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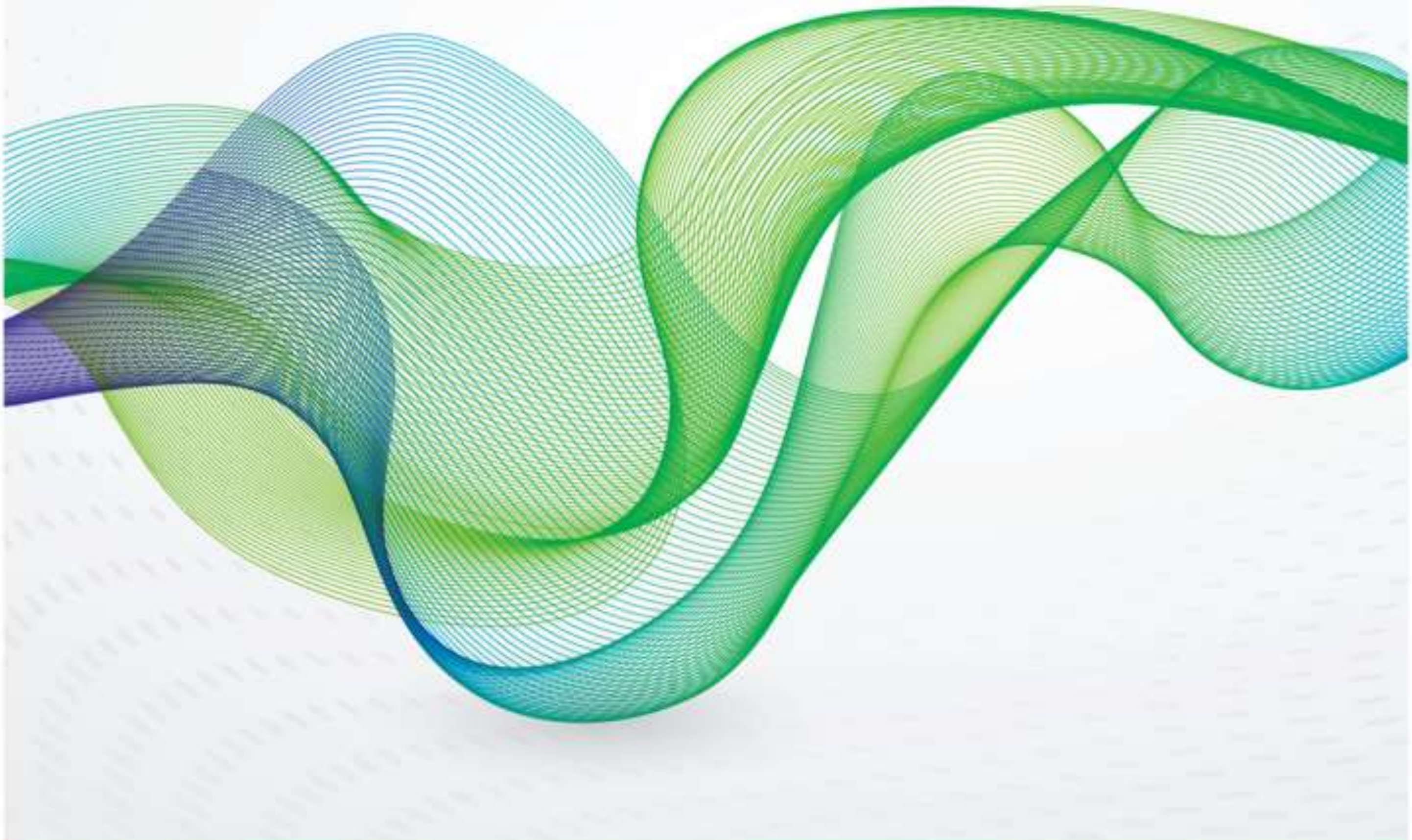
Regulating the future European hydrogen supply industry:

A balancing act between liberalization, sustainability, and security of supply?



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Abstract

The future of the European hydrogen supply industry lies at the heart of the European Union's energy policy, demanding the reconciliation of conflicting interests in liberalization, sustainability, and security of supply. This paper analyses the unique challenges faced by the emerging hydrogen economy, including the lack of an established market, transportation and storage infrastructure, uncertainty about demand and supply, and the manufactured nature of hydrogen production. The main question addressed is how the EU can create a regulatory framework that enables the expansion of the hydrogen economy within the time frame required to meet the net-zero target, while ensuring a well-functioning integrated market.

