Johannes Giehl acknowledges financial support from the Copenhagen School of Energy Infrastructure (CSEI) at the Copenhagen Business School (CBS).

Abbreviations:

BNetzA – Bundesnetzagentur, German Federal Network Agency

CT – Continuous trading

FP – Fixed Price

LT – Long-term trading

OTC – Over-the-counter

SE – Stock exchange

UP – Uniform Pricing

1. Introduction

The energy carrier hydrogen is increasingly becoming the focus of scientific and public discussions. Renewable hydrogen based on wind or solar power is an essential part of reaching climate neutrality in Germany by 2045 [1] and supports the realisation of the Sustainable Development Goals by the United Nations [2]. The hydrogen economy promotes sustainable development not only in terms of climate action and access to clean energy. The transition enables also the development of new business models and associated markets, and thus a more sustainable form of industry [3]. The National Hydrogen Strategy was published by the government in 2020 to demonstrate the need for the use, the potential of renewable hydrogen and the implementation of a hydrogen economy. Hydrogen technology is considered to play a key role in the energy transition due to the wide range of possible applications in the various sectors. The aim is to create a ramp-up of the hydrogen market in Germany and to position German companies competitively for the international market [4].

In the short and medium term, renewable hydrogen is to be used in industry. In the long term, additional use in the transport and further hard-to-abate sectors is conceivable if there is no feasible alternative. Extensive use cases in the building heating sector are to be rated as unlikely. The scientific discussion is primarily focused on the future demand quantity as well as the potential production processes and costs [5]. This is linked to the debate about the future hydrogen infrastructure. The size of a hydrogen network depends significantly on the volume of demand and production [6]. The question of the design of the future hydrogen market remains largely unaddressed. The central question of the paper is: What can the future hydrogen market design look like, using Germany as an example?

The identification and systematisation of potential design options of energy markets is the first step in answering the research question. Current energy markets function as references to derive the design options for a hydrogen market. Grid-based energy markets are suitable given the assumption that hydrogen grid infrastructure will ensure the supply in the long term. Thus, the German electricity and gas markets are references for the design. The German electricity market is a good reference as has been the subject of numerous debates in recent years. Furthermore, the electricity market is one of the most liquid energy markets in Europe [7]. The natural gas market is suitable because of the analogy between natural gas and hydrogen [8–11]. The physical similarities enable the transfer of conclusions on hydrogen. This aspect applies to the transport and infrastructure dimension of a hydrogen market [9,12–14].

The morphological analysis is a proven method for the systematisation of a complex market structure like gas and electricity [15,16]. A keyword-based literature review serves to identify the elementary characteristics of both markets. To answer the research question, the morphological analysis for the hydrogen market is assessed using a web-based expert survey. Different market design options are derived based on three infrastructure scenarios. The adaption of the scenarios of the Bundesnetzagentur (BNetzA) provides different scenarios [6]. The consideration of three scenarios enables the evaluation of the hydrogen market under different framework conditions.

The paper is structured as follows. Chapter 2 presents the state of research. Chapter 3 describes the methodology in detail. Chapter 4 presents the results of the morphological analysis of the electricity and gas market. Chapter 5 presents and assesses the hydrogen market design based on the expert survey, considering the three infrastructure scenarios. Chapter 6 concludes with a summary and provides an outlook.

2. Status Quo

Various recent studies highlight the importance of hydrogen as an energy carrier for the energy transition. Two dimensions prevail in the debate of the hydrogen market development. Research and public debate focus on production and use in the consumption sectors.

On the one hand, it concerns the area and scope of application in the demand sectors. This ranges from focused use in industry and long-distance transport to more extensive use of hydrogen in further applications. The debate relates to the spectra of direct electrification versus indirect electrification via hydrogen and synthetic energy carriers [5,17,18]. The efficiency aspect reduces the use cases for hydrogen [19], e.g., in the heating sector [20] or transportation [21]. The focus on hard-to-abate sectors like the industry [22] is also supported by an infrastructure perspective as the conversion of distribution grids is economically questionable [23]. These aspects concern the scope and scale of the hydrogen economy and the suitable market design.

Second, the debate includes managing the development of the supply side. The discussion focuses on the production processes and their climate impact. The spectrum here ranges from exclusively renewable hydrogen from renewable energies (e.g., wind or photovoltaics) to a product based on fossil natural gas (e.g., in combination with carbon capturing and storage) [24,25]. The background of this discussion is the scarcity of renewable hydrogen within the next years [5]. In the long term, different energy system studies show a high range of supply quantities to cover the demand for renewable hydrogen [5,17]. However, Blanco et al. (2022) show that most energy system models do not consider aspects of the market design [26].

Various studies investigate measures to improve the economic situation of hydrogen production and applications. Farell (2023) investigates support schemes for different sectors and the benefits concerning a cost-effective energy transition [27]. Further studies focus on the coordination of the electricity and gas sectors to improve the integration of renewable hydrogen production into both systems.

Further authors investigate hydrogen market aspects from a modelling perspective. Guo et al. (2021) apply an equilibrium model to a regional hydrogen market. They assume peer-to-peer trading and see further requirements for clearing mechanisms in a coordinated electricity and hydrogen market [28]. Zhu et al. (2023) derive conclusions on the framework of a local integrated energy market using a two-stage market-clearing model. Their focus is on the integration of intermittent renewable energies by proposing a trading mechanism for market clearing to maximise profit [29]. However, the authors do not discuss further elements of a hydrogen market. The authors Bucksteeg et al. (2023) focus on a single aspect of the hydrogen economy. They investigate the integration of the power-to-gas sector into the electricity sector by analysing the effect of carbon pricing schemes [30].

The current research shows a research gap regarding the market design of the hydrogen market. Mulder et al. (2019) investigate possible market failures in the development of a Dutch hydrogen market. They identify that the implementation of a wholesale and retail market and regulatory aspects along the hydrogen value chain is beneficial for the hydrogen economy [31]. Robinius (2015) considers the market design of a hydrogen market exclusively in the context of domestic generation for road transport. He uses analogies to gas market design for his evaluation [11]. Krieg (2012) [8] and Reuß (2019) [10] also refer to the gas market design in their studies on hydrogen infrastructure but focus on technical elements of regulation. In addition, previous approaches consider the development and regulation of the infrastructure [6]. Thus, the current research is limited to single elements of a hydrogen market. There is a need for research on the elements and options of hydrogen market design.

3. Methodology

The elaboration of market design options consists of two parts (see Figure 1). The first part derives the general market design options using a morphological analysis [32]. The grid-based energy markets for electricity and gas serve as a basis for the morphological analysis. A literature review enables the systematisation of the two markets. The second part uses expert interviews to evaluate the market design options using possible market developments. Three scenarios are assumed for the possible hydrogen economy development. The three scenarios are based on infrastructure development scenarios by the BNetzA [6]. The scenarios represent the widest possible range of solutions regarding the possible use of hydrogen.

