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Discussion Paper

How to Create a Hydrogen Market

Lessons from Electricity and Gas Markets on Pricing and Investment Approaches

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Summary

To promote low-carbon hydrogen, which is produced in a way that results in no or near-zero greenhouse gas (GHG) emissions, for decarbonization, substantial investments are required across the hydrogen value chain. Despite the potential of hydrogen in several applications, various uncertainties hinder investment in production, transport, and infrastructure. Thus, it is crucial to address business-related risks to establish a thriving market for low-carbon hydrogen. This work assesses market reforms and advancements in the renewable energy (RE), natural gas, and liquefied natural gas (LNG) sectors to identify crucial market design features and relevant enablers that can support the creation of and transition to a hydrogen-based economy.

The key findings, synthesized via the structure-conduct-performance-regulation (SCPR) framework and supplemented through stakeholders' discussions, are as follows:

- Unlike the gas and electricity markets, the hydrogen industry lacks a reference price for trade and commercial contracts. Thus, establishing a reference price is essential for creating an organized market. As the prices of RE and natural gas can significantly impact the cost of low-carbon hydrogen, integrating these factors as fundamental components of any formula-based mechanism for establishing a market reference price for hydrogen is crucial.
- Despite several decades of gas market development, there is still no universally accepted method for pricing natural gas and LNG. Additionally, these diverse methods of gas price indexation have evolved over time. Similarly, developing benchmarks for low-carbon hydrogen takes time and exhibits regional characteristics.
- As different hydrogen users may have varying levels of willingness to pay for low-carbon hydrogen, it is pivotal to consider implementing a differential pricing strategy for setting retail tariffs. This approach has been successfully utilized to price electricity, gas, and other energy commodities and can help stimulate demand for low-carbon hydrogen.
- A fixed-price approach can incentivize hydrogen producers to take action early, but it increases the government's responsibility to bridge the gap between production costs and consumer affordability. Moreover, leveraging a variable premium approach can optimize the use of public funds. Nonetheless, establishing a reference price for this method can be a complex and challenging task that requires careful consideration and analysis.
- A take-or-pay (ToP) contract can attract investments by mitigating the risk of unpredictable cash flows, as seen in LNG and early RE projects. However, most hydrogen buyers are reluctant to commit to high-priced, long-term contracts. Centralized procurement by a government entity can enhance hydrogen project attractiveness through an agreed-upon ex ante offtake commitment, driving greater dedication in identifying and securing hydrogen end users.
- Hydrogen hubs can help maintain consistent demand for early producers, ensuring a reliable and cost-effective supply for users while managing risks for both parties. To succeed, fair access, transparent pricing, standardized product definitions, contracts, and common data formats for information sharing are crucial. Furthermore, promoting these hubs as "virtual trading hubs" can create opportunities for future trading in the form of certificates.

- The use of double auctions facilitated by an intermediary can provide price and volume stability to producers and shield buyers from making long-term, high-priced commitments. Although the current risk management scope for hydrogen producers is limited, a shift to value-based pricing and the implementation of the carbon border adjustment mechanism (CBAM) in the future can enhance this business model.
- Enabling third-party access (TPA) to the electricity and gas grid has benefited consumers and businesses alike. Extending this approach to hydrogen producers can enhance market liquidity, attract investments, and expedite market development but requires supportive regulatory and legal frameworks, as well as appropriate technical standards.

1. Introduction

The focus on the use of hydrogen energy to facilitate the global energy shift from fossil fuels to clean energy has significantly increased in recent years. A major obstacle to this transition is the underdevelopment of hydrogen markets, despite the potential of hydrogen as a versatile energy carrier. Currently, hydrogen is produced and used primarily in the same location, eliminating the need for transport infrastructure. The low volumetric density and the need for the compression and conversion of hydrogen pose significant challenges in its storage, transport, and distribution. Almost all hydrogen consumed today is gray hydrogen (i.e., via natural gas without capturing the resulting carbon dioxide), with only approximately 1% of global hydrogen output being generated from renewable energy (RE) sources.

In their quest to develop a hydrogen economy, more than 50 countries have announced a hydrogen strategy or roadmap, and another 30 countries are working on developing such a framework (BNEF 2024). Nearly 2,000 new hydrogen projects have been announced worldwide (IEA 2023b). Most projects are concentrated in Europe and the U.S., with a growing number planned in Africa, Australia, China, India, and Latin America. In just 4%-5% of cases, project developers have been able to make final investment decisions due to the unprofitability of early hydrogen projects without subsidies (IEA 2023b). Other barriers to developing a future hydrogen economy include demand, regulatory and technology uncertainties, and a lack of transport and delivery infrastructure.

As policymakers aim for net-zero emissions and to fulfill the Sustainable Development Goals (SDGs), particularly SD7 (affordable and clean energy) and SD13 (climate action), the lack of consensus on hydrogen sustainability further exacerbates the challenges faced by the industry. The central question that this work seeks to answer is as follows: What market design features and regulatory frameworks can facilitate the development of a sustainable hydrogen economy, thereby overcoming existing barriers? This question is answered by examining the electricity and natural gas markets in an effort to learn from previous experience.

RE faced similar challenges when it first emerged over two decades ago. RE was significantly more expensive than was fossil fuel-based electricity, similar to the situation faced by low-carbon hydrogen today compared with the fossil fuels it aims to replace. At the time, electricity companies, mostly vertically integrated utilities (VIUs), were reluctant to purchase pricier renewables, posing potential revenue and offtake risks to RE developers. Innovations in creating a compatible market design that addresses the concerns of RE developers and lenders, especially in the early stages of RE deployment, have been crucial in driving renewable growth (IEA-RETD 2016). Similarly, the liquefied natural gas (LNG) industry has been established on a take-or-pay (ToP) type of contractual agreement that reduces risk and encourages investment in the sector (IEF 2023).

While many studies have analyzed market reforms in each of these sectors individually, the relevance of these findings for developing the low-carbon hydrogen industry has not been systematically examined.
By identifying key elements from the growth trajectories of the RE, natural gas, and LNG sectors, we aim to provide actionable insights for hydrogen market development. We utilize the structure-conduct-performance-regulation (SCPR) framework to explore

the relationships and interdependencies among these sectors, identifying critical enablers for developing hydrogen infrastructure.

This work aims to fill the existing knowledge gap concerning the essential features of a hydrogen market and the policies and regulations required to support industry development. By addressing the complexities and challenges of creating a viable hydrogen economy, we hope to contribute valuable insights for policymakers, investors, and industry stakeholders, thus facilitating a smoother transition to a sustainable energy future.

The remainder of this paper is organized as follows. Section 2 assesses the current state of the hydrogen industry and reviews the relevant literature. Section 3 details the research method adopted in this work, while Section 4 discusses pertinent market design issues specific to the hydrogen industry. Finally, Section 5 concludes the paper by summarizing the key findings and offering recommendations.

2. Hydrogen Outlook and Literature Review

2.1 State of Play of Hydrogen

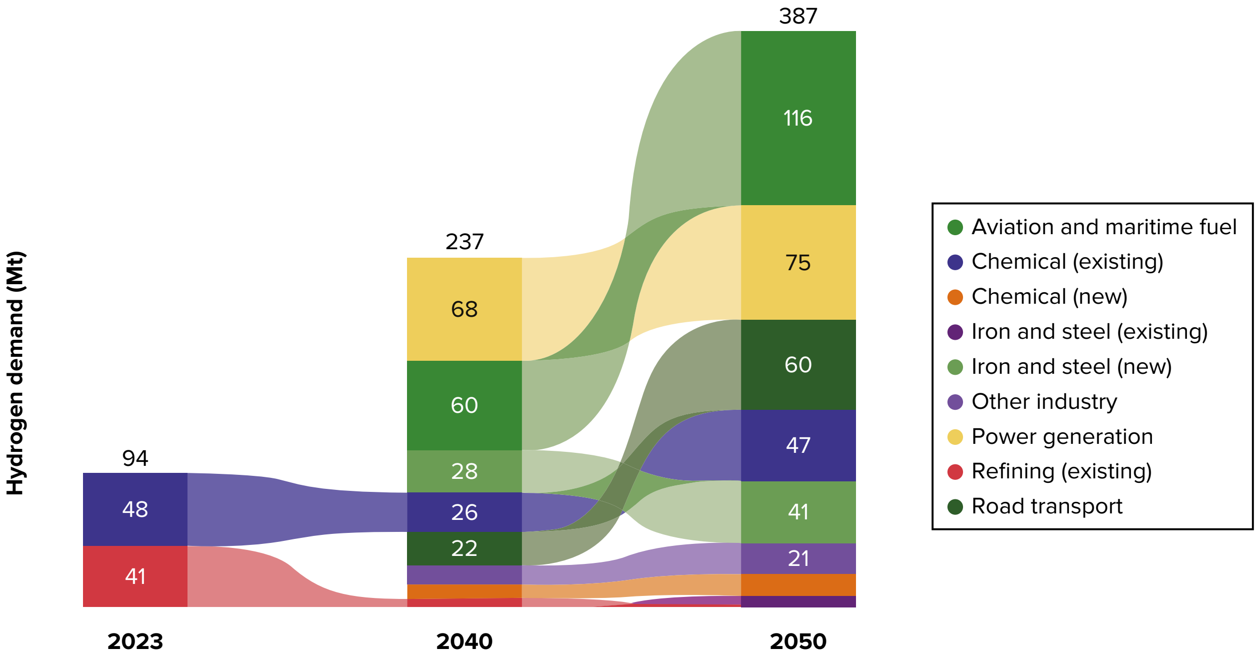
In recent years, hydrogen has garnered significant attention due to its potential in transitioning to a sustainable energy future. Currently, approximately 95 million tonnes (Mt) of hydrogen are used, with the majority consumed in traditional applications such as refining (40 Mt), ammonia production (34 Mt), methanol production (15 Mt), and the steel industry (5 Mt for the production of direct reduced iron) (IEA 2023b). The demand for hydrogen in new applications, such as heavy industry, transport, power generation, buildings, and the production of hydrogen-derived fuels, is currently at a low level, at approximately 40 kilotonnes (kt).

However, the market for hydrogen in these new sectors is expected to grow in the long term due to the enactment of decarbonization policies and technological advancements. Various estimates suggest that global demand for hydrogen will reach between 290 Mt and 660 Mt by 2050 (HC 2022; Hunter 2021; IEA 2023a) (Figure 1). Nearly one-fourth of the global hydrogen demand by 2050 will likely come from hard-to-electrify, energy-intensive industries such as the iron, steel, and chemical industries.