The paper argues that directly copying the liberalization model used in the gas and electricity sectors may not be suitable for hydrogen, and could lead to delays and uncertainties. Instead, it suggests combining existing provisions from natural gas and electricity regulations with novel elements tailored to the hydrogen supply industry. The first set of recommendations involves leveraging existing regulations to ensure non-discriminatory access to future hydrogen networks, fostering competition, and enhancing system resilience. Additionally, established instruments and institutions for European coordination should be extended to include hydrogen, promoting cross-border cooperation and integration between hydrogen and electricity. The paper also recommends new regulatory guidelines to address the unique characteristics of the hydrogen industry. It suggests aligning unbundling rules for hydrogen transport infrastructure with sustainability and security objectives, and exploring synergies with existing natural gas infrastructure while ensuring transparency and fair competition. Given the limited cost recovery potential of the nascent hydrogen market infrastructure, policymakers may need to depart temporarily from strictly cost-reflective tariff models, exploring alternative methods such as merged tariffs across different energy carriers, and public interventions such as grants, subsidies, or guarantees, to ensure sufficient infrastructure investments.

Overall, the proposed approach aims to create a robust regulatory framework that facilitates the creation of the European hydrogen market while addressing the diverse goals of the EU's energy policy.

Executive Summary

- The EU's ambitious hydrogen production targets introduce a time-sensitive element, demanding accelerated deployments, regulatory approvals, and infrastructure developments.
- The amplified urgency around security of supply, especially in light of geopolitical tensions as a result of the Russian invasion of Ukraine, further complicates the hydrogen strategy by intertwining it with international relations and global geopolitics.
- Regulatory frameworks need to be acutely sensitive to the technological nuances and economic dynamics intrinsic to hydrogen production and transport, ensuring that regulations are not only shaped by current technologies and economics but are also anticipative of future advancements and shifts.
- The divergence between the imperative for rapid hydrogen economy development (sustainability) and the cautious, equilibrium-seeking nature of traditional market liberalization mechanisms signals a nuanced challenge in achieving speedy yet stable market evolution. The tension between ensuring rapid advancement (for climate goals) and maintaining market stability and fairness (via liberalization) might require innovatively balanced strategies that don't strictly adhere to conventional liberalization paradigms.
- The non-existent mature hydrogen market introduces a peculiar regulatory scenario where regulations might need to concurrently facilitate market formation, ensure fair competition, and stimulate investments, thus requiring a forward-looking, innovative regulatory design that pre-emptively addresses potential market failures and barriers.
- The non-existent mature hydrogen market, coupled with the current use of hydrogen, primarily on-site in chemical plants, underlines a profound foundational challenge: regulations must simultaneously incite the establishment of both the market and its physical infrastructure, a complex, bidirectional task that may necessitate nuanced incentives, safeguards, and provisional structures to entice investment and participation from diverse stakeholders.
- The likely adoption of various hydrogen transport modes—from pipelines to sea transport—introduces a sophisticated logistic challenge, demanding advanced planning and real-time management of supply chains. Regulations must intelligently interface with this economical-logistical matrix, enabling a dynamic, adaptable market that can organically leverage the most viable transportation modalities in varied contexts, ensuring economic and operational efficiency.
- A dichotomy faced by the nascent hydrogen market: to build infrastructure, a customer base is needed to justify and recover costs; yet, to attract customers, infrastructure must be in place, highlighting the classic "chicken and egg" problem faced by new markets. This illustrates the crux of the problem of establishing hydrogen infrastructure in the absence of a robust market and reflects broader challenges in initializing novel energy markets.
- The presence of uncertainty, especially related to infrastructure planning amidst variable future hydrogen supply and demand, indicates a nuanced approach to risk management in policy and planning. A phased and adaptive infrastructure development approach is insightful but will require significant agile management capacity and strategic foresight. This uncertainty management can be an area for developing new frameworks or tools to guide infrastructural investment and development amidst ambiguity.
- The utilization and import of hydrogen in derivative forms (like ammonia or methanol) necessitate a unique regulatory focus. Regulations must address not only the physical and safety aspects of these derivatives but also their certification, conversion, and legal status within the broader hydrogen market. This demands developing regulatory mechanisms that ensure derivative forms of hydrogen are seamlessly, safely, and transparently integrated into the market, ensuring supply integrity and consistency with sustainability objectives.