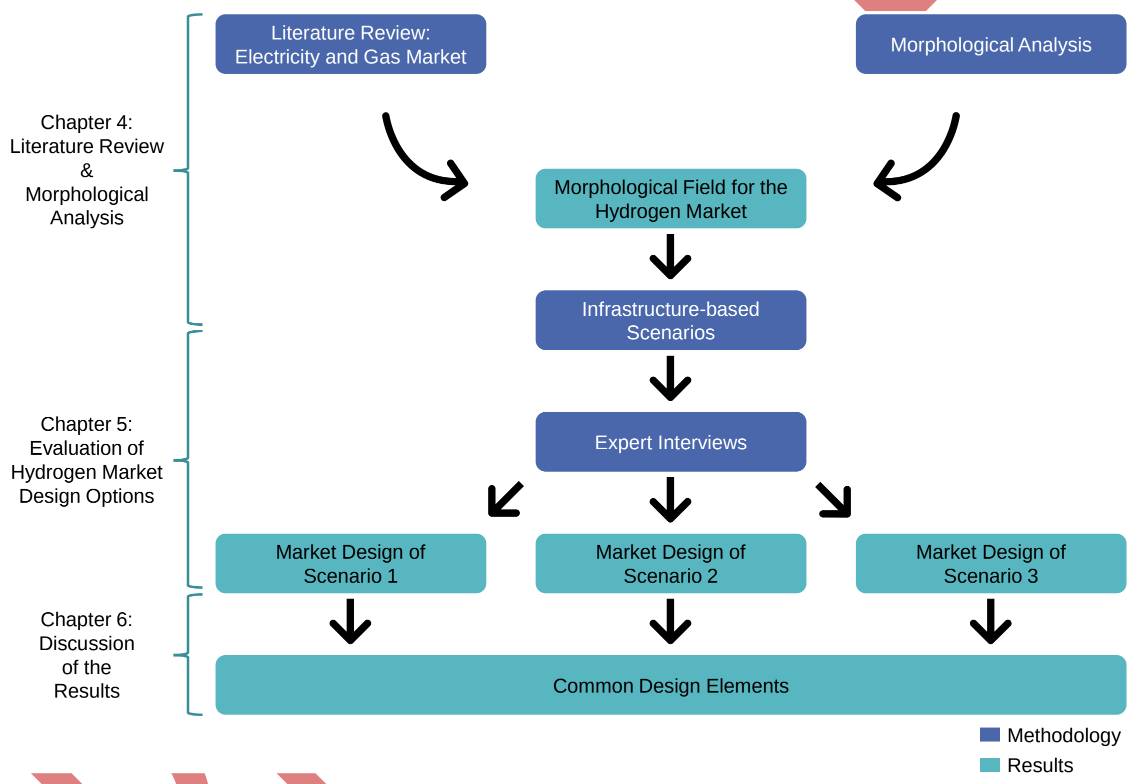


Figure 1: Approach to identify scenario-dependent design options for a hydrogen market.

The presentation of the general design options for the energy markets of electricity and gas uses the morphological analysis. The morphological analysis is a creativity technique for investigating relevant aspects of a problem [16,33,34]. The method enables the systematic identification of solutions and the generation of new concepts, e.g., business models and market segments [34,35]. The method of the morphological analysis is proven in management and for the segmentation of a complex market [16,33].

Hence, the morphological analysis is well suited for the identification of design options for a hydrogen market. The use of the method classifies the complex overall system of the electricity and gas market into its basic elements. Each element can take on different values, e.g., the commodity can be “electricity”, “gas” or “hydrogen”. The set of considered elements of a system and their values form the morphological field of the market [34]. This field represents the complete solution space for the research question about the hydrogen market design options. Potential solutions can be achieved by combining the values of different elements [33]. Solutions that cannot be realised can be excluded [16].

The identification of the elements and values of the morphological field uses a keyword-based literature review. Separate viewing of the electricity and gas markets allows a structured presentation of all aspects. The literature review uses the keywords "electricity market", "gas market", "energy market" or "-economy" individually and in combination with the keywords "structure", "design" and "layout". The literature search uses the keywords in English and German. The publications are limited to the years after 2011 as the so-called “Energiewende” caused a transformation of the energy sector. This ensures that the elements and values of the current electricity and gas market are captured.

Following the review, literature is examined regarding the available information on the design of the electricity and gas markets. This approach identifies articles in the literature that deal with the structure of one or both markets. The analysis and comparison of the articles enable the identification of the elements of both markets. The analysis of the fundamental market elements and values starts with the electricity market. The literature on the electricity market is more comprehensive providing better analyses and more information. The analysis of the gas market adds specific aspects of gaseous energy carriers. The additional information is relevant due to the physical similarities between methane and hydrogen. The solution space for a hydrogen market is represented by the elements and values of both markets.

The future role of hydrogen as an energy carrier is currently the subject of controversial debate. The final infrastructure and scale of the hydrogen economy are still unclear. For this reason, the three scenarios exemplify a different extent of use of hydrogen including the regional scale. The scenarios exemplarily represent a range from a local to an extensive, interregional hydrogen supply. The grid infrastructure scenarios are a theoretical construct for three hydrogen grids with different degrees of development and regional coverage. The scenarios serve as a tool for verbalising the hypothetical solution space.

Scenario 1: Local, island networks. The individual regions are not interconnected and there is almost no exchange between the regions.

Scenario 2: Local, island grids, additional connected via some individual long transport pipelines. The demand in some clusters cannot be fulfilled by local generation. There are regional centres of hydrogen production and consumption that have limited exchange with each other. Thus, not all hydrogen clusters have connections, and the local networks are rather small.

Scenario 3: Closely meshed distribution grids, individual long transport lines.

For Scenario 3, BNetzA's report states that infrastructure with close-meshed distribution grids and long transport lines is conceivable if hydrogen is used in the heating or building sector [6]. However, there is currently one energy system study that considers the use of hydrogen in decentralised heat as part of the solution space [36–38]. Scenario 3 is thus purely representative of a scenario in which hydrogen is primarily traded in a much more liquid market with considerably more market participants than in Scenario 2.

The general solution space of the morphological analysis, together with the three infrastructure scenarios, represents the starting point of the expert interviews. The interviews evaluate the design options of the different scenarios. The screening for the survey is based on professional background and includes stakeholders from the energy sector and the evolving hydrogen economy [39,40]. The interviewees should have expertise in the market design of the energy industry and/or in hydrogen projects. This includes people from research institutions, industrial companies, associations, and foundations as well as legal and technical-economic consultancies. The selected persons get information on the objective of the research, the elements and values of the solution space and an anonymised survey. The interview design allows the selection of only one value per element. This design enables the identification of a clear tendency among the experts concerning the preferable market design for each scenario.

Market liquidity is used as an additional evaluation criterion. The degree of market liquidity is a prerequisite for the design of a functioning market design [41]. An assumption regarding market liquidity is made by each interviewee at the beginning of each evaluation of a scenario. This aspect is important as the number of players, the number of bids and the trading volume are the main factors influencing liquidity. In principle, the more players, the higher the number of bids and the greater the trading volume, the more liquid and the more "perfect" the market [42].

4. Morphological field of the electricity and gas market

The elements and values of the morphological field characterise the electricity and gas market (see Figure 2). “Electricity” and “gas” (values) are the **commodities** (elements) of the investigated markets to derive the design elements and values of the hydrogen market. The **marketplace** is a further key element of the morphological field. The market serves to match supply and demand for a commodity. This is where the conditions for concluding a transaction are created [7,43–52]. The conformity of the literature on the importance of the periods in which a deal is agreed suggests another important element. The term **trading period** summarises the temporal differentiations of trading (e.g., time-dependent submarket, trading period or fulfilment period) [7,43,47–49,49–51,51,53–60]. The literature review shows that the formation of the price is an integral element of the market. The different terms (e.g., price setting, price formation or price setting procedure) characterise the **price formation** process of the morphological field [20,43,47–50,52,53,55,55,56,58,61,62,62,63].