Despite this optimism, uncertainties surrounding future demand growth persist, owing primarily to the high cost of low-carbon hydrogen. Additional challenges, such as insufficient midstream infrastructure and a lack of conducive policy and regulatory support, including carbon intensity standardization, can hinder the hydrogen industry's scalability in the short term. Currently, only 10% of the low-carbon hydrogen capacity planned by 2030 has identified offtakers.

Advances in hydrogen production technologies are increasing in efficiency. Proton exchange membranes (PEMs), solid oxide (SO), and alkaline electrolytes are expected to increase the viability of green hydrogen production in the future. Hydrogen transport and storage are critical in supporting low-carbon hydrogen ambitions. Existing pipelines can be repurposed to transport hydrogen in a blended form. Research and development (R&D) in transport and storage can significantly impact the cost and competitiveness of global hydrogen trade. As global energy markets are struggling to develop a viable model for scaling up hydrogen production, policymakers are considering hydrogen hubs to attract investments and address challenges in supply, demand, and transportation. The main goal of promoting hydrogen hubs is to establish a strong business case for investments by reducing those risks and uncertainties related to hydrogen supply and demand, as well as circumventing the challenges and costs associated with hydrogen transportation. At present, hydrogen pricing is determined through negotiations between buyers and sellers. The absence of an organized market and reference price complicates the establishment of hydrogen as a viable energy commodity.

Figure 1. Global hydrogen demand (IEA Net Zero Scenario).



Source: Authors' illustration based on data from the IEA (2023a).

2.2 Literature Review

The economic, political, and administrative challenges in the transition to a hydrogen economy represent a burgeoning area of academic inquiry. In response to the rapid developments in this field, we conducted a systematic mapping of relevant studies to identify the related key concepts – including the hydrogen economy, the hydrogen market, the hydrogen energy system, the hydrogen industry, low-carbon hydrogen, and hydrogen policies and strategies. This mapping highlights the growing recognition of the importance of public policy and regulation in establishing and supporting a functional hydrogen market. We present the literature review in this paper.

Several studies have underscored the necessity of embedding local elements and actors within any proposed hydrogen market. Ávalos Rodríguez et al. (2022) argue that the success of market creation is intricately tied to the legal and political frameworks that underpin regulatory measures. For the hydrogen market to flourish, an alignment between regulations and local conditions is crucial. Moreover, effective monitoring and evaluation mechanisms are essential for assessing the success of hydrogen development strategies and moving beyond mere policy formulation (Koneczna and Cader 2024).

Asna Ashari, Oh, and Koch (2024) conduct a multidimensional stakeholder analysis and highlight the role of stakeholders in hydrogen technological innovation systems. Their multidimensional stakeholder analysis integrates concepts of quality infrastructure and social perspectives to identify the barriers to and drivers of hydrogen development in Germany and South Korea, concluding that increasing the public awareness of hydrogen technologies can enhance social acceptance and facilitate their adoption. The importance of incorporating social elements into the hydrogen economy is further emphasized by De-León Almaraz et al. (2024), who advocate leveraging sociotechnological and socioeconomic linkages. Additionally, Mozakka, Salimi, and Hosseinpour (2024) offer a composite index that utilizes various indicators – including conflict, regulatory quality, hydrogen policy, RE use, and climate policy – to illustrate the complex relationships influencing hydrogen deployment. While these findings enhance the understanding of potential challenges, they lack actionable insights into the specific policy levers and regulatory frameworks needed for effective hydrogen market establishment.

Spek et al. (2022) offer their perspective on the potential development of the hydrogen economy over the next decade as a means to achieve net-zero carbon dioxide (CO_2) emissions in Europe. The above authors conclude that establishing a hydrogen economy entails overcoming various barriers across different areas, including technology development for hydrogen production and conversion, infrastructure creation, policy, market design, and business model development. The adoption of carbon-free energy carriers such as hydrogen requires sound infrastructure regulations and appropriate modifications in gas market designs to accommodate larger shares of sustainable gases.

In the context of international policy frameworks, Lorentz, Truby, and Philip (2023) provide a review of the law and policy landscape surrounding hydrogen in various jurisdictions, including the U.S., the European Union (EU), Germany, Namibia, Australia, Morocco, and the United Arab Emirates (UAE). The authors argue that to advance the green hydrogen value chain, improve financing conditions, and encourage investments, it is essential to create an appropriate hydrogen market. Hamilton et al. (2022) also emphasize the need to create a hydrogen market but do not clearly articulate the specifics of such a market. Moreover, Ávalos Rodríguez et al. (2022) examine the regulatory framework of the hydrogen market in Mexico in the context of global energy governance. The focus and contributions of the remaining literature covered in this study are presented in Table 1. By leveraging these insights, this work aims to fill the gaps in understanding and contribute to the ongoing discourse on the development of a sustainable hydrogen industry.

Table 1. Primary literature sources for the hydrogen market.

Study	Thematic focus	Contributions
Barreto, Makihira, and Riahi 2003	Hydrogen economy	Conducts a thorough analysis of the long-term, hydrogen-based scenario in the global energy system, identifying technological, institutional, political, and social hurdles in transitioning toward sustainability.
Tsenga, Lee, and Friley 2005	Hydrogen economy	Explores the impacts of hydrogen technologies on the U.S. energy system, emphasizing the need for economic incentives in the form of R&D funding to drive costs, develop hydrogen infrastructure, and encourage market growth.
Penner 2006	Hydrogen economy	Explores hydrogen production through electrolysis and renewables, concluding that developing a hydrogen economy requires new discoveries and innovations.
Clark and Rifkin 2006	Hydrogen economy	Illustrates the opportunities and challenges of transitioning to a green hydrogen-powered economy, emphasizing the need to seek and create new markets.
Murray et al. 2008	Hydrogen market, economy	Examines stakeholders' perceptions for developing a hydrogen economy in Poland and highlights the need for government-industry cooperation and stakeholder-based visions for hydrogen economy.
Ball and Wietschel 2009	Hydrogen market	Uses a multidisciplinary qualitative approach to explore the opportunities and challenges of introducing hydrogen in the transport sector, highlighting the need for decisive policy support and incentives for integrating hydrogen into future energy markets.

(Continued)

Study	Thematic focus	Contributions
Bleischwitz and Bader 2010	Hydrogen strategies and policies	Assesses the EU policy framework for hydrogen and fuel cell development, concluding that current policies are inadequate and suggesting a new policy approach needed for large-scale hydrogen market development.
Amoretti 2011	Hydrogen economy	Proposes a peer-to-peer hydrogen economy framework based on decentralized production, as well as the storage and trading of energy.
Apak, Atay, and Tuncer 2012	Hydrogen strategies and policies	Identifies regulatory and political interferences as significant barriers to the widespread promotion of hydrogen.
Pudukudy et al. 2014	Hydrogen economy	Investigates the potential for creating a renewable hydrogen economy in Asia, emphasizing the need for a strategic, gradual development of hydrogen infrastructure for a successful transition.
Ball and Weeda 2015	Hydrogen economy	Stresses the importance of creating a strong government intervention framework to help manage risks during the early stages of transition.
Ajanovic and Haas 2018	Hydrogen economy	Assesses the economic potential of replacing fossil fuels with green hydrogen in passenger vehicles, indicating that surplus renewable electricity can be converted into hydrogen and re-electrified when necessary.
Tlili et al. 2019	Hydrogen market	Considers the market entry feasibility of hydrogen in the transport and natural gas sectors for the U.S., Europe, Japan, and China.
Brigljević, Byun, Lim 2020	Hydrogen market	Conducts market uncertainty analysis of liquid organic hydrogen carrier (LOHC)-based carbon-free hydrogen delivery systems using process design and simulation approach.
Newborough and Cooley 2021	Hydrogen strategies and policies	Stresses the need for appropriate sector-specific and sector-coupling policies and regulatory arrangements to facilitate demand growth and support developments in the global hydrogen market.
Falcone, Hiete, and Sapio 2021	Hydrogen economy	Qualitatively reviews the policy framework for hydrogen economy in supporting SD7 (affordable and clean energy), showing that both centralized and distributed green hydrogen paradigms involve significant tradeoffs, requiring tailored policy solutions.
Hesel et al. 2022	Hydrogen market	Considers integrated hydrogen and a long-term electricity optimization model for Germany, showing that RE sources and electrolyzers are complementary technologies, which mutually increase their profitability.
Nuñez-Jimenez and De Blasio 2022	Hydrogen market	Constructs a green hydrogen trade cost optimization model for the EU considering the RE potential and hydrogen production cost curves in each member state, as well as transportation costs.
Wappler et al. 2022	Hydrogen market	Analyzes 25 country-specific hydrogen roadmaps to identify the potential market ramp-up scenarios for electrolyzers and green hydrogen demand management.

(Continued)

Study	Thematic focus	Contributions
Schlund, Schulte, and Sprenger 2022	Hydrogen market	Conducts risk profiling of stakeholders in Germany to guide a hydrogen market ramp-up, suggesting that during the market ramp-up phase, political interventions should mostly focus on bridging the economic gap between low-carbon hydrogen and fossil fuel alternatives.
Pingkuo and Xue 2022	Hydrogen market	Performs a comparative analysis of the markets and the policies of the hydrogen industry in the world's four largest economies (China, the U.S., Japan and Germany) based on the institution-economic-technology-behavior framework.
Zhu et al. 2023	Hydrogen market	Proposes a framework of a local integrated electricity-hydrogen market to mitigate the spatial imbalance of RE distribution for hydrogen production.
Lodewyckx, Beasy, and Mattila 2023	Hydrogen market	Analyzes the opportunities and challenges of Australian hydrogen mobility market, suggesting a strong correlation between the technological and social engagement context and perceived challenges in the hydrogen mobility industry.
Reed et al. 2023	Hydrogen market	Performs multi-element analysis to assess least-cost approaches to scaling the renewable hydrogen sector for deep decarbonization using California as a reference market.
Gatto et al. 2024	Hydrogen market	Reviews green hydrogen uptake policies in the U.S. and the EU, as well as the selected subsidization schemes from other renewable markets, to suggest suitable subsidization path to empower large-scale growth in a market for green hydrogen.
Bucksteeg, Mikurda, and Weber 2023	Hydrogen market	Integrates power to gas (PtG) into electricity markets during the ramp-up phase to assess the general effects of carbon pricing on PtG and identify needed market-driven incentives.
De-León Almaraz et al. 2024	Hydrogen economy	Identifies social aspects, defined as all aspects that concern people and their interactions and relationships within a hydrogen system, related to the hydrogen economy.
Zhao, Liu, and Jamasb 2024	Hydrogen business model	Constructs a business model design for distributed hydrogen refueling stations using a multilevel game model.
Lee et al. 2024	Hydrogen economy	Considers the coevolution of technology and institutions to drive innovations for hydrogen economy in South Korea, and finds that energy policy needs to be constructed based on certain policy goals.
Asna Ashari, Oh, and Koch 2024	Hydrogen economy	Assesses the determinants of a transition toward a hydrogen economy using industrial, political, and social factors using technological innovation systems for Germany and South Korea.