- The regulatory precedents set by past reforms in the natural gas and power sectors may not be wholly applicable to hydrogen, given the fundamental shift from a liberalization-focused approach to a sustainability and security-driven strategy.
- The underdeveloped state of the hydrogen market poses a unique challenge to conventional cost-reflective tariff models, demanding regulatory creativity in devising alternative cost-recovery mechanisms and potentially integrating tariffs across different energy vectors, which might involve exploring novel cross-subsidization models and dynamic tariff structures to foster investment while ensuring economic viability.
- A nuanced balance between coordination and competition in the hydrogen sector, as opposed to the gas and electricity sectors, is pivotal due to the emergent state of the hydrogen industry. The implication here is that the regulatory approach should dynamically adapt to the development stage and specific challenges of the energy sector in question.
- The contemplation of adapting unbundling principles—specifically, the possibility of applying less stringent unbundling in the nascent stage of hydrogen infrastructure to stimulate investments and reduce financial entry barriers—represents a tactical deviation from conventional energy regulation models.
- While support schemes for green hydrogen production could borrow from historical analogues within renewable electricity generation, the unique characteristics and applications of hydrogen warrant bespoke mechanisms that address its specific production, distribution, and utilization challenges and opportunities.
- The move towards decentralized and diversified hydrogen production, akin to the recent developments in the power sector with renewable energy, signifies a shifting energy landscape. This not only entails a physical transformation in energy production but also suggests that regulatory and infrastructural adaptations must be flexible and adaptive to a spectrum of production scales and technologies, ensuring that regulations and infrastructure can effectively cater to and integrate varied production contexts, scales, and technologies.
- The intrinsic synergies and interdependencies between hydrogen, electricity, and natural gas markets demand an adaptive, cross-sectoral regulatory framework, which might necessitate flexible interpretations and applications of traditional unbundling provisions and could redefine market operations and cooperative strategies among different energy carriers.
- The embryonic state of the hydrogen market in the EU, underscored by its non-existence and partial decentralization of future production, means regulatory frameworks need to navigate through a blank slate, lacking mature market mechanisms, defined player roles, or existing governance structures. This could offer opportunities for innovative, future-forward regulatory designs but also possesses the risk of unintended consequences due to the unknown market dynamics.

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1. Introduction

Policymakers worldwide have identified hydrogen as a potential key component for the decarbonization of economies. Hydrogen, especially when produced via electrolysis using electricity from renewable power sources such as wind and solar (commonly referred to as "green" hydrogen), is particularly suitable for cutting CO_2 emissions in sectors where direct electrification proves to be problematic. Prime examples of these industries are steel, chemicals, glass, and heavy-duty transport. The immense potential hydrogen holds for reducing greenhouse gas emissions has led to numerous ambitious regional, national, and supra-national hydrogen strategies and pledges. For instance, at the European Union level, the EU Hydrogen Strategy sets a goal of 40 GW electrolyser capacity by 2030 and envisions a comprehensive European hydrogen economy[1]. In the short term, the 2022 REPowerEU Strategy sets the goal of 17.5 GW electrolyser capacity by 2025[2]. In turn, hydrogen is set to be a cornerstone of the EU's goal to achieve climate neutrality by 2050, as outlined in the European Green Deal[3].

The decarbonization of various industrial sectors through green hydrogen introduces a complex logistical landscape. While demand centres are traditionally situated near industrial hubs, large-scale production of green hydrogen is most cost-efficient in locations with abundant renewable energy sources—often on the geographical periphery of Europe. For example, wind energy is most effectively harvested in areas around the North and Baltic Seas[4], while solar energy has the greatest potential near the Mediterranean[5].

However, it is worth considering the possibility that future hydrogen demand may relocate closer to these production centres to minimize transport costs and inefficiencies. Moreover, European hydrogen production will be characterized by some degree of decentralization, similar to, and in part ensuing from, developments in power generation from renewable sources (see section 5). Multiple modes of hydrogen transport could be employed depending on the specific application and logistical requirements: these could range from pipelines to trucking and even sea transport for imported hydrogen. The scale of the future hydrogen network remains uncertain, influenced by a host of factors including technological advances, policy measures, and market dynamics.

Given this uncertainty, and the natural monopoly characteristics of some infrastructures such as pipelines, there is a compelling need for a carefully crafted regulatory model. This is especially important given that the European Commission (EC) envisions an "open and competitive EU market with unhindered cross-border trade"[6]. Aligning with its tradition of liberalizing and regulating sectors that feature natural monopolies (such as telecommunications, electricity, and natural gas), the EC is in the process of shaping the regulatory framework for the future European hydrogen market. This framework will need to be nimble and adaptive, capable of accommodating various modes of transport and of facilitating investment in an evolving and uncertain environment.

Similar to the three energy liberalization packages in 1996/98, 2003, and 2009, the goals of a regulation for a European hydrogen industry are competition, transparency, consumer protection, and market access[7]. Nevertheless, the wider political framing of the previous electricity and natural gas sectors' regulation reforms differs crucially from that of a new hydrogen industry's regulation. While the primary political driver for the former was liberalizing markets by introducing competition in supply, the latter is driven chiefly by the goals of mitigating climate change—the principal driving force behind the sustainability pillar of EU energy policy—and the desire to increase security of supply. With regard to mitigating climate change via widespread application of hydrogen, a timely ramp-up is required. Indeed,

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[1] European Commission (2020a).
[2] European Commission (2022b).
[3] European Commission (2019).
[4] European Commission (2020c).
[5] Šúri et al. (2005).
[6] European Commission (2020a, section 5).
[7] Schubert et al. (2016); European Commission (2020a).

already by 2030 the EU aims to produce 10 million tons of green hydrogen, more than today's total annual consumption of hydrogen[8]. Moreover, security of supply considerations have been massively amplified by the Russian invasion of Ukraine in February 2022 and are characterized by high urgency[9].