In this context, the authors of the reviewed literature mention the **cost components** that have an impact on pricing. The cost component is a further element of the market description [43,48,49,51,53,55,55,56,58,62,64]. Furthermore, the literature contains information on various factors that influence the price. The element **price orientation** covers the price influencing characteristics [7,43,47–49,51–53,60,62–64]. Participation in an energy market involves further preconditions. The element **prequalifications** contain these requirements [55,62,65–68]. The literature agrees on the importance of the size of the geographic coverage for the design of the market. The element **geographical coverage** shows the different versions of this element (e.g., price zone, bidding zone, market area) [42,49,55,57–60,69–71].

Element	Value					
Commodity	Hydrogen					
Marketplace	Over the Counter	Stock Exchange				
Trading Period	Long-term Trading	Day Ahead	Intraday			
Price Formation	Bilateral	Continuous Trading	Uniform Pricing	Pay as Bid	Fixed Price	
Cost Components	Extraction	Generation	Transport & Distribution	Storage	Sales	Taxes, Duties, Levies
Price Orientation	Cost	Demand	Supply	Competition: Competitors	Competition: Substitutes	
Pre-qualifications	No Requirements	Minimal Supply Volume	Energy Carrier	Emissions	Reaction Time	Quality
Geographical Coverage	Local	Regional	National	International		

Extension by the Gas Market

Figure 2: Elements and values of the morphological field of the electricity and gas market design.

The analysis of the gas market shows additional aspects. Unlike electricity, gas can be stored economically in large quantities in underground storages [55]. This aspect relates to seasonal fluctuations in demand, adjustments during the day, or the provision of balancing energy to provide flexibility [7,55]. The term “Storage” expends the values of the element cost components. The storage costs result from the fixed costs, the reservation of storage capacities and the variable costs for the injection and withdrawal [54,72].

“Extraction” is a further value of the element cost components in the methane value chain. The costs for the gas commodity include extraction as the costs are determined specifically per gas field [73]. Thus, extraction represents an extension of the morphological field. A further difference from the electricity market is the pricing model for transportation. The determination of the grid usage fees uses the so-called entry-exit model [54].

The value “Competition: Substitutes” extends the element price orientation. In the electricity market, the price is based on marginal costs. For the gas market, the literature indicates that pricing was historically strongly characterised by substitution possibilities. The influence of substitutes is still existing today [55,74,75]. Long-term contracts should ensure the achievement of full cost coverage and revenues. The contracts contain obligations for quantity purchases and deliveries as well as price adjustment conditions and are often based on a competitive energy carrier [7,55,75]. Despite the increasing importance of short-term trade, long-term contracts are concluded for new projects. The reason is that long-term contracts ensure the amortisation of the high investments in infrastructure [74].

The value “Quality” represents a further aspect of the element prequalifications. In contrast to electricity, gas trading considers the different qualities of methane. Historically, the distinction between H-gas and L-gas covers differences regarding the calorific value (high and low) [7,55]. In Germany, there were two trading places for the two qualities until 2011 [49,76,77]. Since 2021 there is only one market for all gas products in Germany [49].

The values of the element trading period are similar. However, the separation in short-term gas trading is less strict than in wholesale electricity trading [7]. The trading products on the gas spot market require a longer preliminary time and are divided into less temporally fragmented profiles compared to the electricity market [43]. The use of various trading products arises as gas demand is strongly seasonal. This includes the trading of products such as months, quarters, calendar years, seasons, and gas business years [43,55].

5. Market design options for the hydrogen market

The expert-based interviews provide the basis for the evaluation of the hydrogen (commodity) market designs for three different scenarios. The possible answers in the interviews were single choice to obtain a tendency as distinctive as possible. For this reason, an adjustment of the values compared to the morphological field from Section 4 ensures a clear result (see Figure 3). Some answer options were added to cover combinations of values by the market design. An example is the element marketplace with the values “over-the-counter” (OTC) and “stock exchange”. In practice, both trading possibilities may exist in parallel. Thus, there are three answer options OTC, OTC and stock exchange, and stock exchange.

Element	Value					
Commodity	Hydrogen					
Marketplace	Over the Counter	OTC + Stock Exchange	Stock Exchange			
Trading Period	Long-term Trading	LT + Day Ahead	LT + DA + Intraday			
Price Formation	Bilateral	Bilateral + CT	Bilateral + UP	Bilateral + Pay as bid	Bilateral + Fixed Price	
Cost Components	Extraction	Generation	Transport & Distribution	Storage	Sales	Taxes, Duties, Levies
Price Orientation	Cost	Demand	Supply	Competition: Competitors	Competition: Substitutes	
Pre-qualifications	No Requirements	Minimal Supply Volume	Energy Carrier	Emissions	Reaction Time	Quality
Geographical Coverage	Local	Regional	National	International		

OTC – Over the Counter
LT – Long-term Trading
CT – Continuous Trading
UP – Uniform Pricing

Figure 3: The answer options for the hydrogen market design.

The survey-based expert interviews were conducted in November and December 2021. The survey sample covers 36 experts. 8 experts answered the anonymised interviews. In each case, two experts from the fields of research, industry, legal services, and economic-technical advice were registered.

5.1. Scenario 1

Element	Value				
Commodity	Hydrogen				
Marketplace	Over the Counter 87.5 %	OTC + SE 12.5 %	Stock Exchange 0 %		
Trading Period	Long-term Trading 62.5 %	LT + Day Ahead 37.5 %	LT + DA + Intraday 0 %		
Price Formation	Bilateral 75 %	CT + Bilateral 12.5 %	UP + Bilateral 12.5 %	Pay as Bid + Bilateral 0 %	FP + Bilateral 0 %
Cost Components	Generation 75 %	Transp. + Distribution 0 %	Storage 0 %	Sales 0 %	Taxes, Duties, Levies 25 %
Price Orientation	Demand 50 %	Supply 12.5 %	Competitors 37.5 %	Substitutes 0 %	
Pre-qualifications	No Requirements 12.5 %	Minimal Supply Volume 12.5 %	Emissions 62.5 %	Reaction Time 12.5 %	Quality 0 %
Geographical Coverage	Local 75 %	Regional 25 %	National 0 %	International 0 %	

OTC – Over the Counter
SE – Stock Exchange
LT – Long-term Trading
CT – Continuous Trading
UP – Uniform Pricing
FP – Fixed Price

Figure 4: Results of the expert interviews for Scenario 1

The first scenario contains individual hydrogen regions that are not interconnected via pipeline infrastructure. The market design resulting from the expert interviews reflects this characteristic (see Figure 4). Reliable price structures and purchase guarantees reduce risks for the participants within a local, island network. For this reason, an OTC contract market (87.5 %) with longer-term futures contracts (62.5 %) adapted to the local market participants is advantageous. The result of the expert interviews shows that stock exchange trading seems unlikely in this scenario. Short-term options on quantities could be specified in the bilateral contracts in addition to long-term contracts. Assuming the renewable hydrogen production takes place locally to supply industry, the financing of electrolysers and production must be secured in the long term.

Most of the experts (75 %) rate bilateral pricing as suitable for price formation. This rating is in line with the assessment of the first two elements. OTC trading platforms often involve transactions of futures with bilaterally agreed prices. For three-quarters of the experts, generation is the decisive cost component. The experts also indicate taxes, levies, and surcharges as a further crucial cost component (25 %). Both aspects show the connection to a current debate about electricity prices and electricity price components as critical factors for the economic viability of electrolysis.

The experts do not have a clear tendency for element price orientation. 50 % of the experts consider the demand to be the relevant factor. This would be the case when demand exceeds supply in this scenario. The scarcity of supply creates a seller's market where the price expectations of the suppliers set the price. Furthermore, the interviews indicate the value "Competition: Competitors" as an important orientation for the price. In this case, competing hydrogen producers influence the prices indirectly as customers (e.g., industry) can benefit from relocation in the long term.