3. Research Design

This study employs the structure-conduct-performance-regulation (SCPR) framework, an enhanced version of the structure-conduct-performance (SCP) model originally developed by Bain (1959). The SCP model serves as a theoretical framework in industrial economics for analyzing the causal relationships among major market elements, namely, industry structure, firm conduct, and market performance (Gordon 2023). The SCP model has been extensively utilized to establish a theoretical rationale for industry policies (Ferguson 1988) and has been applied in the energy sector to analyze the behavior and performance of the gas and electricity markets (Peng and Poudineh 2016), as well as transformations in the global energy market in terms of various aspects (Burmaka and Rudkovskyi 2021).

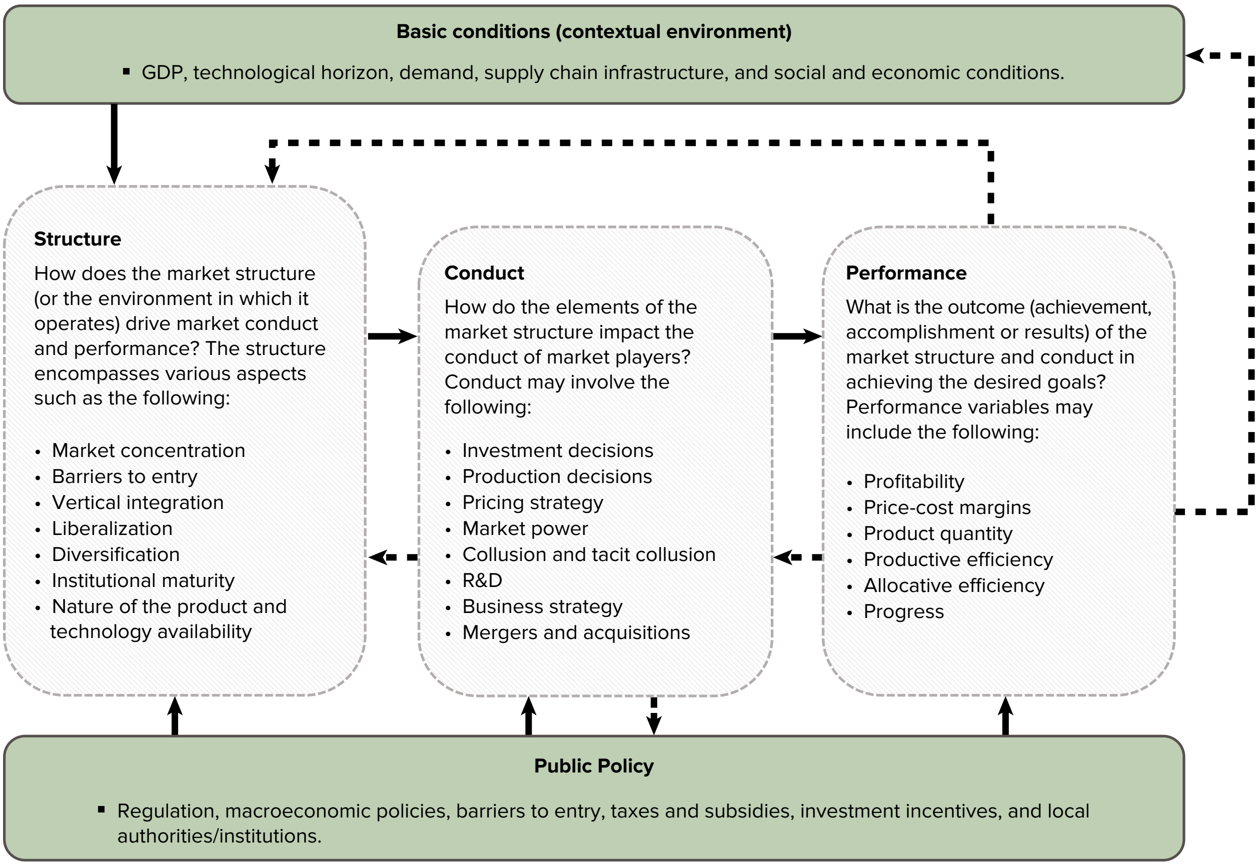
Given that the original SCP framework does not account for regulatory factors, which are vital to the energy market, Peng and Poudineh (2016) introduced an additional component, thus yielding the SCPR model. This modification integrates regulatory aspects as an external influence on market structure and firm conduct, thereby creating a feedback loop that affects overall industry performance.

In the context of the burgeoning low-carbon hydrogen industry, the SCPR model is particularly applicable. This analysis focuses on the following three primary barriers to market entry: price, offtake, and access to hydrogen infrastructure. By utilizing the SCPR framework, this study aims to provide insights into market conditions that can catalyze the growth of the hydrogen economy.

Furthermore, the SCPR model is essential for identifying specific regulations that can stimulate demand in emerging sectors, establish effective pricing mechanisms, facilitate access to necessary infrastructure, and ensure safety standards. Figure 2 illustrates the fundamental elements of the SCPR model, which serves as a guide for the analytical process employed in this study.

We also utilized a bottom-up approach to supplement SCPR analysis by hosting structured stakeholder discussions on this topic. Over 40 local, regional, and global stakeholders involved in the development of low-carbon hydrogen took part in the roundtable dialog. Participants shared their viewpoints, which we synthesized to identify the primary challenges and crucial pathways for advancing the low-carbon hydrogen market.

Figure 2. Contextually adapted SCPR model for analyzing energy transformation.



Source: Authors.

4. Low-Carbon Hydrogen and Market Design

This section examines developments in the renewable electricity (RE) and natural gas/LNG markets via the SCPR framework. This work considers the RE, natural gas and LNG sectors to understand the dynamics and challenges of energy transformation (Appendices A, B, and C, respectively). The goal is to identify synergies for creating a hydrogen market. On the basis of the SCPR analysis and workshop discussions, three core issues – pricing, business model, and access – have been identified for developing further insights. Table 2 illustrates the scope and focus of this paper. The key findings relevant to the hydrogen industry are discussed below.

Table 2. Hydrogen producers' risk factors and potential mitigation measures.

Major risk factors	**Price**	**Volume**
Risk mitigation measures	**Pricing strategies** ❖ H2 reference price ❖ H2 retail price ❖ H2 pipeline access ❖ H2 offtake price ➢ Fixed-price contract ➢ Fixed-premium contract ➢ Variable-premium contract	**Potential business models** <u>Direct</u> ❖ Take or pay ❖ Centralized procurement ❖ Hubs <u>Indirect</u> ❖ Production-based model ❖ Carbon contracts for difference (CCfDs)

Notes: Mitigation strategies for other risk factors, such as a lack of midstream infrastructure, policies, and regulatory and technological uncertainties, are not within the scope of this paper.

Source: Authors' illustration.

4.1 Hydrogen Pricing

The global effort to establish a hydrogen market raises the following question: What pricing mechanism accurately reflects consumers' perceived value of hydrogen energy and provides efficient investment signals? As the hydrogen industry transitions from small-scale testing to larger commercial ventures, securing financing becomes vital for launching major projects. However, the lack of an established market for hydrogen and standard pricing, akin to LNG, complicates this process for project developers. Therefore, developing a pricing mechanism to support the early stages of hydrogen deployment and market development is crucial. This work explores the potential connections among natural gas, LNG, and electricity pricing to evaluate their relevance for hydrogen pricing. We discuss pricing fundamentals, methodologies, and challenges faced from both wholesale and retail perspectives in these sectors to determine their relevance (or lack thereof) for hydrogen pricing.

4.1.1 Setting a Market Reference Price for Hydrogen

The market reference price for energy commodities, including gas, LNG, and coal, is essential for ensuring transparency and predictability in their trade. While these commodities benefit from such benchmarking, the same advantage is lacking for hydrogen. Establishing a market reference price or index for hydrogen can unlock its potential as a vital energy commodity, including the effective implementation of subsidy programs on the basis of a contract for differences (CfD). It is important to assess whether linking hydrogen prices to other energy commodities is suitable or if alternative methods better reflect the unique characteristics of hydrogen.

To answer these questions, we compare the evolution of the natural gas and LNG markets and pricing to analyze their relevance for establishing a hydrogen benchmark. Natural gas is traded globally in various forms – spot, short term, medium term, and long term. Traditionally, natural gas exports were priced under long-term ToP bilateral sale contracts, often indexed to crude oil prices to ensure returns on costly investments in gas/LNG transportation and storage infrastructure (GECF 2024). With the expansion of LNG, new trading, contracting, and pricing methods have emerged, although the correlation between natural gas and oil prices has not completely vanished (Hasanli 2024). Natural gas markets continue to exhibit diverse pricing responses, which can be categorized into four major regional groups.

Table 3 presents a comparison of this asymmetric approach and its associated features. It shows that despite decades of market development, there is no standardized method for pricing natural gas. Various markets use different pricing approaches influenced by factors such as market maturity, price volatility, infrastructure adequacy, and alternative fuel availability in major importing countries. Consequently, numerous gas price indexing methods have emerged globally. In the Asia-Pacific region, where countries rely heavily on LNG imports owing to limited domestic resources, pricing is often tied to crude oil. This connection is driven by the liquidity and transparency of oil prices, as well as the substitutability of natural gas with petroleum products (EIA 2015). Japan's historic reliance on crude oil shifted in 1969 when it began importing LNG, setting the stage for oil-linked pricing agreements. These contracts provide producers with certainty in terms of recovering substantial investment costs (Cassidy and Kosev 2015) and enable them to fund infrastructure using long-term contracts as collateral (Chandra 2020). Over time, these contracts have adapted to include more flexible terms, mitigating price risks for buyers as oil prices fluctuate.

Gas-to-gas markets (Group 1), which utilize transparent price formation and competitive trading environments, can provide an ideal method for benchmarking hydrogen pricing. Hubs such as the Henry Hub (HH) in the U.S., the National Balancing Point (NBP) in the UK, and the Title Transfer Facility (TTF) in the Netherlands exemplify this model. However, given the nascent state of the hydrogen market – with limited production capacity and infrastructure – it is unlikely that hydrogen will independently establish competitive pricing in the near future.