Therefore, a future EU hydrogen network regulation has to take into account liberalization as well as decarbonization and security of supply, creating an inevitable conflict between these pillars of European energy policy. On one hand, liberalization foresees the application of internal market rules, such as unbundling, competition, and transparency. Therefore, liberalization would address those parts of the value chain where competition is principally possible, namely production, trading, and retail. Similarly to the liberalization reforms in the natural gas and electricity sectors, the grid-bound transport of hydrogen constitutes a natural monopoly, and would thus be expected to remain the regulated part of the value chain. However, the development of a nascent European hydrogen economy conceivably features a set of unique aspects, as investigated in this paper. Hence, the mere adoption of previous liberalization strategies would potentially delay the creation of a hydrogen economy by not fully utilizing existing synergies. This is especially problematic because the strategic goal of sustainability is likely to demand the rapid build-up of a comprehensive hydrogen sector to achieve the EU's ambitious decarbonization goals. Furthermore, the strong cross-sectoral interdependencies and synergies of hydrogen with both electricity and gas markets would need to be reflected in a regulatory framework, potentially through exemptions from strict forms of unbundling provisions and the creation of other regulatory arrangements. Additionally, the introduction of support schemes for (green) hydrogen production, based on lessons learned from similar developments in the generation of electricity from renewable energy sources, could facilitate the smooth creation of a European hydrogen economy. However, these and other elements would undermine existing EU liberalization principles.

The central question that arises from this conflict between liberalization and sustainability is: which regulatory framework does the EU need to facilitate the ramp-up of a European hydrogen economy within the time frame required to meet the net-zero target, while equally guaranteeing a functioning integrated market?

This paper explores how regulation of the European hydrogen supply industry could contribute to achieving the wider policy goals of liberalization, sustainability, and security of supply. At the same time, shifting priorities in EU energy policy are taken into consideration. In the context of a developing hydrogen economy, transport infrastructure will be vital for creating an efficient physical internal hydrogen market, which in turn facilitates competition, bolsters production and demand, and increases security of supply. While potential conflicts and synergies between the three described goals of energy policy is central to the development of an efficient regulation of hydrogen, this paper also explores a number of other factors that can potentially impact hydrogen regulation. These factors are the non-existent hydrogen market, technological aspects of hydrogen transport, its character as a manufactured energy source, and the economics and potential applications of hydrogen. The paper discusses the extent to which these aspects may shape future hydrogen transport regulation.

The paper first presents primary architectures for a future hydrogen supply industry, and discusses the factors that might shape the ultimate structure of this industry in Europe. It then elaborates on the conflict between liberalization, sustainability, and security of supply as part of a wider discourse on EU energy policy. This forms the basis for better understanding of this conflict's implications for regulation of the hydrogen supply industry. Section 4 provides an analytical framework that is used to highlight two important features: the impact of industry-specific features on the modes of regulation; and why regulation of a future hydrogen supply chain has a different objective from that of the natural gas and electricity sectors in the twentieth century. Section 5 discusses unique factors that may impact the form of regulation of a future hydrogen supply industry, including the non-existent market, and technological aspects. Section 6, the central analytical section, explores different regulatory provisions that emerge from the identified conflict. In particular, this section identifies two sets of regulatory elements that can

[8] Piebalgs and Jones (2021).
[9] Tubiana et al. (2022).

potentially be applied to a hydrogen regulatory framework: first, principles of existing natural gas and electricity regulations; and second, new elements that particularly reflect the unique and crucial aspects of the future European hydrogen supply industry. The results are summarized in the section 7.

2. Structure of the hydrogen supply industry

As Europe steers towards a hydrogen economy, its potential network topologies—the very architectures that would underpin its production, distribution, and consumption—merit meticulous examination. However, navigating the intricate maze of a burgeoning hydrogen economy is not only about identifying the most efficient or technologically advanced topologies; it is equally about aligning these systems with adept regulatory frameworks. This interplay between the structure of the hydrogen supply industry and regulation forms the cornerstone of this paper.

Several potential models of hydrogen network topologies, ranging from Interconnected Pan-European Networks to localized hydrogen valleys, present opportunities across the European landscape. Each model, with its distinct set of attributes, implications, and challenges, embodies a unique vision of how hydrogen might integrate seamlessly into Europe's energy fabric. Recognizing the nuances of these models is not just an academic endeavour; it is a crucial step towards understanding their real-world implications, from socio-economic impacts to environmental considerations.