The answers for the element of prequalifications reflect the debate on the different technical production types. Most experts state that the limitation of the emissions is the most relevant aspect (62.5 %). Thus, the definition of renewable hydrogen is relevant as it affects the possible energy sources for production. Most responses see a regional geographical coverage. This is in line with the scenario setting with a local island network and no or only limited interregional exchange of hydrogen.

5.2. Scenario 2

Element	Value				
Commodity	Hydrogen				
Marketplace	Over the Counter 25 %	OTC + SE 75 %	Stock Exchange 0 %		
Trading Period	Long-term Trading 25 %	LT + Day Ahead 62.5 %	LT + DA + Intraday 12.5 %		
Price Formation	Bilateral 37.5 %	CT + Bilateral 50 %	UP + Bilateral 0 %	Pay as Bid + Bilateral 0 %	FP + Bilateral 12.5 %
Cost Components	Generation 62.5 %	Transp. + Distribution 25 %	Storage 0 %	Sales 0 %	Taxes, Duties, Levies 12.5 %
Price Orientation	Demand 50 %	Supply 25 %	Competitors 25 %	Substitutes 0 %	
Pre-qualifications	No Requirements 12.5 %	Minimal Supply Volume 0 %	Emissions 62.5 %	Reaction Time 12.5 %	Quality 12.5 %
Geographical Coverage	Local 12.5 %	Regional 75 %	National 12.5 %	International 0 %	

OTC – Over the Counter
SE – Stock Exchange
LT – Long-term Trading
CT – Continuous Trading
UP – Uniform Pricing
FP – Fixed Price

Figure 5: Results of the expert interviews for Scenario 2

Scenario 2 covers local, island grids with additional connections via some long transport pipelines and the characteristics of the market design option differ from Scenario 1 (see Figure 5). A total of 75% of the experts favour the introduction of a stock exchange in addition to the OTC market in this scenario. In Germany, a nationwide infrastructure has been the basis for integrating a stock exchange into the market design of electricity and gas. Sufficient players are necessary to integrate a stock exchange in scenario 2. A high number of players enables enough bids and trading volumes to achieve a certain liquidity and stability of the price.

The stock exchange would increase the transparency of the market. Published volumes and prices provide important information to players. This information increases market security and lowers barriers for new actors. The information further provides orientation for bilateral agreements.

The element trading period consists of long-term contracts and short-term hydrogen procurement. Thus, 62.5 % of the experts assess day-ahead trading as an additional option to medium- and long-term futures. Half of the experts evaluate continuous trading in addition to bilateral pricing as realistic values of the price formation. Similar to the gas market, continuous trading can be realised if the market is liquid with a diverse demand and supply structure to ensure the necessary trading volumes. The current gas market shows this price formation but offers a broader range of options due to the meshed, nationwide infrastructure and high liquidity. It is difficult to assess if there will be enough players and trading volume in scenario 2 to provide the liquidity that short-term trading requires.

As in scenario 1, most experts rate generation costs as the cost component with the highest impact (62.5 %). Further 25% opt for the value “transmission and distribution”. This assessment indicates the increasing importance of infrastructure. Compared to Scenario 1, the infrastructure includes extensions of the island grids and the construction of individual transport pipelines to connect islands. The increase in infrastructure cost explains the reduced relevance of generation costs, taxes, levies, and surcharges.

Half of the experts rate the value “demand” as decisive for the element price formation. the hydrogen market would be a seller’s market according to this evaluation. As in scenario 1, the price expectations of the supply side provide the orientation for the price. The influence of the value “Competition: Competitors” is lower compared to scenario 1. The transport pipelines could enable contracts between the players of different island grids and reduce the impact of local rivalry. The transport pipelines could have a positive impact on the whole market through local clusters with good production conditions. A quarter of the experts favour a demand market in which supply grows faster than demand. This will depend on the political decision on the extent to which non-renewable hydrogen will be part of the market ramp-up.

The emissions are also the most relevant aspect of the element prequalifications, like in scenario 1. Further 12.5 % state the quality of the hydrogen as an important prequalification aspect. Quality refers in this context to the purity of hydrogen. Several regional islands create a common market area in this scenario. It is reasonable to assume that the hydrogen quality might differ between the clusters. The common market requires quality standards for such a case. Three-quarters of the experts specify a regional geographic limitation. In addition, 12.5 % state that the market could be classified as national. This shows that the market area is greater than in scenario 1 but does not necessarily cover the whole of Germany. The morphological analysis shows that a higher liquidity can be assumed for greater market areas. The change in the values of the elements between scenarios 1 and 2 reflects this aspect.

5.3. Scenario 3

Element	Value				
Commodity	Hydrogen				
Marketplace	Over the Counter 0 %	OTC + SE 87.5 %	Stock Exchange 12.5 %		
Trading Period	Long-term Trading 12.5 %	LT + Day Ahead 25 %	LT + DA + Intraday 62.5 %		
Price Formation	Bilateral 12.5 %	CT + Bilateral 62.5 %	UP + Bilateral 0 %	Pay as Bid + Bilateral 25 %	FP + Bilateral 0 %
Cost Components	Generation 50 %	Transp. + Distribution 37.5 %	Storage 0 %	Sales 0 %	Taxes, Duties, Levies 12.5 %
Price Orientation	Demand 25 %	Supply 25 %	Competitors 25 %	Substitutes 25 %	
Pre-qualifications	No Requirements 12.5 %	Minimal Supply Volume 0 %	Emissions 37.5 %	Reaction Time 25 %	Quality 25 %
Geographical Coverage	Local 0 %	Regional 37.5 %	National 50 %	International 12.5 %	

OTC – Over the Counter
SE – Stock Exchange
LT – Long-term Trading
CT – Continuous Trading
UP – Uniform Pricing
FP – Fixed Price

Figure 6: Results of the expert interviews for Scenario 3

Scenario 3 describes extensive coverage with a hydrogen infrastructure. The results of the expert interviews show characteristics of an extensive market area (see Figure 6). The experts state that trading via a stock exchange becomes more relevant than in scenario 2. 87.5% vote for a stock exchange in parallel with OTC trading and 12.5% for a stock exchange market only. Stock exchange trading can support to increase the market liquidity as has happened in the case of the electricity and gas market in Germany. The creation of a uniform trading place is a condition for trading liquidity in a pipeline-based market. The virtual pooling of all volumes into one point enables a single market area. A hydrogen hub comparable to the natural gas market could exist in this scenario. Security and transparency could be increased for market participants. The design of regulatory requirements, such as accounting systems and payment schemes is an important aspect of creating such a single market.

The expert interviews show that short-term trading is becoming more relevant in scenario 3. More than half of the experts assume that trading would not be limited to long-term term contracts and the previous day (day-ahead market) but trading will be possible within the day of delivery. The characteristics of the trading period are then comparable to the electricity and gas market.

The element price formation shows the same pattern towards a broader market. 62.5% of experts opt for continuous trade alongside bilateral pricing. This assessment is in line with the current set-up of the gas market's pricing procedures. Continuous trading requires a trading platform and could be realised by the stock exchange. Continuous trading should be possible in scenario 3 as the market liquidity, the number of bids and the trading volume are high. A quarter of the experts indicated the pay-as-bid auction as a possible pricing method. The electricity market uses auctions for short-term trading. This type of auction intends to reduce economic costs by favouring low-cost bidders and giving them exactly the price they specify. The introduction of an auction form can increase liquidity. The success will depend on the number of bids in short-term trading in the hydrogen market.