In contrast, regulated markets (Group 2) use a pricing approach that combines wholesale and retail elements, employing a "cost-plus[1]" method to ensure reasonable returns for producers. Segmented retail tariffs enable the recovery of necessary costs from end users on the basis of their ability to pay or other economic and political considerations. While this approach simplifies implementation and can stimulate hydrogen demand among cost-sensitive end users, it often lacks transparency and can distort those price signals essential for attracting private investment. The government may choose to sell hydrogen to end consumers at prices lower than its production cost or the average pooled cost of various hydrogen production sources. However, this approach may impose an additional financial burden on the government.

Table 3. Asymmetries in global gas market pricing strategies.

Group 1: Gas-on-gas markets	**Group 2: Regulated markets**	**Group 3: Hybrid markets**	**Group 4: Oil-linked markets**
North America, the UK, and northwestern Europe	Europe (central and southern), South Africa, Southeast Asia	Japan, Korea, Taiwan, LNG China, LNG India	Middle East, Russia, non-LNG Asia
- Gas prices influenced by the dynamics of supply and demand within a defined market, typically a virtual hub. - Prices generally not in sync with other energy commodities. - Liberal markets with volatile prices. - Gas traded on open exchanges (such as NYMEX in the U.S. and the NBP in the UK). - Pricing information that is transparent, readily available, and updated regularly. - Ample storage and transportation systems. - Infrastructure that is openly accessible through regulated usage fees.	- Gas prices set by the regulatory body using a nonmarket approach (such as “cost plus”). - Approach used mainly in domestic markets, where price regulation is often segmented by customer type and demand sector. - No or limited influence of market forces. - Pooled prices often being used, and government taking price risk.	- Gas prices indexed to substitute energy prices (especially oil-based products and coal or even electricity) under majority long-term contracts. - Limited number of suppliers and many buyers. - Storage and transport controlled by few players. - Some financial markets trading gas.	- Gas prices linked directly to oil prices or that can be administered by the government. - Gas that can be used domestically only with no trading happening. - Limited number of suppliers and many buyers. - Storage and transportation controlled by buyers. - No significant financial markets trading gas.

Source: Chandra (2020).

The most prevalent pricing practices remain those tied to oil and substitutable energy sources (Groups 2 and 3). Historically, LNG prices have been correlated with competing fuel prices due to competitive and economic factors (Chen et al. 2021) and because of their roles as primary energy sources (Smith 2024). Under this mechanism, formula-linked gas prices also change when the substitute fuel price changes, sometimes significantly deviating from the natural gas spot market price. As hydrogen production relies on other primary energy sources, indexing hydrogen prices on the basis solely of substitute fuels may not capture the full pricing dynamics. For example, the costs of renewable electricity and natural gas significantly impact hydrogen production costs. Consequently, the cost of feedstocks for hydrogen production should be a fundamental component of any formula-based mechanism for indexing hydrogen prices. Emerging models, such as Germany’s HYDRIX model, aim to establish a price index on the basis of supply and demand dynamics for green hydrogen (EEX 2024). However, more research is needed to create a comprehensive index that accounts for the dynamic nature of hydrogen prices and their dependence on various market, technical, and policy factors.

4.1.2 Setting Retail Hydrogen Prices

In economic theory, the "first-best" approach to setting end-user prices aims to recover the long-run costs from users. However, in practice, applying this principle uniformly across consumer groups, especially where utilities or the government are the sole suppliers, can be challenging. Differential pricing, or tiered pricing, allows for different prices for various purchasers. Developed by Frank Ramsey in 1927, the Ramsey pricing rule suggests charging higher prices to less price-sensitive consumers to maximize overall social welfare (Baumol 2000). Similar findings by Marcel Boiteux on public monopolies have led to the Ramsey-Boiteux (R-B) pricing model, which advocates for price differentials on the basis of demand inelasticity (Hourcade 2021). While criticized as a suboptimal solution, R-B pricing effectively addresses social inequality and willingness-to-pay within public and regulated private-sector monopolies. This concept underpins regulatory policy and is commonly applied in the electricity and gas sectors, where tariffs may not align with utility costs but aim to account for various consumer impacts.

Given that hydrogen, like the oil, gas, and electricity sectors, is likely to be regulated during its development, a differential pricing approach may also be appropriate for hydrogen retail tariffs, similar to practices in other energy sectors. For example, fertilizer and steel producers using green hydrogen are expected to face different cost impacts than are producers of other materials. A study by Argus indicates that carbon-free nitrate fertilizer based on green ammonia can be 1.5 to 2 times more expensive than can its carbon-intensive counterparts (Hatfield 2022). Germany's H2Global pilot auction has shown that the lowest cost for green ammonia is €1,000 per ton, compared with €465 for gray ammonia in Europe (BNEF 2024). If the cost of carbon-free fertilizer is spread out across the entire agricultural value chain, then its impact on food items produced from agricultural products may be minimal. However, farmers often bear the brunt of higher input costs and struggle to pass these costs on to end users. Conversely, transitioning from a natural gas-based Direct Reduced Iron – Electric Arc Furnace (DRI-EAF) process to a hydrogen-based DRI-EAF only increases green steel costs by 15%-30%. The incorporation of green steel into products such as cars results in a minimal increase in the overall price. Therefore, implementing differential pricing for hydrogen on the basis of the sensitivity of end users can promote its greater utilization.

4.1.3 Setting Offtake Prices for Hydrogen

There are potentially three well-known methods for structuring hydrogen production prices that parties can consider in their offtake contracts. Each method has its own advantages and disadvantages, which we discuss below.

1. **Fixed-price contract**: This straightforward method compensates the hydrogen producer with a set price for each unit of hydrogen sold. The price reflects the expected production costs, including a reasonable return on investment, regardless of the value of hydrogen. In the initial phase of RE development, feed-in tariffs (FiTs), which represent a fixed-price approach, were the main driver encouraging private-sector involvement (Azhgaliyeva et al. 2023). Similarly, in the natural gas/LNG sector, fixed-price contracts remain the predominant method used by sellers and buyers to set prices (Chen et al. 2021). Although this approach simplifies revenue forecasting and enables producers to secure financing, it can also bring about the following economic inefficiencies:
    - Fixed prices for hydrogen provide producers with price certainty and revenue stability. However, if these prices are adopted, then they can also increase the government's burden to cover the price gap with what consumers can afford.
    - Fixed prices expose producers to input price (i.e., supply chain) volatility, as a locked-in price may not cover the rising feedstock costs of producing hydrogen over time. Diversifying feedstock sources and using various contract types (short- to long-term, including spot purchases for feedstocks) can help mitigate this risk. An example is H2Global's double auction mechanism to safeguard the interests of both hydrogen producers and buyers (see Section 4.2.4).
    - A reduction in production costs does not always lead to lower consumer prices. However, this situation highlights the potential advantages of including price review clauses in long-term contracts. An example of this was when the spot prices of LNG decreased, but the 25-year fixed-price sale contract for LNG from Qatargas (now QatarEnergy LNG) remained unchanged, thus

prompting Japanese buyers to insist on including such clauses.

- Establishing an acceptable price level that balances investment incentives and consumer affordability is challenging; high fixed prices may lead to windfall profits, whereas low prices may deter investment, as observed in the case of FiTs.

2. **Fixed-premium contract**: Similar to the feed-in premium (FiP) model for renewables, this approach allows hydrogen producers to receive a fixed premium in addition to the price that a hydrogen producer can fetch from the market. The pros and cons of fixed premium contracts are as follows:

   - This model provides better certainty since it helps producers recover fluctuating input costs. However, determining the premium can be difficult without an established market.
   - Since the premium is fixed at the start of the contract, any subsequent changes in the market value of hydrogen cannot be adjusted. Producers benefit from high market prices but risk losses during price declines. Caps and floors can be incorporated to balance such risks (Georgopoulos and Issaias 2012). The European Hydrogen Bank offers fixed premiums to support renewable hydrogen production, bridging the gap between cost and consumer price (EC 2023).

3. **Variable-premium contract**: This pricing model supports hydrogen producers with a variable premium calculated as the difference between the "strike price" (representing the cost of producing hydrogen) and a "reference price" (reflecting the market value of hydrogen). By being paid the difference between the strike price and the market price, the producer can achieve the desired return over the contract's lifetime. If the reference price exceeds the strike price, then the producer must pay the government counterparty the surplus (Figure 3). This pricing concept, known as CfD, has effectively incentivized the adoption of new clean technologies in the UK and the EU, overcoming the limitations of other support mechanisms such as fixed prices (e.g., FiTs) and fixed premiums (e.g., FiPs) (Ason and Poz 2024). The pros and cons of variable-premium contracts are as follows:

   - A variable premium offers better revenue certainty and the more efficient use of public funds. The strike price can be either determined through negotiation or discovered through a competitive allocation process. Additionally, it can be adjusted to accommodate the fluctuating input costs over time. Thus, this approach is more economically efficient in utilizing government support and mitigating the risk of overcompensating for the producer than are other approaches. Furthermore, this offers flexibility in setting a premium that is tailored to a specific end-use segment by choosing a different reference price, making it suitable for adjusting the level of the subsidy during the development phase of the hydrogen market, the end points of which bracket the price range within which the reference price can vary. Furthermore, setting a single reference price throughout the contract's duration may be too simplistic. However, as the market value of hydrogen changes, different reference prices can be set for various contract durations, often referred to as a reference window.
   - Countries such as Japan and the UK use CfD-style support to promote low-carbon hydrogen. In Japan, the proposed reference price is based on the market price of counterfactual fuels such as LNG and coal (Kobayashi 2024). The UK uses this mechanism to allocate revenue support to low-carbon hydrogen producers selected through its hydrogen allocation rounds.
   - The primary challenge of variable-premium pricing is establishing a fair and agreed-upon reference price for hydrogen. If this price remains low for a long time, then the government is burdened with having to cover the gap between the strike price and the reference price for the producer. Furthermore, this approach may pose unintended challenges for small producers owing to its complexity and administrative burden.

Each of these pricing options presents unique challenges, emphasizing the need for careful consideration in terms of their implementation to ensure the growth and adoption of hydrogen in energy markets.