In parallel, the nascent state of the hydrogen industry offers the EU a rare opportunity to craft regulations not as reactive measures, but as proactive instruments guiding the industry's evolution. Historically, the energy sector has often witnessed regulations playing catch-up with technology and market dynamics. With hydrogen, the EU can rewrite this narrative, allowing informed regulatory design to walk hand-in-hand with technological and infrastructural developments. (Or, alternatively, badly designed regulation can stifle market development.)

Yet, how can regulations be effectively sculpted without a profound understanding of the hydrogen network topologies they aim to govern? It's akin to constructing rules for a game whose dynamics are not yet fully understood. Each potential topology presents specific regulatory needs, challenges, and opportunities, from ensuring third-party network access in interconnected systems to addressing safety and environmental concerns in localized setups. Therefore, a holistic comprehension of these models is the bedrock upon which sound, efficient, and forward-looking regulations can be built.

A spectrum of topologies, each embodying distinct characteristics and premises, emerges. In this section we delve into key possible models, elucidating their key features and investigating the conditions under which their economic viability is most pronounced.

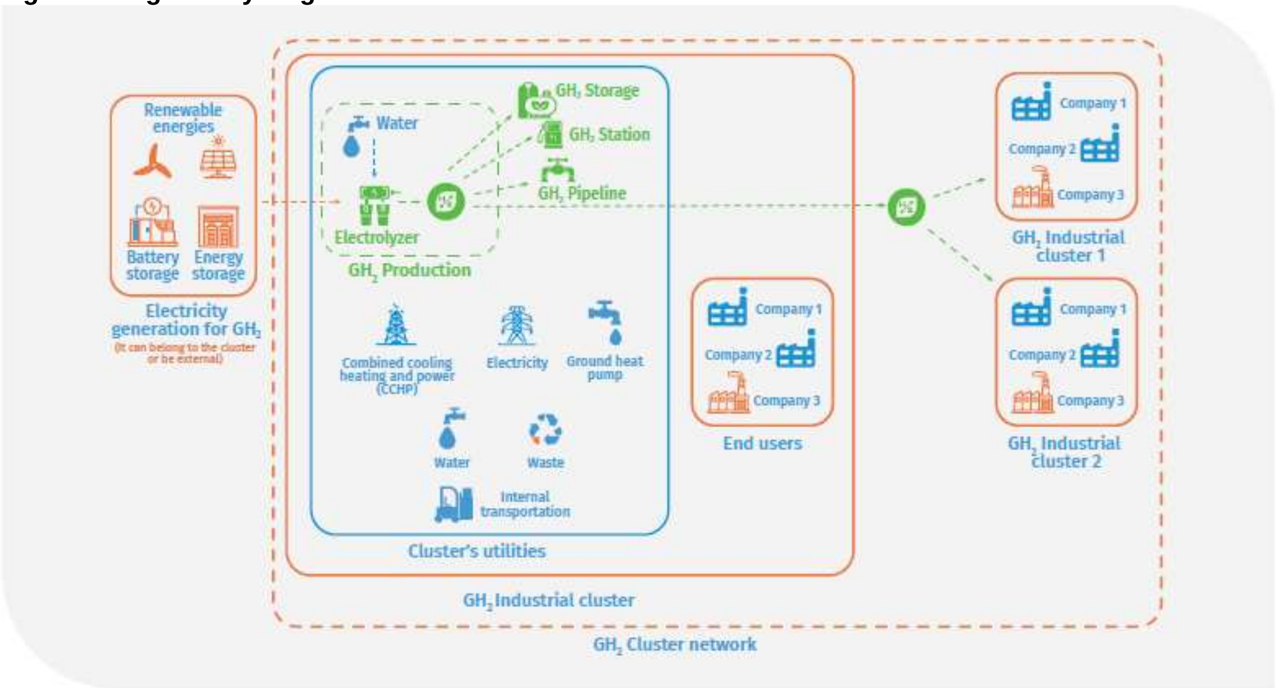
2.1 Industrial clusters

These are specialized regions or corridors championing the entire hydrogen value chain from production, storage, and distribution to varied applications such as mobility, industry, and energy. Significant investment is made in establishing cutting-edge infrastructure to facilitate hydrogen production, transport, and usage. These clusters foster collaboration between stakeholders including governments, industry players, research institutions, and the public, creating an integrated ecosystem[10].

Often, industrial clusters become centres of research and innovation, pioneering new technologies, applications, and business models related to hydrogen. Such regions benefit from tailored policies, incentives, and regulations that support and stimulate growth of the hydrogen economy.

[10] European Commission (2023a).