Half of the experts opt for generation as the decisive value of the element cost components. 37.5 % of the experts consider it the strongest cost component. The value “transportation and distribution” gains in relevance compared to scenario 2. This aspect is in line with the scenario setting of a more developed network infrastructure. The impact of the two values will depend on the share of hydrogen imports, the hydrogen production cost within the market area and the interconnections with foreign countries. The price setting will be comparable to the electricity market in case of a high share of domestic production. Assuming most hydrogen is imported, the form of the orientation of the exchange price could be similar to today's gas market.

The element price orientation does not show a clear tendency. All four values show 25 % of the voting. As described in the definition of the characteristic, the price is always oriented towards different influencing variables. The disagreement of the experts illustrates the different possibilities. Thus, it can be conceivable that supply and demand have an equal impact on the price in the long term given a liquid market.

The expert’s opinion on the element prequalifications is comparable to scenario 2. 37.5% of the experts chose the “emission factor” as the most important value. A quarter of the experts consider the value “Quality” as the most relevant. All experts agree that prequalification criteria are necessary in scenario 3 e.g., by minimum quality requirements as the more developed network infrastructure improves the exchange between production sites. Furthermore, 25 % of the experts indicated “response time” as the most important value. The speed of the provision of the commodity is decisive for participation in the market under short-term trading. This aspect is in line with the preference for shorter trading periods until intraday trading.

50 % of the experts assume a national market area as most realistic in scenario 3. The relevance of regional markets decreases in comparison with scenario 2 to 37.5 %. 12.5 % of the experts opt for an international market and show that international connections gain importance in such a scenario. The rating for the geographical coverage is in line with the rating for the elements marketplace, trading period and price formation.

6. Discussion

The presented approach enables the identification of the basic features of a hydrogen market design using Germany as an example. The analysis with the morphological field based on the electricity and gas market and expert interviews shows the preferable market design for the three scenarios. The chapter discusses the three main differences between the market design options, presents limitations of method and scope, and shows the need for further research.

The first important difference between the scenarios is the implementation of a stock market. Scenarios 1 and 3 show different market designs. Scenario 2 shares aspects of the market organisation of both scenarios. The expert interviews highlight that already in scenario 2 a stock exchange is an option as a marketplace. The stock market is an important element as the geographical coverage expands beyond local clusters. The integration of a stock exchange in the electricity and gas market in Germany took place after the realisation of an extensive infrastructure. Thus, there is a need for research on the time to introduce a hydrogen stock exchange.

The second aspect concerns the market liquidity and is linked to the implementation of a stock market. Market liquidity is relevant concerning the successful introduction of stock exchange trading. A larger market area and an increased number of market participants are necessary to enhance market liquidity. This is in line with the expert statements on low market liquidity in scenario 1. The experts state that liquidity is the highest in scenario 3 due to a high number of participants and a large trading volume. The trend towards short-term exchange trading requires liquidity, which a national bidding zone can presumably fulfil. This requires that the number of players and the trading volume would be comparable to today's gas market.

In contrast, the statement on the market liquidity does not provide a clear assessment for scenario 2. The results of the expert assessment indicate sufficient market liquidity to enable short-term exchange trading. The critical factor of this development will be the infrastructure coverage to connect local hydrogen clusters. The experts assume that several regional market areas could be possible in this scenario. The investment for infrastructure and hydrogen production could be aligned with the regional conditions and reduce risks for market participants.

In this context, there is a need for further research on the effects of interconnections between different hydrogen clusters. For example, there is potentially less liquidity than in large bidding zones and reduced market liquidity is a factor that results in a higher risk of price variability [42]. Furthermore, the design of the market zone and trading organisation requires caution as it can be vulnerable to strategic behaviour [78].

The scale of demand is the third important impact on the market design. The demand is also the first limitation since the difference exists only implicitly between the scenarios. The aspect of how extensively different demand sectors are entering the hydrogen economy impacts the discussion of market liquidity, marketplace, and trading organisation. At present, there is uncertainty regarding future hydrogen demand in the sectors, as well as generation volumes and production processes. The update of the German hydrogen strategy in 2023 shows the broad range of import and production options. The strategy update also considers hydrogen for decentral heating applications in the long term, depending on the cost of alternative heating technologies and grid conversion [79]. Additionally, the timeline of the hydrogen implementation has several phases of market development. The alignment of the overall strategy and measures of the phases is a prerequisite for achieving the target design of the hydrogen market [80].

The possible import of derivatives is another exemplary aspect of the uncertainties. The hydrogen economy possibly consists of submarkets for pure hydrogen and derivatives. In this case, the market volume of pure hydrogen is reduced. In the same way, the extent of the European interconnection of the infrastructure has an impact on the trading volumes and participants within a market area. All these aspects concern the market liquidity and the need for at least an early implementation of trading via a stock exchange. Consequently, there remains room for interpretation for the qualitative assessment of the market liquidity of each scenario. The scenarios require a more detailed description to improve the assessment of market liquidity. The assessment of market liquidity could be improved by a quantitative estimation in terms of demand, trading volume or number of market participants.

A limitation of the approach and design concerns the expert interviews. First, there is a conflict between random selection and purposeful returns [81]. The number of eight interviews shows the difficulty of conducting a high number of qualitative interviews as they have to cooperate, and a random selection process reduces the response rate [82,83]. The self-selection of anonymised interviews is an appropriate solution as it ensures the coverage of experts from different fields of the evolving hydrogen economy. Second, the smaller the number of interviews the higher the impact of one interview. The aspect is of relevance as the establishment of the hydrogen economy is at the beginning. Therefore, it is important to keep in mind that the answers are also linked to the interviewees' interests.

Another aspect of this limitation relates to the focus on Germany. Expanding the approach beyond the German context could reduce the relevance of this issue through a greater number of and more diverse interviewees. The broader view from a European perspective could create further advantages. The member states have different approaches to establishing a hydrogen market despite efforts by the European Union. The German government plans a two-stage auctioning market for the production and consumption of hydrogen and hydrogen derivatives focusing on renewable hydrogen [84]. The European Union plans independent auctions for renewable hydrogen and guarantees fixed premiums for recipients [85]. There are further differences besides the approaches for price formation mechanisms. The Polish strategy includes low-carbon hydrogen [86] in contrast to the German and EU actioning approach that focuses on renewable hydrogen. A more comprehensive, European approach could lead to a clearer picture of a hydrogen market design and simultaneously reduce the bias of individual experts.

Another limitation relates to the use of the morphological analysis. This aspect concerns the selection of the elements and the details of the values. The integration of institutions (e.g., regulatory authorities and structures) could contribute to further aspects of market organisation. An examination of individual market players could provide further details on the values of the market elements. The feedback on the expert interviews shows that the number of elements and values limits the result. For instance, there were indications that a more precise differentiation of the cost components could be beneficial. The separation of transport and distribution or more details of manufacturing cost values would make the morphological field more concrete. Adding additional (grid-based) energy markets to improve the morphological field is possible. The markets for oil or district heating could be a starting point. The extension could lead to new characteristics and provide further design options for a hydrogen market.

7. Outlook & Conclusion

The use of the literature review and the morphological analysis results in seven elements that are crucial for the future hydrogen market design. The reference markets of electricity and gas provide the information that marketplace, trading period, price formation, cost components, price orientation, prequalifications, and geographical coverage provide the basis for the design options. Three market scenarios based on infrastructure coverage, expert interviews, and assumptions on market liquidity show the detailed configuration of these elements.