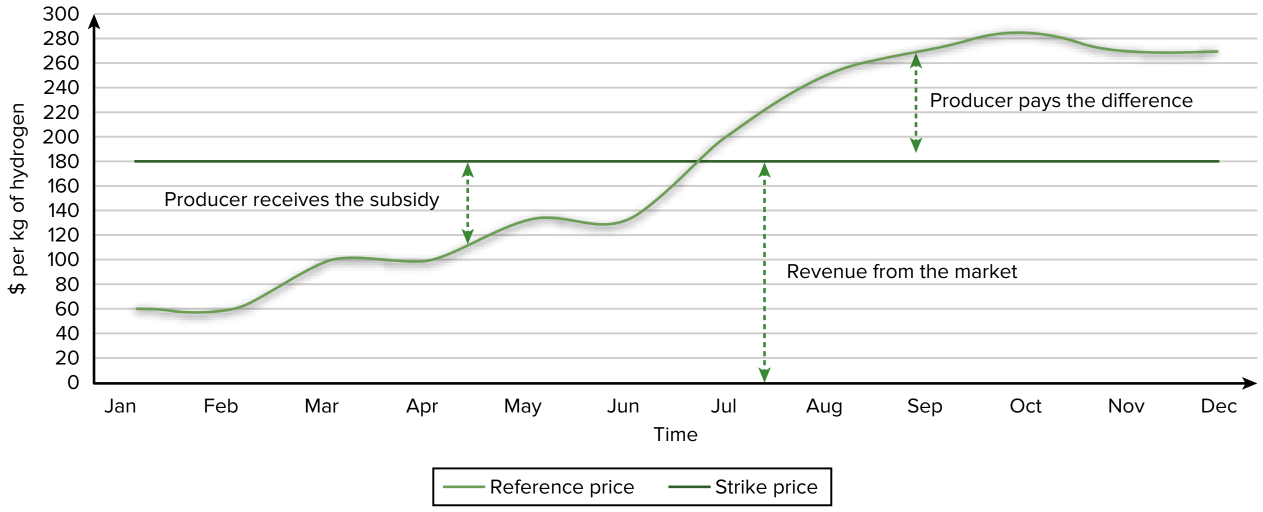
4.1.4 Approach to Pipeline Access Pricing

In the gas industry, regulatory frameworks for gas pipeline access, pricing, and safety requirements are well established globally. However, when hydrogen is blended with natural gas, the resulting mixed gas has different physical properties, such as density, calorific value, and compressibility, than does pure natural gas. Furthermore, hydrogen is more corrosive than are other chemicals and can potentially degrade and embrittle gas pipelines and storage materials. Consequently, a re-evaluation of the economic and safety aspects of the natural gas pipeline system is needed. The following issues merit attention:

1. **Operating cost**: Hydrogen has a lower volumetric density than does natural gas, requiring a larger volume to deliver equivalent energy. Increased flow rates and compression increase operating costs, including higher methane leakage rates (Topolski et al. 2022). Studies suggest that mixtures with 10% and 20% hydrogen require flow increases of approximately 4% and 9%, respectively (Galyas et al. 2023). Tariff regulations need to assess how these costs should be shared among consumers – regardless of whether from those who have agreed to purchase the hydrogen-blended gas or from all consumers receiving gas through the pipeline.
2. **Effective transfer capacity**: Mixing hydrogen with natural gas can reduce the energy transfer capacity of pipelines. For example, a 20% hydrogen blend may decrease the transferred energy content by approximately 9%, which necessitates a revaluation of transport costs by regulators.
3. **Offtake contracts and billing**: Contracts often stipulate minimum quality standards for gas. If hydrogen is blended, then the characteristics of the blended gas may not be within the acceptable tolerance levels for certain consumers, such as power producers, industrial users, and gas utilities. This situation may require the modification of seller-buyer contracts.

As countries aim to promote hydrogen for decarbonization, regulations around tariff structures and discounts for blended gases need to be developed. The EU has reached a consensus on the gas package, offering a 100% discount on tariffs for renewable gases with up to 2% hydrogen blending (Store 2023). Additionally, there is a 75% discount for low-carbon gases, alongside capacity-based tariff discounts for storage for low-carbon gases, and both renewable and low-carbon gases receive a 100% discount on capacity-based tariffs on storage (Martin 2024). In several markets, transmission wheeling charges are waived for those using the grid to transport renewable electricity to promote clean energy and achieve the government's policy goals.

Figure 3. Variable-premium (or two-sided CfD) mechanism.



Source: Authors' illustration.

4.2 Business Models

Establishing a viable business model for hydrogen projects is essential because of the significant capital investment and inherent risks involved. Economic, regulatory, technological, and demand uncertainties heighten the need for a well-defined business model. A recent report (Clean Hydrogen Partnership and Mission Innovation 2024) has indicated that 78% of respondents believe that developing a robust business model for early-stage projects is the most critical success factor for hydrogen ventures, closely followed by the availability of funding, at 77.4%.

The hydrogen value chain is multifaceted, encompassing production, transport, storage, and end-use applications. Each segment presents unique challenges and is interdependent, necessitating tailored business model designs to address risk factors effectively during the early deployment phase (see Table 3). In the early stages of a hydrogen economy, where no established market exists, encouraging investment poses significant challenges for governments and developers. The key among these challenges is how to finance projects, especially for hydrogen producers, who face risks from uncertain demand and a lack of committed offtakers. Customized solutions are necessary to minimize volume risks and ensure that producers can sell enough hydrogen to cover costs while securing returns on their investments.

Historical lessons from the renewable and LNG sectors provide relevant insights, as detailed as follows.

4.2.1 Take-or-Pay (ToP) Contracts

In ToP agreements, buyers commit to "taking" a minimum volume of and paying for hydrogen, regardless of whether or not they utilize the full amount. This situation makes sellers' revenue more predictable, making early hydrogen projects more attractive to investors. Under such commercial contracts, buyers are guaranteed the delivery of supply, minimizing their supply-related risks. ToP contracts are widely used for natural gas and LNG projects and have also been applied to early RE projects and independent power projects (IPPs) in certain situations. In the LNG industry, ToP contracts have been beneficial in attracting investments by eliminating the risk associated with unpredictable cash flows (Tuff et al. 2023). However, providing volume support through ToP contracts can also pose challenges to the associated parties, as outlined below.

- Buyers may incur costs for hydrogen that they do not need, particularly if supply issues arise for the producer. While it is preferable to include a mechanism to determine nonavailability, identifying the root causes for all such instances can be complex and challenging.

- These contracts can be inflexible, potentially leading to financial losses if a buyer's facility delays commissioning or fails to receive the agreed-upon supply. The terms of the ToP contract need to be clearly defined to prevent financial losses for the buyer. Such terms include outlining conditions for force majeure events where mandatory payments do not apply.

- Fixed payment obligations limit buyers' ability to refinance debt or adjust to market conditions.

4.2.2 Centralized Procurement by a Government Entity

In this model, a government entity commits to purchasing a specified quantity of hydrogen for a set duration, mitigating producers' volume risk. This procurement can involve either direct purchase or financial settlement without receiving the hydrogen itself. This commitment to procure a certain minimum quantity stands firm, independent of the hydrogen producer's efforts to secure alternative buyers through separate commercial contracts. The advantages and disadvantages of this strategy include the following:

- Payments are tied to actual production, ensuring that producers are compensated only for generated volumes, unlike fixed ToP commitments (GH2 2023).
- Government involvement can improve project reliability and investor confidence. However, implementing this model necessitates the establishment of new institutional and regulatory frameworks to safeguard against payment delays. Additionally, the government's role as a committed buyer with financial obligations

Table 4. Hydrogen industry business segments.

Segment	H2 Production	H2 Transport	H2 Storage	H2 End Users
Value creation (process of generating value through activities)	• Development of large-scale, zero- or low-carbon-emission hydrogen production assets. • Conversion of primary energy (renewables and gas) into energy carriers of hydrogen.	• Development of hydrogen transport and delivery infrastructure.	• Development of needed storage (surface and underground) infrastructure.	• Use of zero or low-carbon-emission hydrogen as fuel and feedstock.
Value proposition (unique value provided by an offering)	• Zero or low-carbon alternatives to fossil fuels. • Maximization of the use of fluctuating renewables through electrolyzers. • Upgrading RE to a secondary carrier at low costs (e.g., retiring plants opting to continue operation). • Helping to validate technology performance in case of R&D projects.	• Delivery of zero- or low-carbon-emission hydrogen to customer's location as needed.	• Addressing imbalances in hydrogen production and demand. • Making hydrogen energy continuously available during peak demand periods by storing the excess energy during off-peak periods. • Supporting decarbonization by avoiding curtailment of renewables for electrolytic hydrogen production. • Optimizing new investments by maximizing supply.	• Helping to decarbonize newer and hard-to-abate sectors.
Key partners	• RE producers – for the purchase of electricity for electrolysis. • Natural gas suppliers – for sourcing gas for steam methane reforming (SMR)-based hydrogen production. • Hydrogen offtakers (direct and intermediary) – for selling zero- or low-carbon hydrogen. • Government/government agencies – for securing the needed financial support to bridge the current cost gap and manage cashflows.	• Hydrogen producers – for transporting their supplies using various methods of transportation. • Pipeline operators – for all aspects of the performance, safety, and security of pipelines. • Suppliers/offtakers – as counterparties for managing commercial contracts. • Government – for securing the needed financial support to cover the initial capital cost and/or subsidize operational costs.	• Government – for securing any subsidy or grants. • Pipeline owners – for integrating storage with the gas grid (natural gas or hydrogen). • Pipeline operators – for balancing the entry and exit volumes. • Suppliers/offtakers – as counterparties for managing commercial contracts.	• Gas grid owners – for accessing the energy supply system. • Suppliers – for entering commercial contract to buy zero or low-carbon-emission hydrogen.

(Continued)

Segment	H2 Production	H2 Transport	H2 Storage	H2 End Users
	• Lenders – for securing loans to help develop capital intensive projects. • Technology providers – for adopting cutting-edge technologies for hydrogen production and R&D. • Other companies – for adding their complementary experience. • Certification body – for obtaining the necessary certificates to monitor and authenticate production-related emissions.	• Storage providers – for enhancing the overall value proposition. • Users – for delivering the zero or low-carbon-emission hydrogen to various end users.		
Potential risks	• Price and volume (both domestic demand and/or export market). • Feedstock risks (RE and natural gas). • Internationally aligned hydrogen certification rules.	• High upfront costs and uncertain financial returns. • Untested technologies (e.g., large capacity pure hydrogen pipelines, ships capable of carrying liquid or hydrogen derivatives, cryogenic liquid tanker trucks, and gaseous tube trailers).	• High upfront capital expenditure. • Demand risks that are beyond the control of the storage provider. • Unproven technologies at a large scale.	• Expensive and uncompetitive zero- or low-carbon-emission hydrogen compared to incumbent fossil fuels. • Not all manufacturing processes being able to readily use hydrogen without suitable technology upgrades. • Reliable and sufficient supply of zero- or low-carbon-emission hydrogen to meet needs.