Figure 1: A green hydrogen industrial cluster



Source: UNIDO (2023).

2.2 Localized mini-grids

This model for hydrogen envisions a small, decentralized system where hydrogen production, storage, and consumption are contained within a localized geographical area or community. In essence, each mini-grid operates as a self-sufficient entity, producing and using hydrogen without substantial reliance on external sources. This is analogous to microgrids in the electricity sector, where local generation, often from renewables, serves the immediate community.

In this model, hydrogen is produced locally, often using energy sources such as solar panels or wind turbines, then consumed within the same geographical or community boundary, reducing the need for long-distance transport. Localized storage solutions, such as metal hydrides or compressed hydrogen tanks, ensure a steady supply, catering to demand fluctuations. Such a structure benefits from adaptability as it can be tailored to the specific needs and characteristics of a community or locality, ensuring energy solutions that align with local demand patterns, resources, and constraints.

A combination of factors offer a rationale for this model. For example, if transporting hydrogen from external sources becomes prohibitively expensive due to distance or logistical challenges, local production and consumption through mini-grids become more attractive. The presence of abundant renewable energy resources, such as consistent sunlight or wind, can make local hydrogen production via electrolysis economically viable. Furthermore, mini-grids make economic sense for communities or localities where the scale is not large enough to justify major infrastructure investments, but there is still a consistent demand for hydrogen.

2.3 Hub and spoke model

Predicated on centralized hydrogen production facilities (hubs) feeding satellite consumption sites (spokes), this model emphasizes distribution efficiency. At the heart of the model lies the hub, a central location where large-scale hydrogen production or import occurs. This hub is equipped with significant infrastructure to handle high capacities. From the hub, hydrogen is transported to various spokes through pipelines, trucks, or other means, ensuring timely supply to demand centres.

Spokes are typically located in areas with substantial hydrogen demand, such as industrial clusters, urban centres, or transportation hubs. Owing to its centralized nature, a significant portion of storage occurs at the hub, allowing for efficient inventory management and quick response to demand fluctuations.

The model can be adapted to different scales—from a country-wide system where a national hub serves various cities, to a city-wide system where a central city depot serves different neighbourhoods. The hub's location is pivotal. It should be situated to minimize the cumulative transport costs to all spokes. This might mean placing it centrally among all spokes, or in a location with the best transport links.

The hub and spoke model becomes economically viable when there is a wide variance in hydrogen demand across regions, making it inefficient for each region to have its own production facility. Thus its economic rationale is heightened in regions where demand sites are dispersed and where transportation logistics favour a centralized production approach. This model requires operation at a high load factor, implying consistent and high-volume production and distribution.

2.4 Multi-modal transport

This model for hydrogen distribution emphasizes the use of multiple modes of transport to move hydrogen from its production sites to consumption areas. Rather than relying on a singular method, this approach harnesses the strengths of various transport modes—pipelines, road tankers, rail, or even ships—depending on the circumstances, ensuring flexibility, efficiency, and resilience in the hydrogen supply chain.

This approach ensures that the most time- and cost-effective mode is employed for each segment of the transportation journey, optimizing the logistics process. It thus requires integrated infrastructural elements, such as transfer hubs, where hydrogen can be transitioned from, say, a pipeline to a road tanker, or from a rail carriage to a ship.

In regions with diverse terrain, like coastal areas adjacent to mountainous regions, multi-modal transport can be more cost-effective than trying to establish a single mode of transport. Also, when a region is prone to supply chain disruptions, either due to weather, political issues, or technical challenges, the diversified nature of multi-modal transport offers an economically resilient alternative.

In essence, this model champions flexibility and adaptability in the face of diverse challenges. Its strength lies in its ability to adapt to varying conditions, ensuring that hydrogen reaches the destination in the most efficient and timely manner. The economic logic underpinning this model revolves around leveraging existing infrastructures, optimizing logistics, and building resilience against supply chain uncertainties.

2.5 Interconnected Pan-European Network

An Interconnected Pan-European Network for hydrogen can be envisioned as an extensive, integrated pipeline system that spans multiple European countries, aiming to facilitate the production, distribution, and consumption of hydrogen at continental scale. The concept takes inspiration from the interconnected electricity and natural gas grids currently operating in Europe, but is specifically tailored for hydrogen's unique properties and market dynamics[11].

This network offers a continuous and seamless connection of hydrogen pipelines stretching across national borders, linking hydrogen production centres with major demand hubs throughout the continent.

Strategic locations with abundant renewable energy resources, such as solar farms in southern Europe or wind farms in the North Sea region, would serve as major hydrogen production hubs, feeding into

[11] van Rossum et al. (2022).

the interconnected grid. The network facilitates the movement and trade of hydrogen between countries, allowing for a flexible response to supply–demand imbalances, and promoting economic optimization.