Beyond the limitations of the method, there is a need for research into the transformation path towards a final hydrogen market. The research requirement results from the assumption that the scenarios develop chronologically until the infrastructure and market reach a high and interconnected geographical coverage. For this purpose, the analysis of the impact of the different values could show if the design elements inhibit or accelerate the targeted hydrogen economy. The application of the morphological field in interviews for further European market areas could improve the picture of the hydrogen market design options. By doing so, the approach would contribute to the development of the hydrogen economy in Europe. A common approach allows the identification of the most important design components for a European single hydrogen market.

The summary of the key findings of this work consists of three aspects. First, the implementation of OTC and stock exchange trading will be a crucial element of the hydrogen market design as soon as the integration of several clusters ensures a larger market area. Second and in combination with the first aspect, the higher the market liquidity the more temporarily resolved and short-term the trading periods and diversified price formation options. Third, the generation is the crucial cost component and demand will be decisive for the element price formation. The characteristics of a seller's market would be reduced by a larger and more interconnected market area. Thus, the creation of a uniform market area for Germany should be advantageous if the use of hydrogen is extensive. The market participants could benefit from further aspects such as higher transparency, broader access to information and security by institutionalised market mechanisms.

8. Funding

This article was written without direct relation to a funded research project. The work was based on the general funding of the involved institutes.

9. Acknowledgements

We like to thank Friederike Dobler for her feedback during the research and writing process.

Literature

[1] Bundesregierung. Bundes-Klimaschutzgesetz (KSG). Of 12 December 2019 (federal law Gazette I p. 2513), as amended by article 1 of the Act of 18 August 2021. Berlin, Germany; 2021.

[2] Maestre VM, Ortiz A, Ortiz I. Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications. Renew. Sustain. Energy Rev. 2021;152:111628. https://doi.org/10.1016/j.rser.2021.111628.

[3] Khatiwada D, Vasudevan RA, Santos BH. Decarbonization of natural gas systems in the EU – Costs, barriers, and constraints of hydrogen production with a case study in Portugal. Renew. Sustain. Energy Rev. 2022;168:112775. https://doi.org/10.1016/j.rser.2022.112775.

[4] BMWi. The National Hydrogen Strategy, Bundesministerium für Wirtschaft und Energie, Berlin https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6; 2020 [accessed 20 June 2023].

[5] Ueckerdt F, Pfluger B, Odenweller A, Günther C, Knodt M, Kemmerzell J, Rehfeldt M, Bauer C, Verpoort P, Gils HC, Luderer G. Ariadne-Kurzdossier - Durchstarten trotz Unsicherheiten: Eckpunkte einer anpassungsfähigen Wasserstoffstrategie, Wie die Politik Wasserstoffpfade hin zur Klimaneutralität 2045 finden kann, Research Paper funded by the German Ministry for Education and Research, PIK, Potsdam, Germany; 2021.

[6] BNetzA. Regulierung von Wasserstoffnetzen; Eine Bestandsaufnahme der Bundesnetzagentur. Report as of July 2020, Bundesnetzagentur für Elektrizität, Gas, Telekommunikation, Post und Eisenbahnen, Bonn, Germany; 2020.

[7] Löschel A, Rübbelke D, Ströbele W, Pfaffenberger W, Heuterkes M. Energiewirtschaft: Einführung in Theorie und Politik. fourth ed. De Gruyter; 2020. https://doi.org/10.1515/9783110556339.
[8] Krieg D. Konzept und Kosten eines Pipelinesystems zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff, Schriften des Forschungszentrums Jülich, Reihe Energie & Umwelt. Forschungszentrum Jülich, Jülich, Germany; 2012.
[9] Ohta T, editor. Energy carriers and conversion systems, Encyclopedia of life support systems; Energy sciences, engineering, and technology resources. Eolss Publishers, Oxford, U.K.; 2009.
[10] Reuß E. Techno-ökonomische Analyse alternativer Wasserstoffinfrastruktur, Energie & Umwelt / Energy & Environment 467. Forschungszentrum Jülich GmbH, Zentralbibliothek, Jülich, Germany; 2019. ISBN 978-3-95806-414-0.
[11] Robinius M. Strom- und Gasmarktdesign zur Versorgung des deutschen Straßenverkehrs mit Wasserstoff, Energie & Umwelt / Energy & Environment 300. Forschungszentrum Jülich GmbH, Zentralbibliothek, Jülich, Germany; 2015. ISBN 978-3-95806-110-1.
[12] Jaro J, Wang A, van der Leun K, Peters D, Buseman M. Extending the European Hydrogen Backbone - A european hydrogen infrastructure vision covering 21 countries. Guidehouse, Chicago, USA; 2021.
[13] Ogden J, Jaffe AM, Scheitrum D, McDonald Z, Miller M. Natural gas as a bridge to hydrogen transportation fuel: Insights from the literature. Energy Policy 2018;115:317–329. https://doi.org/10.1016/j.enpol.2017.12.049.
[14] v. Mikulicz-Radecki F, Giehl J, Grosse B, Schöngart S, Rüdt D, Evers M, Müller-Kirchenbauer J. Evaluation of hydrogen transportation networks - A case study on the German energy system. Energy 2023;278:127891. https://doi.org/10.1016/j.energy.2023.127891.
[15] Acosta RR, Lehnhoff S, Gomez JM. An Electricity Market Categorization Based on Morphological Analysis for Smart Grid Development. In: 18th International Conference on the European Energy Market (EEM) 2022, IEEE, Ljubljana, Slovenia; 2022, p. 1–7. https://doi.org/10.1109/EEM54602.2022.9921038.
[16] Kaufmann T. Strategiewerkzeuge aus der Praxis: Analyse und Beurteilung der strategischen Ausgangslage. first ed. Springer Berlin Heidelberg, Berlin, Heidelberg; 2021. https://doi.org/10.1007/978-3-662-63105-8.
[17] Capros P, Zazias G, Evangelopoulou S, Kannavou M, Fotiou T, Siskos P, De Vita A, Sakellaris K. Energy-system modelling of the EU strategy towards climate-neutrality. Energy Policy 2019;134:110960. https://doi.org/10.1016/j.enpol.2019.110960.
[18] Chapman A, Itaoka K, Hirose K, Davidson FT, Nagasawa K, Lloyd AC, Webber ME, Kurban Z, Managi S, Tamaki T, Lewis MC, Hebner RE, Fujii Y. A review of four case studies assessing the potential for hydrogen penetration of the future energy system. Int. J. Hydrog. Energy 2019;44:6371–6382. https://doi.org/10.1016/j.ijhydene.2019.01.168.
[19] Ruhnau O, Bannik S, Otten S, Praktiknjo A, Robinius M. Direct or indirect electrification? A review of heat generation and road transport decarbonisation scenarios for Germany 2050. Energy 2019;166:989–999. https://doi.org/10.1016/j.energy.2018.10.114.
[20] Rosenow J, Gibb D, Nowak T, Lowes R. Heating up the global heat pump market. Nat Energy 2022;7:901–904. https://doi.org/10.1038/s41560-022-01104-8.
[21] Plötz P. Hydrogen technology is unlikely to play a major role in sustainable road transport. Nat Electron 2022;5:8–10. https://doi.org/10.1038/s41928-021-00706-6.
[22] Agora Energiewende, AFRY Management Consulting. No-regret hydrogen: Charting early steps for H2 infrastructure in Europe, Study on behalf of Agora Energiewende, Berlin, Germany; 2021.
[23] Giehl J, Hollnagel J, Müller-Kirchenbauer J. Assessment of using hydrogen in gas distribution grids. Int. J. Hydrog. Energy 2023;48:16037–16047. https://doi.org/10.1016/j.ijhydene.2023.01.060.