Source: Authors' compilation.

leads to greater efforts in finding and securing hydrogen end users.

- The government, which acts as the sole buyer, may undermine competition in the production segment. However, as the hydrogen market matures with lower production costs and more willing hydrogen users, the government offtaker may reduce its committed offtake share for new projects while allowing the balance to be sold directly by producers in the open market, thereby increasing competition in hydrogen supply. A similar approach has been successfully implemented in India, where the Solar Energy Corporation of India (SECI), a public-sector entity under the Ministry of Power, acts as the sole purchaser of electricity from RE producers. The SECI allows RE producers to find direct buyers if they take responsibility for long-term connectivity with the transmission utility and manage the associated risks themselves. Alternatively, if they choose the SECI route for the remaining share, then RE producers are guaranteed connectivity, buyers, and risk mitigation for payments.

4.2.3 Hydrogen Hubs

Hydrogen hubs, or clusters, colocate hydrogen producers and users close to each other in the industrial, transport, and energy markets to address market challenges and reduce transportation costs. The key benefits and requirements include the following:

- They provide captive demand, alleviating early-stage producers' uncertainty regarding hydrogen sales. The interconnected network of the hydrogen value chain guarantees users a reliable and more affordable supply.
- Robust offtake agreements are essential for managing risks, and concentrated infrastructure allows for more effective risk distribution among stakeholders.
- Hubs need to have resources, production facilities, end users, and port facilities (if hydrogen export is considered) concentrated in a specific area. This model cannot be easily replicated on a wide scale because of these requirements. The government may fully or partially support the development of hub facilities, such as shared infrastructure for multiple companies involved in the entire hydrogen process, from unloading to final consumption.
- Successful hub implementation requires clear governance, fair access to the hub's infrastructure, transparent pricing, standardized product definitions and contracts, data formats for information sharing, and flexible infrastructure to adapt to future market demand and trade opportunities.

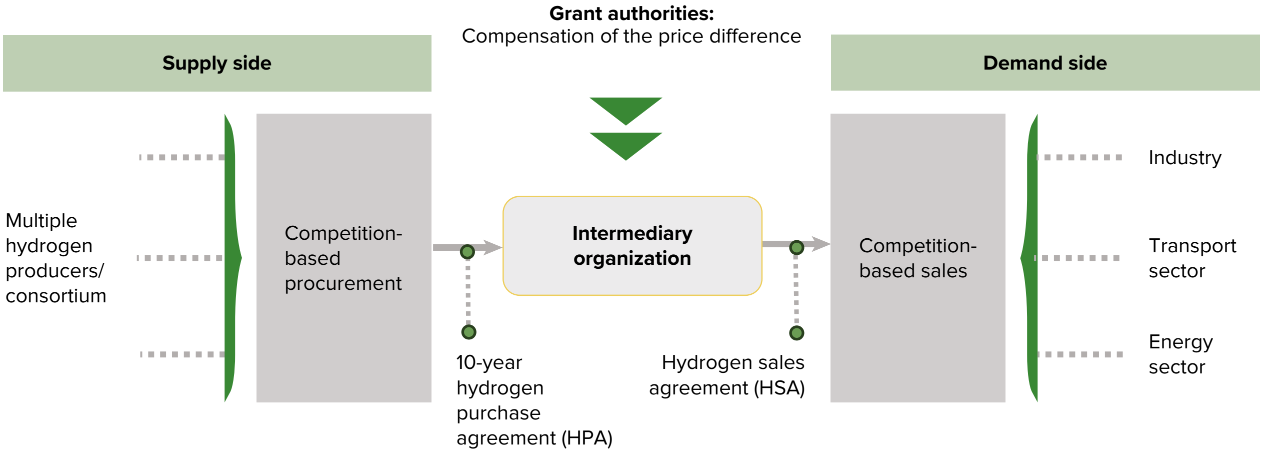
Several countries, including the U.S., Australia, Germany, France, Canada, Spain, the UK, Denmark, Greece, the Netherlands, Japan, China, Portugal, and Oman, are working on hydrogen hubs to make use of existing infrastructure and industrial activities to save costs and improve efficiency. These hubs are mostly physical and are meant to create a linked network of infrastructure covering the entire hydrogen value chain, meeting local, regional, or global needs. It would also be helpful to think of these hubs as "virtual trading hubs," where trading in certificates can be explored independently from the underlying tradable commodity. This arrangement benefits the hub's participants by delivering greater value. Additionally, these hydrogen hubs can assist hydrogen importers by arranging the guarantees of origin and sustainability certificates needed for future hydrogen trading (KAPSARC 2024).

4.2.4 Double Auction via an Intermediary

In light of high hydrogen costs, potential buyers are hesitant to enter into long-term agreements with producers. A double auction (also referred to as a double-sided auction) model can help alleviate the cost implications by allowing multiple buyers and sellers to interact through the market institution to arrange trades when their prices align. H2Global exemplifies this approach, where its subsidiary, Hintco, acts as an intermediary. Hintco manages a competitive procurement process, entering into long-term agreements with producers while offering one-year sales agreements to selected buyers, allowing them to avoid long-term commitments while stabilizing prices (Figure 4).

The double-sided auction mechanism offers several advantages beyond addressing supply and demand concerns. Its flexibility allows for customization to be carried out to align with funding goals related to geography, hydrogen products, and sustainability criteria. This approach can be tailored to various objectives, including price optimization, the promotion of green technologies, the enhancement of energy security, and the support of sector-specific decarbonization initiatives. Additionally, these auctions provide insights into supplier and offtake price dynamics, thus increasing market liquidity and development.

Figure 4. Double-auction sequence: Hintco.



Source: Authors' illustration.

4.2.5 Product-Based Model

The business model described here differs from previous models in that it emphasizes selling finished products made with low-carbon hydrogen rather than focusing solely on hydrogen sales. For example, H2 Green Steel (H2GS) in Sweden aims to create a green value chain that produces hydrogen, green iron, and steel for industrial customers. By securing long-term offtake agreements (five to seven years) for green steel, H2GS has procured over €4.5 billion in debt financing and €2.1 billion in equity for its planned green steel plant. On the supply side, H2GS prioritizes a mix of short- and long-term power purchase agreements (PPAs) to procure carbon-free electricity for its hydrogen production unit. Additionally, a combination of floating and fixed-price PPAs is likely to safeguard investors from potential power price spikes, which would otherwise lead to increased costs for green hydrogen. The success of this model relies on green companies committing to purchasing environmentally friendly raw materials to meet decarbonization goals (McKinsey Sustainability 2023). However, the implementation of the carbon border adjustment mechanism (CBAM) in the future can enhance the prospects of this business model.

4.2.6 Carbon CfD (CCfD)

The model does not directly manage the volume risks of hydrogen producers. Instead, it encourages investment in new end-use technologies that can utilize low-carbon hydrogen, thereby indirectly creating demand for hydrogen. The CCfD works like a traditional CfD, focusing on carbon emission reductions. For example, a steel company carrying out hydrogen-based production may engage in a CCfD to offset the higher costs associated with carbon avoidance than may a conventional producer. The model compensates for differences in carbon avoidance costs, boosting financial attractiveness and investment. Germany has pioneered this approach, aiming to incentivize low-carbon processes in energy-intensive sectors such as the paper, glass, steel, and cement industries (BMWK 2024). Although CCfDs help mitigate initial investment risks, they do not fully address operational cost uncertainties arising from a transition to hydrogen, and establishing an effective CO_2 strike price remains a challenge (Bernstein, Beugin, and Rivers 2023). Additionally, the successful execution of the model necessitates a strong monitoring system. Despite its limitations, Germany is advancing its €50 billion CCfD program, investing €4 billion in initiatives to promote low-carbon processes involving green hydrogen (Parkes 2024).

4.3 Access to a Gas Grid (i.e., Pipeline)

The use of existing natural gas pipelines for hydrogen transport offers several advantages. A well-established network of approximately 1.36 million kilometers of natural gas pipelines is already operational worldwide (GEM 2024) and can be repurposed to allow for the mixing of hydrogen with natural gas, without the need for conversion. The repurposing of the existing pipeline is estimated to cost approximately 10%-35% of the cost of building a new hydrogen line (Monsma et al. 2023). Studies indicate that existing natural gas networks can accommodate 5%-20% hydrogen blending with minimal added risk (Hughes 2019). While transporting 100% hydrogen may be the long-term goal, repurposing current pipeline systems can accelerate hydrogen adoption.

Third-party access (TPA) is essential for maximizing the benefits of using existing gas infrastructure. By granting hydrogen producers access to these pipelines, the need for costly investments in separate hydrogen pipelines is reduced, enabling quicker and more cost-effective market development. As hydrogen blended gas is used by everyone connected to the gas grid, TPA does not provide consumers with the option to choose among natural gas, pure hydrogen, or a blend of the two. However, TPA reduces barriers to entry, which encourages the adoption of clean hydrogen in the early stages of market growth. This approach also promotes innovation and the scaling of production. Ensuring nondiscriminatory access, where all market participants are offered similar terms and conditions, is crucial. This guarantees equal infrastructure access for all market participants, which enhances resource efficiency and supply management. By creating a level playing field, TPA promotes competition and optimizes resource allocation, ultimately improving overall market efficiency. This approach can be further illustrated by examining the experiences of the electricity and gas sectors.

4.3.1 Promotion of Competition and Efficiency, Leading to Lower Prices

The evidence indicates that the introduction of TPA in the wholesale and retail energy markets has effectively eliminated monopolistic barriers, leading to increased competition, lower prices, greater innovation, and improved service quality. Global examples highlight TPA's significant impacts on the electricity and gas sectors, shaping markets and attracting investments.

In Brazil, TPA has facilitated the development of a dynamic wholesale electricity market with numerous independent energy traders. This change has enabled consumers to purchase electricity directly from any type of generation source, whether renewable or not. As a result, consumers benefit from more competitive prices and better contractual terms (Burin et al. 2023). In Peru, open access has enabled large consumers to take part in energy auctions, transitioning the tariff system from an administrative model to a model driven by market principles. Turkey's 2008 Energy Market Law permitted small, distributed generation units to link to the distribution grid and mandated that distribution companies (DISCOMs) accept surplus electricity from these generators. This policy promoted the growth of small-scale RE projects, diversified the energy supply, and attracted investments in local generation capacity. Similarly, in India, the implementation of open access has notably increased the reliability of the power supply and resulted in better prices for consumers.