While it would require new-build pipelines, the system could potentially integrate or repurpose parts of the existing natural gas infrastructure, adapting it for hydrogen transport.

However, for such an expansive infrastructure to be economically viable, there must be a substantial and consistent demand for hydrogen across various European sectors, from industrial uses to transportation and the power sector. The initial investment required for such a network is substantial, so centralized production centers must be able to achieve economies of scale, where producing hydrogen en masse results in cost reductions, making it competitive with other energy carriers.

2.6 Optimum structure of the EU hydrogen supply industry

The optimum structure of the future hydrogen supply industry in Europe does not have a straightforward answer, but rather poses a complex puzzle that hinges on myriad factors, each with power to influence the broader hydrogen narrative.

The location and scale of hydrogen demand is fundamental. Regions with industrial hubs, such as the Ruhr area in Germany or the industrial triangle in Northern Italy, might require different structures compared to areas with dispersed, largely small-scale demand. Similarly, the location and scale of hydrogen supply have profound implications. Production sites rich in renewable energy resources, such as the sunny plains of Spain or the wind-rich North Sea coast, might favour certain topologies over others.

Yet it's not just about internal dynamics: Europe's import dependency on hydrogen plays a crucial role. If the EU leans heavily on imports, the topology must prioritize port cities, import terminals, and corresponding distribution networks. Concurrently, the emphasis on decentralized hydrogen production could tilt the balance towards localized mini-grids, allowing communities to produce, consume, and even store hydrogen within their own confines.

Another pivotal determinant is the role of carbon capture, utilisation and storage (CCUS)-based hydrogen production. Regions rich in natural gas reserves, or those with accessible carbon storage sites, might find this method economically and logistically viable, influencing the network's design. Furthermore, competition between alternative modes of hydrogen transport, whether pipelines, road tankers, or even rail and ship, also defines the network's contours. Each transport mode comes with its own set of efficiencies, costs, and technical demands, and their interplay could shape the overarching transport strategy.

Lastly, the technical and economic limitations of electrification in hard-to-abate sectors are vital. Industries such as steel, cement, and even certain segments of the transport sector (such as aviation) have inherent challenges in direct electrification. For these sectors, hydrogen or hydrogen-derived fuels might be the primary decarbonization pathway, influencing both demand patterns and the required network infrastructure.

The optimum topology for Europe's hydrogen supply industry is a mosaic of numerous determinants. It's not a static vision, but a dynamic entity, ever evolving with shifts in technology, market dynamics, policy imperatives, and socio-economic needs. As the EU embarks on this hydrogen journey, a deep, nuanced understanding of these factors is imperative, ensuring the hydrogen supply industry is not only robust but also resilient, efficient, and forward-looking.

While other transport modes, such as ships for international trade or trucks for last-mile delivery, will undoubtedly play their roles, pipelines are expected to form the backbone of the hydrogen transportation vision. Even if the EU leans heavily towards importing hydrogen, pipelines will be pivotal post-import. Once hydrogen is offloaded at terminals, pipelines can distribute it deep inland, ensuring a seamless transition from international shipment to local distribution.

While the importance of pipelines in the hydrogen narrative remains unchallenged, predicting the exact scale and extent of this infrastructure—how much of it will truly be needed in practice—is riddled with uncertainties. Factors such as unpredictable hydrogen demand growth, possibility of relocating demand centres[12], potential for decentralized production, innovations in alternative transport solutions, import dynamics, possibilities of repurposing existing gas infrastructure, and both economic and technical challenges introduce layers of uncertainty. Overall, navigating Europe's hydrogen future necessitates a flexible, responsive approach, acknowledging the role of pipelines while staying attuned to the many variables that might influence their real-world implementation.

Pipelines, by their very nature, epitomize natural monopolies. Given the high capital costs and infrastructural dominance inherent to them, their establishment and operation are typically limited to a singular entity within a geographical region. This characteristic has informed the regulatory approach to natural gas and electricity industries in the past, where authorities stepped in to ensure that the monopoly does not lead to price gouging or compromised service quality.

Drawing from this historical context, it is foreseeable that regulation of the future hydrogen supply industry would echo elements of natural gas and electricity sector regulations. Just as with gas and electricity, ensuring fair access, preventing anti-competitive behaviours, and safeguarding consumer interests would be paramount in the hydrogen realm. Tariff structures, third-party access rights, and investment incentives might be crafted using tried-and-tested frameworks from these established sectors.

However, the EU's policy milieu, characterized by the energy trilemma (security, affordability, and environmental sustainability), injects nuances into this regulatory landscape. The trilemma presents inherent tensions. For instance, while ensuring energy security might necessitate rapid development of hydrogen infrastructure (favouring monopolies or oligopolies), the equity pillar could push for broader market participation and fair pricing—sometimes pulling policy in divergent directions.