[24] Ajanovic A, Sayer M, Haas R. The economics and the environmental benignity of different colors of hydrogen. Int. J. Hydrog. Energy 2022;47:24136–24154. https://doi.org/10.1016/j.ijhydene.2022.02.094.
[25] Incer-Valverde J, Korayem A, Tsatsaronis G, Morosuk T. “Colors” of hydrogen: Definitions and carbon intensity. Energy Convers. Manag. 2023;291:117294. https://doi.org/10.1016/j.enconman.2023.117294.
[26] Blanco H, Leaver J, Dodds PE, Dickinson R, García-Gusano D, Iribarren D, Lind A, Wang C, Danebergs J, Baumann M. A taxonomy of models for investigating hydrogen energy systems. Renew. Sustain. Energy Rev. 2022;167:112698. https://doi.org/10.1016/j.rser.2022.112698.
[27] Farrell N. Policy design for green hydrogen. Renew. Sustain. Energy Rev. 2023;178:113216. https://doi.org/10.1016/j.rser.2023.113216.
[28] Guo Z, Wei W, Chen L, Zhang X, Mei S. Equilibrium model of a regional hydrogen market with renewable energy based suppliers and transportation costs. Energy 2021;220:119608. https://doi.org/10.1016/j.energy.2020.119608.
[29] 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;202:961–972. https://doi.org/10.1016/j.renene.2022.12.015.
[30] Bucksteeg M, Mikurda J, Weber C. Integration of power-to-gas into electricity markets during the ramp-up phase—Assessing the role of carbon pricing. Energy Econ. 2023;124:106805. https://doi.org/10.1016/j.eneco.2023.106805.
[31] Mulder M, Perey PL, Moraga JL. Outlook for a Dutch hydrogen market: economic conditions and scenarois, CEER Policy Papers. Centre for Energy Economics Research, University of Groningen, Groningen, Netherlands; 2019.
[32] Zwicky F. The Morphological Approach to Discovery, Invention, Research and Construction, In: Zwicky F, Wilson AG, editors. New Methods of Thought and Procedure. first ed. Springer Berlin Heidelberg, Berlin, Heidelberg; 1967, p. 273–297. https://doi.org/10.1007/978-3-642-87617-2_14.
[33] Álvarez A, Ritchey T. Applications of General Morphological Analysis from Engineering Design to Policy Analysis. Acta Morphologica Generalis 4, Swedish Morphological Societ; 2015.
[34] Schawel C, Billing F. Top 100 Management Tools. sixth ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2018. https://doi.org/10.1007/978-3-658-18917-4.
[35] Storbacka K, Nenonen S. Competitive Arena Mapping: Market Innovation Using Morphological Analysis in Business Markets. J. Bus.-to-Bus. Mark. 2012;19:183–215. https://doi.org/10.1080/1051712X.2012.638464.
[36] Fraunhofer ISI, consentec, ifeu, Technische Universität Berlin. Langfristszenarien für die Transformation des Energiesystems in Deutschland 3 - Kurzbericht: 3 Hauptszenarien. https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2021/LFS_Kurzbericht.pdf; 2021. [accessed 15 June 2022].
[37] Gerhardt N, Bard J, Schmitz R, Beil M, Pfennig M, Kneiske T. Hydrogen in the energy system of the future: focus on heat in buildings. Fraunhofer IEE, Kassel, Germany; 2020.
[38] Gerhardt N, Bard J, Schmitz R, Beil M, Pfennig M, Kneiske T. Wasserstoff im zukünftigen Energiesystem: Fokus Gebäudewärme, Studie zum Einsatz von H2 im zukünftigen Energie-system unter besonderer Berücksichtigung der Gebäudewärmeversorgung. Fraunhofer IEE, Kassel, Germany; 2020.
[39] Faulbaum F. Methodische Grundlagen der Umfrageforschung. first ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2019. https://doi.org/10.1007/978-3-531-93278-1.
[40] Verbong GPJ, Beemsterboer S, Sengers F. Smart grids or smart users? Involving users in developing a low carbon electricity economy. Energy Policy 2013;52:117–125. https://doi.org/10.1016/j.enpol.2012.05.003.
[41] Han B, Tang Y, Yang L. Public information and uninformed trading: Implications for market liquidity and price efficiency. J. Econ. Theory 2016;163:604–643. https://doi.org/10.1016/j.jet.2016.02.012.

[42] Eicke A, Schittekatte T. Fighting the wrong battle? A critical assessment of arguments against nodal electricity prices in the European debate. Energy Policy 2022;170: 113220. https://doi.org/10.1016/j.enpol.2022.113220.
[43] Baumhögger J, Perret C. Großhandelsmärkte für Strom und Gas. In: Matzen FJ, Tesch R, editors. Industrielle Energiestrategie. Springer Fachmedien Wiesbaden, Wiesbaden; 2017, p. 75–98. https://doi.org/10.1007/978-3-658-07606-1_5.
[44] Cramton P. Electricity market design. Oxf Rev Econ Policy. 2017;33:589–612. https://doi.org/10.1093/oxrep/grx041.
[45] Glachant JM, Joskow PL, Pollitt MG, editors. Handbook on electricity markets. first ed. Edward Elgar Publishing Limited, Cheltenham, Gloucestershire, UK; Northampton, MA; 2021.
[46] Gochermann J. Expedition Energiewende. first ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2016. https://doi.org/10.1007/978-3-658-09852-0.
[47] Linnemann M. Energiewirtschaft für (Quer-)Einsteiger: Einmaleins der Stromwirtschaft. first ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2021 https://doi.org/10.1007/978-3-658-33144-3.
[48] Pw, editors. Regulierung in der deutschen Energiewirtschaft, first ed. PricewaterhouseCoopers LLP. Haufe Gruppe, Freiburg; 2017.
[49] Schiffer HW. Energiemarkt Deutschland: Daten und Fakten zu konventionellen und erneuerbaren Energien. first ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2019 https://doi.org/10.1007/978-3-658-23024-1.
[50] Schittekatte T, Meeus L. Flexibility markets: Q&A with project pioneers. Util. Policy 2020;63:101017. https://doi.org/10.1016/j.jup.2020.101017.
[51] Schnorr S. Energiebeschaffung in Industrieunternehmen: Erfolgreiches Agieren am Energiemarkt, essentials. first ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2019 https://doi.org/10.1007/978-3-658-26952-4.
[52] Würfel P. Unter Strom. second ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2017 https://doi.org/10.1007/978-3-658-15164-5.
[53] Akbari-Dibavar A, Mohammadi-Ivatloo B, Zare K. Electricity Market Pricing: Uniform Pricing vs. Pay-as-Bid Pricing. In: Nojavan, S, Zare K, editors. Electricity Markets. Springer International Publishing, Cham; 2020, p. 19–35. https://doi.org/10.1007/978-3-030-36979-8_2.
[54] Böttger T, Grimm V, Kleinert T, Schmidt M. The cost of decoupling trade and transport in the European entry-exit gas market with linear physics modeling. Eur. J. Oper. Res. 2022;297:1095–1111. https://doi.org/10.1016/j.ejor.2021.06.034.
[55] Burger M, Graeber B, Schindlmayr G. Managing energy risk: a practical guide for risk management in power, gas and other energy markets, Second ed. ed. Wiley, Chichester, West Sussex, United Kingdom; 2014.
[56] Graeber DR. Handel mit Strom aus erneuerbaren Energien: Kombination von Prognosen. first ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2014 https://doi.org/10.1007/978-3-658-03642-3.
[57] Kath C, Ziel F. The value of forecasts: Quantifying the economic gains of accurate quarter-hourly electricity price forecasts. Energy Econ. 2018;76:411–423. https://doi.org/10.1016/j.eneco.2018.10.005.
[58] Kirschen DS, Strbac G. Fundamentals of power system economics, second ed. Wiley, Hoboken, USA; 2019.
[59] Nowotarski J, Raviv E, Trück S, Weron R. An empirical comparison of alternative schemes for combining electricity spot price forecasts. Energy Econ. 2014;46:395–412. https://doi.org/10.1016/j.eneco.2014.07.014.
[60] Zepter JM, Lüth A, Crespo Del Granado P, Egging R. Prosumer integration in wholesale electricity markets: Synergies of peer-to-peer trade and residential storage. Energy Build. 2019;184:163–176. https://doi.org/10.1016/j.enbuild.2018.12.003.
[61] Keles D, Renz L, Bublitz A, Zimmermann F, Genoese M, Fichtner W, Höfling H, Sensfuß F, Winkler J. Zukunftsfähige Designoptionen für den deutschen Strommarkt: Ein Vergleich des Energy-only-Marktes mit Kapazitätsmärkten. Produktion und Energie 10, KIT Scientific Publishing; 2016.https://doi.org/10.5445/KSP/1000050759.