In the UK, EU, Malaysian, and Australian gas markets, TPA has facilitated greater access to transportation networks for multiple suppliers. As a result, this situation has led to lower prices, increased numbers of service options for consumers, and the effective utilization of the existing gas network. TPA has led to competitive pricing in the gas market in the U.S., resulting in lower transportation tariffs, as multiple shippers compete for market share. Similarly, by allowing TPA to the gas grid, hydrogen producers can expand their customer base more rapidly and cost-effectively, thus accelerating market development. Furthermore, by lowering barriers to entry and facilitating the early adoption of low-carbon hydrogen, TPA can promote innovation and the expansion of production capabilities. These examples collectively illustrate TPA's transformative impact across energy markets, highlighting its role in fostering competition, enhancing efficiency, attracting investments, and improving energy security and affordability for consumers.

4.3.2 Investment and Infrastructure Development

The implementation of TPA has been vital in fostering investment in energy infrastructure and creating new business opportunities, thereby ensuring the long-term security and efficiency of the energy supply. TPA can potentially increase investment in infrastructure, especially when supported by strong regulatory measures that ensure fair access and pricing. In Germany, the transition from negotiated to regulated TPA has led to increased investment in RE sources and the modernization of existing infrastructure. This regulatory clarity establishes a stable investment climate that is essential for ongoing development. In Peru, open access has led to increased private sector investments in transmission and generation. Similarly, the U.S. Energy Policy Act of 1992, along with Federal Energy Regulatory Commission (FERC) Order No. 888, established open access rules that promote competition and attract independent power producers, boosting investments in diverse energy sources. In countries such as Pakistan and Ukraine, the TPA regime has created a favorable investment climate, encouraging companies to invest in new gas pipelines and facilities.

Drawing from the experiences of electricity and gas TPA models, potential TPA services for hydrogen can include the following:

- **Firm capacity**: Guaranteed access to pipeline capacity for hydrogen producers.
- **Interruptible capacity**: Access that can be curtailed during periods of high demand.
- **Long-term contracts**: Stability for large-scale investments.
- **Short-term contracts**: Flexibility for emerging producers.

The incorporation of hydrogen producers into existing gas pipelines can present challenges similar to those faced in the gas market, such as the need for transparent and fair access rules, tariff structures, and network reliability. The distinct safety considerations of hydrogen may require modifications to pipelines and stricter safety protocols. By addressing these challenges, TPA can facilitate the growth of the hydrogen market and ensure its integration into current energy systems.

5. Conclusions

The transition to a hydrogen economy presents both significant opportunities and challenges. As highlighted throughout this paper, establishing effective market mechanisms, such as various pricing and offtake models, is essential for promoting investment in hydrogen production and infrastructure. The lessons drawn from the RE, gas, and LNG sectors provide valuable insights that can inform the development of the hydrogen market and drive the industry forward.

To conclude, we outline a specific, step-by-step plan for the development of the hydrogen market, serving as a comprehensive pathway for hydrogen.

1. **Define and standardize**: The initial step is to establish a clear, acceptable, and legally enforceable definition of “clean hydrogen” that covers various production methods. It is also important to establish or improve regulatory frameworks for hydrogen infrastructure. This approach should encompass technical and safety standards, available state incentives, and goals for low-carbon hydrogen production and use.
2. **Leverage existing gas infrastructure**: Introducing TPA, starting with a low percentage of hydrogen blending, can accelerate the development of the hydrogen market more cost-effectively in the short term while also promoting public acceptance. Setting fair and transparent regulatory rules is essential for this purpose. The impact of TPA in the electricity and gas industry has been overwhelmingly positive.
3. **Identify the appropriate business model**: To reduce the risk involved in hydrogen production, it is crucial to identify and promote appropriate business models. These models should be tailored to the specific local context to maximize their effectiveness. Key business strategies, such as ToP contracts, government-led offtake agreements, and innovative approaches such as hydrogen hubs and CCfDs, can help mitigate risks for producers and encourage broader participation in the market. Each model offers unique benefits and challenges, underscoring the need for their adaptability to the local context. Considering the multitude of benefits that hubs offer and their potential to advance countries’ initiatives to reduce greenhouse gas (GHG) emissions, it is imperative to investigate and consider the feasibility of establishing a public–private partnership-led hub at the local or regional level.
4. **Implement a hybrid pricing mechanism**: In tandem with the business model, a hybrid pricing mechanism should be established to support hydrogen technologies. This establishment begins with fixed-price contracts for early-stage producers to promote investment and innovation, such as RE FiTs or fixed-price gas and LNG contracts. As technologies mature, producers should shift toward a variable premium model and eventually implement a competitive double-sided auction system for established markets. On the retail side, it is important to consider implementing a differential pricing strategy for setting retail tariffs due to varying levels of willingness to pay for expensive hydrogen among end users.
5. **Scale-up and improve market maturity**: Once these foundational elements are in place, the focus should shift to scaling up hydrogen production and expanding hydrogen hubs to larger networks. There is also a need to promote standardized trading practices, including contracts, and price indices that support global trade and the hydrogen economy.

By embracing this strategic approach, policymakers can adeptly maneuver through the intricacies of establishing a hydrogen market, effectively positioning hydrogen as a clean and viable energy source that contributes to a more sustainable future.

Appendix A

Appendix Table A. SCPR analysis of the UK gas sector.

Dimension	Observations
Infancy stage (1985-1995) – Start of gas market reforms **Policy and regulatory environment** – In 1982, the Oil and Gas Enterprise Act introduced competition into the UK energy sector. The UK's gas sector was partially opened to competition in 1986 when the government privatized British Gas, previously a monopoly supplier. This energy policy aimed to enhance competition, reduce consumer prices, and protect consumer interests through the establishment of the Office of Gas Supply (OFGAS), later merged with the electricity regulator to become the Office of Gas and Electricity Markets (OFGEM). This policy focused on creating a market for commodity trading and ensuring that the necessary infrastructure is overseen by the regulator.	
Market structure	
Number of sellers	Despite legislation, regulation, and the creation of OFGAS, there was little change in BG's monopoly/monopsony position in Phase I (1982-88). BG retained a monopoly to supply consumers using less than 25,000 therms (732,000 kWh) per year at regulated prices and to control the distribution and transmission system for other consumers.
Number of buyers	Consumers with demand over 25,000 therms (732,000 kWh) can now buy gas directly from producers. This threshold was lowered from 25,000 therms to 2,500 therms in July 1992.
Barriers to entry and exit	In 1988, BG's statutory right of first refusal on gas purchases was removed, allowing third-party providers greater access to the gas value chain. From 1988 to 1994, such measures brought new entrants into the gas market, requiring BG to release some long-term contract-acquired gas. In 1993, competition for domestic gas customers was introduced, and in 1994, full market liberalization was announced.
Market conduct	
Price setting	Before gas market liberalization, upstream gas prices were complex and variable due to individually negotiated terms. Downstream pricing was based on the weighted average cost of gas (WACOG) plus a margin for transportation, distribution, and profit. In 1988, the Monopolies and Mergers Commission report forced BG to publish its price schedule and transmission charge information for its competitors. Price cap (RPI-X) regulation was the preferred method for setting gas transportation charges.

(Continued)

Dimension	Observations
Buying and selling practices	Development of standard contracts for third-party gas transportation and TPA agreements. Only residential and small commercial consumers remained within the BG monopoly.
Market performance	Gas market restructuring led to an increase in the number of suppliers, causing BG's market share to drop to 55%. The surplus gas supply and competition led to lower prices. New entrants focused on long-term contracts that involved a high volume of gas with new power generators, capturing approximately 75% of the market by 1991.
Development stage (1995-2000) – Deepening of gas market reforms **Policy and regulatory environment** – The government introduced competition in the domestic gas market to benefit more consumers with lower prices, better choices, and improved services. OFGAS oversees the process to ensure customer benefits. The NBP was established as the central trading hub for natural gas in the UK. The development of the Network Code was a fundamental enabler of the development of gas trading in Britain. Gas contracts shifted from longer-term to shorter-term and spot contracts. Industry regulation now focuses on pipeline transportation and distribution, which have natural monopoly characteristics.	
Market structure	
Number of sellers	The Gas Act of 1995 allowed for a fully liberalized gas market, enabling competition in the residential sector, which led to the entry of new companies to ship and sell gas directly to end users, allowing over 4 million customers to switch from the former monopoly supplier, BG Trading.
Number of buyers	Competition was introduced into the domestic gas market between April 1996 and May 1998. All customers can now choose their gas supplier.
Barriers to entry and exit	In 1997, BG's transportation, exploration, production, and international business operations were separated.
Market conduct	
Price setting	Bulk supplies are priced using various indexation formulas, with an increasing proportion tied to spot prices, which have remained consistently below long-term contract prices. The market price (spot or futures) for gas to be delivered over a future period is determined by expectations of supply and demand balance.
Buying and selling practices	Most gas is sold under short-term contracts, and their prices have sharply decreased since 1995. In principle, heavy-fuel-oil prices provide a ceiling for gas prices to retain large industrial and commercial customers (especially those with dual-firing capabilities) if gas becomes uncompetitive. The 1995 price collapse caused issues for long-term ToP contract holders. Entry capacity into the National Transmission System (NTS) was established through UK terminal auctions.

(Continued)

Dimension	Observations
Market performance	
Volume (quantity) and margin	Consumer prices have substantially decreased due to competition and other factors. Since privatization, all customer classes have seen significant reductions in real gas prices, with residential and industrial customers experiencing declines of 24%-27% and over 50%, respectively. As of November 1997, 80% of the actual daily NTS throughput was traded.
Innovation (2000-onward) – Fully competitive market **Policy and regulatory environment** – The UK's gas market structure has evolved through three phases of policy initiatives and regulatory refinement. The energy policy focused on liberalizing the end-user market, managing a single publicly owned network, and ensuring fair competition for gas players. With declining domestic gas production, LNG imports are increasing, now with more flexible contracts.	
Market structure	
Number of sellers	In the gas value chain, multiple players, including producers/suppliers, transporters, storage, traders, and exporters, exist. No single player holds dominant market power.
Number of buyers	All consumers, including residential customers, have the freedom to choose their gas supplier.
Barriers to entry and exit	No restrictions on the importation of gas supply exist. Full access to gas infrastructure including pipelines, gas storage, and LNG terminals is provided.
Market conduct	
Price setting	The price formula is fully linked to the cost of production, fuel competition, or gas-to-gas competition. The price is transparent, with price movements fully reported and publicly available.
Buying and selling practices	There is a combination of short-term contracts, spot contracts, and long-term contracts.
Market performance	
Volumes, margins, and costs	Diversity in gas supply sourcing exists, avoiding overreliance on specific suppliers or types of supply.

Sources: GoUK (2022); Green and Newbery (1993); IEA (1998); NAO (1999); Ofgem (1999).

Appendix B

Appendix Table B. SCPR analysis of RE growth in India.

Dimensions	Observations
Infancy stage (1985-1990) **Policy and regulatory environment** – The promotion of RE aimed to achieve energy self-sufficiency. The focus was on wind technology to exploit a 20-gigawatt potential. To encourage renewable resource development, fiscal incentives included tax breaks and liberalized foreign investment norms. India's electricity industry was dominated by state-owned VIUs. India had no independent regulatory entity in 1996.	
Market structure	
Number of sellers	A few wind farms with capacities ranging from 550 kW to 1 MW exist.
Number of buyers	VIUs were the sole buyer of RE.
Barriers to entry and exit	- Setting up wind installations requires significant initial investment. - Low-cost fossil fuel-based electricity offers an absolute cost advantage over expensive wind energy. - Private wind developers face difficulties in accessing credit and the electricity grid. - Utilities are hesitant to take on the financial burden of integrating wind power, leading to concerns about payment uncertainty. - Wind farms are currently perceived as more of a nuisance than a benefit due to their low reliability and nondispatch ability (Mallet 2001). - Time-consuming licensing procedures involving 22 clearances from government departments hinder private investments in wind installations. - There is a lack of institutional setup to support the growing wind industry. - The Indian Renewable Energy Development Agency (IREDA) was established in 1987 to provide support through soft loans for RE and energy-efficiency projects.
Market conduct	
Price setting	Wind power is purchased by the VIUs at specified tariff rates.
Buying and selling practices	A monopsony market structure exists with the mandatory purchase of all electricity from wind producers by one buyer, such as a VIU, operating in the province. Some states allow third-party sales of power generated from wind projects.

(Continued)

Dimensions	Observations
Market performance	
Volumes (quantity)	Incentives drove widespread wind power adoption, increasing capacity from 2.2 MW to 37 MW from 1985 to 1990, respectively (IRENA 2013). External support from DANIDA enabled two 10 MW commercial projects, the first of their kind in India. Despite capacity growth, wind energy had minimal impact on alleviating power shortages.
Development stage (1991-2002) – Market in development **Policy and regulatory environment** – In 1991, India introduced economic reforms focusing on liberalization, privatization, and globalization. The government opened the electricity sector to private investors and set a target of 500 MW during the 8th Five-Year Plan (1992-97). To accelerate progress, new policies and state nodal agencies were established. This included the creation of federal- and state-level electricity regulators to regulate the electricity sector, including renewables. Fiscal incentives, such as accelerated depreciation, continued to drive wind energy development.	
Market structure	
Number of sellers	The number of sellers grew steadily.
Number of buyers	VIUs and new DISCOMs are the main buyers of RE. The electricity industry was progressively liberalized, with VIUs split into separate generation transmission companies and DISCOMs.
Barriers to entry and exit	The wind energy sector faces challenges such as high investment costs. In the absence of a top-down policy to stimulate demand for RE, electricity DISCOMs and VIUs have shown limited interest in purchasing wind energy. VIUs and DISCOMs faced heavy financial losses and wind producers viewed them as unreliable buyers. State-run utilities treated wind power as a peripheral supply option due to the absence of an RE purchase obligation. High borrowing costs, the lack of land availability, the time-consuming land acquisition process, and an inadequate intra- and interregional transmission grid were obstacles to wind energy sector growth. The onus of acquiring land rests with the manufacturers/ developers. Integrating wind energy into the grid presents technical challenges, as fluctuations in grid frequency and voltage create operational difficulties for wind farms. The government imposed a minimum alternate tax (MAT) of 12.9% in 1997 on companies going for “zero-tax” planning using the wind market as a tax-saving investment (Sharma and Sinha 2019).

(Continued)

Dimensions	Observations
Market conduct	
Price setting	The offtake price was set in accordance with the tariff guidelines issued by the Indian government in 1993. According to this policy, the power purchase price for wind projects was 2.25 Rs/kWh (~7.2 US cents/kWh) for the base year 1994-95, with a 5% yearly escalation. This price setting mechanism provides long-term certainty to investors.
Buying and selling practices	State-run VIUs and DISCOMs were the main purchasers of wind power through long-term PPAs. Additionally, some state governments allowed the sale of energy to third parties at negotiated prices.
Market performance	
Volume (quantity) and margin	India experienced steady growth in wind energy installations, making it the world's fifth-largest producer of wind energy by 2002, with an installed capacity of approximately 1,667 MW (NIWE 2015). The incentives provided to wind producers covered their costs and stimulated investments, leading to the successful commercialization of wind power plants and the emergence of a local industrial base for manufacturing wind turbines and components (Rajsekhar, Hulle, and Jansen 1999).
Innovation stage (2003 onward) – Advanced market Policy and regulatory environment – In 2003, legislative reforms emphasized renewables and the advanced liberalization, regulation, and privatization of the electricity industry. This period introduced solar energy and market-oriented policies, including: - the Mandatory Renewable Purchase Obligation (RPO) quota to be set by regulators. - a progressive increase in RPO – Target of 22 GW (later increased to 175 GW) of solar capacity by 2022 and the establishment of India as a global leader in solar energy through conducive, predictable, and market-oriented policy environment. - major reforms in price setting and offtake mechanisms. - time-bound policy formulation by central and state governments and actions by electricity regulators to promote RE.	
Market structure	
Number of sellers	The number of RE producers increased significantly. By the end of 2023, the country had 41 solar parks and a large fleet of RE producers operating (PIB 2023). Additionally, there are 17 R&D projects focused on cost reduction, reliability, and efficiency improvements for RE systems and components.
Number of buyers	DISCOMs remain the main buyers through long-term PPAs, while RE producers can also sell power on trading platforms. The corporate renewable procurement market is rapidly expanding.

(Continued)

Dimensions	Observations
Barriers to entry and exit	State-owned DISCOMs are the main buyers of RE electricity through long-term PPAs. However, delayed payments to RE producers has emerged as a major concern for investors. In response, the Indian government established a payment security scheme through the SECI to protect developers from payment delays or defaults by DISCOMs.
Market conduct	
Price setting	The approach to price setting for solar projects in India shifted from negotiated deals to competitive auctions in 2010. This change resulted in a significant 39% to 51% decrease in the strike price compared to the forbearance prices set for the bidding rounds (Hasan and Bhatt 2022). Following success at the national level, state-level policies have also transitioned to auction-based approaches. This shift has lowered solar tariffs and is helping India achieve its ambitious RE targets.
Buying and selling practices	State-owned electricity DISCOMs, large consumers with RPO obligations, and hundreds of corporate consumers purchase RE. The SECI, a public-sector company, acts as an intermediary for buying solar and wind power. RE producers sign 10-25-year PPAs with corporations to supply a percentage of their power requirements.
Market performance	
Volume, margin, and costs	The cumulative RE capacity reached 136 GW by March 2024, accounting for approximately 33% of the overall generation capacity mix excluding large hydropower. Competitive auctions have lowered procurement costs for buyers and impacted producers' revenues.

Appendix C

Appendix Table C. Evolution of the RE and gas/LNG sectors.

Dimensions	Infancy stage – No market	Development stage – Market in development	Innovation stage – Advanced market
Electricity (renewables)[#]	• Renewables are characterized by high cost, little or no appetite to buy RE, high levels of government support, no quota mandate, etc. • Pricing set through negotiated deals/FiTs. • PPA – mostly long-term. • Risks – shift to the government, good for providing support to newer technologies. • FiTs do not reflect the true market price but offer stable conditions during execution.	• FiPs gradually began replacing FiTs and providing a minimum level of market revenues for RE projects while avoiding overcompensation by governments. • Market for PPAs steadily increased due to electricity price volatility (in the EU), allowing businesses and electricity retailers to hedge against fluctuating energy prices. • RE investments are still supported by various forms of assistance, such as production tax credits (PTCs) and investment tax credits (ITCs). • Emergence of competitive auctions, which shifted the risks toward project developers.	• More innovative support schemes, such as two-way CfDs and green certificates, alongside auctions, have significantly improved the competitiveness of RE. However, the PPA market still dominates.
Natural gas[##]	• Fixed prices were the standard during the 1960s. • At that time, there were no established pricing principles or benchmarks for international trade. • Buyers and sellers directly negotiated the fixed price. Buyers made offers considering the domestic gas price and terminal gas cost, while sellers considered upstream production, liquefaction, and shipping. The final price was dependent on the bargaining power of both sides.	• From the 1970s to the beginning of 21st century, LNG prices were linked to oil prices. • Gradually, LNG prices were linked with the prices of competing fuels and related products such as crude oil, gasoline, fuel oil, and steel due to competitiveness and economic factors. • Price setting indices were also adjusted to include the prices of other markets. • In 2002, the majority of global LNG prices (87% by volume) were linked to oil prices, while only a small portion (13% by volume) were tied to gas–gas competition by 2005.	• Since 2010, multiple methods for natural gas trading have coexisted. • Spot trading now accounts for a larger share, and LNG trade pricing has gradually become less dependent on oil prices. • However, oil prices became linked, and gas–gas competition went parallel. • Oil prices still have an impact, and competition between different gas sources has increased. • In 2019, trade linked to oil prices dropped to 59%, while gas–gas competition increased to 41%.

(Continued)

Dimensions	Infancy stage – No market	Development stage – Market in development	Innovation stage – Advanced market
	• Contracts were mostly long-term without indexation or inflation adjustment provisions.	• In response to inflation, long-term contracts began to include variables linked to economic indicators and S curves.	• Hybrid indices have also emerged, but a unified pricing system for the global LNG market has not been established yet. • In Europe, the UK was the first country to complete natural gas market reform in 1996, leading to the establishment of the NBP. • Since the 2000s, there has been progress in the Europe-wide market integration and interconnection of natural gas pipelines. • In North America, the U.S. began sector reform in the 1970s.

Sources: Authors based on Chen et al. (2021).

Endnote

[1] Cost-plus regulation is a method of regulating natural monopolies, where the government or the regulator sets prices based on the firm's actual costs plus an allowed profit margin.

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Notes

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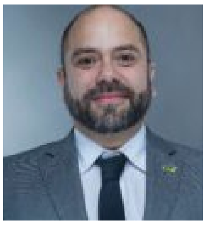

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About the Project

This workshop was organized as a part of the Regional Market Integration project within KAPSARC's Utilities and Renewables Program. The project seeks to understand various aspects of electricity market integration, including the development of power pools in other regions and their potential application in the MENA region. Additionally, the project aims to provide insights into the ongoing energy transition by studying and learning from electricity markets worldwide, including their role in promoting clean hydrogen.

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