[62] Synwoldt C. Dezentrale Energieversorgung mit regenerativen Energien. first ed. Springer Fachmedien Wiesbaden, Wiesbaden; 2016. https://doi.org/10.1007/978-3-658-13047-3.
[63] Würzburg K, Labandeira X, Linares P. Renewable generation and electricity prices: Taking stock and new evidence for Germany and Austria. Energy Econ. 2013;40:159–171. https://doi.org/10.1016/j.eneco.2013.09.011.
[64] Hirth L. The market value of variable renewables. Energy Econ. 2013;38:218–236. https://doi.org/10.1016/j.eneco.2013.02.004.
[65] Götz M. Ökonomische Effekte durch die Einführung von Kapazitätsmechanismen im deutschen und europäischen Strommarkt. Universität Leipzig, Leipzig, Germany; 2018. DOI: 10.13140/RG.2.2.36069.22242..
[66] Hirth L, Ziegenhagen I. Balancing power and variable renewables: Three links. Renew. Sustain. Energy Rev. 2015;50:1035–1051. https://doi.org/10.1016/j.rser.2015.04.180.
[67] Müsgens F, Ockenfels A, Peek M. Economics and design of balancing power markets in Germany. Int. J. Electr. Power Energy Syst. 2014;55:392–401. https://doi.org/10.1016/j.ijepes.2013.09.020.
[68] Vogel M, Bauknecht D. Flexibilität für das Netz. Study on behalf of the German Ministry of Education and Research, Öko-Institut, Freiburg, Germany; 2020.
[69] Hirth L, Schlecht I, Maurer C, Tersteegen B. Zusammenspiel von Markt und Netz im Stromsystem, Eine Systematisierung und Bewertung von Ausgestaltungen des Strommarkts. Study on behalf of the German Ministry of Economics and Energy, Neon and Consentec, Berlin, Aachen, Germany; 2018.
[70] Korte K, Gawel E. Räumliche Koordination im liberalisierten Strommarkt: angemessene Anreize für die Einspeisung. Wirtschaftsdienst 2018;98:60–67. https://doi.org/10.1007/s10273-018-2242-6.
[71] Nicolosi M, Burstedde B. Transformation des Strommarktes bis 2050 – Optionen für ein Marktdesign mit hohen Anteilen erneuerbarer Energien, Final Report. Climate Change 09/2012, Study on behalf of the Federal Environment Agency, Umweltbundesamt, Dessau-Roßlau, Germany; 2021.
[72] Süßenbacher W, Schwaiger M, Stigler H. Kapazitätsmärkte und -mechanismen im internationalen Kontext., in: IEWT 2011. Presented at the 7. Internationale Energiewirtschaftstagung an der TU Wien, Technische Universität Wien, Wien; 2011.
[73] Wang Q, Chen X, Jha AN, Rogers H. Natural gas from shale formation – The evolution, evidences and challenges of shale gas revolution in United States. Renew. Sustain. Energy Rev. 2014;30:1–28. https://doi.org/10.1016/j.rser.2013.08.065.
[74] Bergschneider C. Entwicklungen auf dem internationalen Gasmarkt, in: Matzen, F.J., Tesch, R. (Eds.), Industrielle Energiestrategie. Springer Fachmedien Wiesbaden, Wiesbaden, pp. 53–74; 2017. https://doi.org/10.1007/978-3-658-07606-1_4.
[75] Hulshof D, Van Der Maat JP, Mulder M. Market fundamentals, competition and natural-gas prices. Energy Policy 2016;94:480–491. https://doi.org/10.1016/j.enpol.2015.12.016.
[76] Keller JT, Kuper GH, Mulder M. Mergers of Germany’s natural gas market areas: Is transmission capacity booked efficiently? Util. Policy 2019;56:104–119. https://doi.org/10.1016/j.jup.2018.11.005.
[77] Miriello C, Polo M. The development of gas hubs in Europe. Energy Policy 2015;84:177–190. https://doi.org/10.1016/j.enpol.2015.05.003.
[78] Hirth L, Schlecht I. Market-Based Redispatch in Zonal Electricity Markets. USAEE Working Paper No. 18-369. 2018 https://doi.org/10.2139/ssrn.3286798.
[79] BMWK. Fortschreibung der Nationalen Wasserstoffstrategie, NWS 2023. Bundesministerium für Wirtschaft und Klimaschutz, Berlin, https://www.bmbf.de/SharedDocs/Downloads/de/2023/230726-fortschreibung-nws.pdf?__blob=publicationFile&v=1; 2023 [accessed 22 June 2023].
[80] BDEW. Diskussionspapier für ein Marktdesign für Wasserstoff. Bundesverband der Energie- und Wasserwirtschaft e.V, Berlin, Germany; 2023.
[81] Alsaawi A. A Critical Review of Qualitative Interviews. Eur. J. Bus. and Soc. Sci. 3, 2014;4:149-156, https://doi.org/10.2139/ssrn.2819536.

[82] Bryman, A. Social research methods. first ed. Oxford University Press, New York, NY; 2022. ISBN 978-0-19-085368-6.
[83] Seidman I. Interviewing as qualitative research: a guide for researchers in education and the social sciences, 4th ed. Teachers College Press, New York; 2013.
[84] BMWK. Was ist eigentlich H2 Global? Bundesministerium für Wirtschaft und Klimaschutz, Berlin, https://www.bmwi-energiewende.de/EWD/Redaktion/Newsletter/2022/01/Meldung/direkt-erklaert.html; 2023 [accessed 7 July 2023].
[85] European Commission. Commission outlines European Hydrogen Bank to boost renewable hydrogen. https://energy.ec.europa.eu/news/commission-outlines-european-hydrogen-bank-boost-renewable-hydrogen-2023-03-16_en; 2023 [accessed 7 July 2023].
[86] Ministry of Climate and Environment. Polish Hydrogen Strategy until 2030 with an outlook until 2040, Summary. https://www.gov.pl/attachment/06213bb3-64d3-4ca8-afbe-2e50dadfa2dc; 2020 [accessed 8 July 2023].