Further complicating the landscape are the unique attributes of the hydrogen sector. The hydrogen market is yet to be established. This embryonic stage means that regulatory interventions might need to be more nurturing, fostering market growth while preventing monopolistic pitfalls. Technological facets of hydrogen transport, particularly around issues such as multi-modal competition, may require specific regulatory considerations. Moreover, hydrogen's characterization as a manufactured energy source, produced primarily from fossil fuels (with carbon capture) or through electrolysis, implies a broader regulatory scope.

While the foundational tenets of natural monopoly regulation, as seen in the natural gas and electricity sectors, will undoubtedly influence the hydrogen industry's regulatory paradigm, the unique challenges and attributes of hydrogen necessitate a tailored approach. Striking a balance between these learnings and the novel demands of the hydrogen sector will be central to the EU's regulatory endeavour.

3. Policy context: Conflicting goals in EU energy policy

The EU's energy policy pursues three overarching goals: security of supply, sustainability, and affordability. As the principal political actor in European energy policy, the European Commission intends to achieve these goals by reducing energy import dependency and diversifying suppliers, decreasing greenhouse gas emissions, and completing the internal market for energy through liberalization[13].

Naturally, synergies as well as potential conflicts exist between the three goals and their respective instruments. For instance, decreasing greenhouse gas emissions through energy efficiency gains diminishes the need to import fossil fuels, which in turn strengthens the security of supply[14]. On the

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[12] Conceivably, energy-intensive industries might relocate to regions within or outside Europe, where production of renewable energy, and thus green hydrogen, is particularly favourable. Nevertheless, political considerations at EU member state level apparently aim to counter such relocation. In this context, Germany's €2 billion subsidy for a single steel plant for transition to hydrogen is an example (European Commission, 2023b).
[13] Buchan (2009); Helm (2012); Schubert et al. (2016).
[14] Fischer (2017).

other hand, national subsidies for boosting renewable energy output undermine the internal market completion, and may jeopardize the goal of affordability[15].

Over the course of the past 30 years, when Europeanization of energy policy gradually emerged, the balance between the three policy goals described above shifted multiple times. Analysing these changing prioritizations and their underlying motivations facilitates the understanding of existing conflicts in EU energy policy and helps derive implications for regulation of the hydrogen industry.

Prior to the Europeanization and liberalization initiatives of the 1990s, energy policy was considered by member states to be a strictly national subject and a strategic sector. The reliable provision of energy was directly linked to national security and the prosperity of both citizens and domestic industries. Hence, national governments viewed energy as a largely domestic policy area, and were thus reluctant to transfer competencies from national to EU level. The energy industry was dominated by national champions: often state-owned, monopolistic, vertically integrated companies that covered the entire value chain of the power, natural gas, and/or oil sectors. These national champions controlled production and import, transport and distribution, sales, and all services related to the energy business. Through their national champions, governments had a direct impact on the domestic energy sector and pursued the security of supply as their primary energy policy goal at the national level[16].

With the trend towards liberalization and Europeanization that started in the late 1980s, slow and gradual Europeanization of energy policy evolved. The central political actor and driver of reforms in this process was the EC[17]. With its goals of Europeanization and European integration in mind, the EC—against partly vehement opposition from member states—pushed for fundamental reforms in the energy sector and the creation of a European energy policy[18]. The EC's key instrument for achieving its goals was the inclusion of energy in the internal market through liberalization and competition. In these two areas, the EC holds its key competences, and is capable of enforcing reforms even against opposition from member states. For instance, the Commission may start an infringement process against any member state that does not apply EU competition law, and could fine individual companies, such as national energy champions, for not adhering to monopoly rules[19]. As a result, liberalization and the completion of the internal market for energy were central elements of the creation of European energy policy in the 1990s[20]. Sustainability and security of supply, in comparison, played a marginal role and selectively entered the policy stage as late as the early 2000s[21]. The results of the EC's efforts to create a European energy policy materialized in the three liberalization packages in 1996/98, 2003, and 2009[22]. These reform packages, through tedious negotiations between the Commission and member states, introduced tremendous changes for both power and natural gas sectors, and determined today's energy industry landscape in Europe.

These reforms included, among others, consumer protection, market access provisions, and European network planning. The most crucial reforms, however, were the breaking-up and unbundling of national champions. The vertical unbundling of these companies meant separating business activities where competition may emerge (production, trading, sales) from activities where competition is restricted because of natural monopolies (transport and distribution via power lines and pipelines), and converting them into different companies[23]. On one hand, where possible, competition would reduce costs, provide flexibility to consumers, and allow new players to enter the market. On the other hand, monopolistic business areas need to be regulated to prevent operators of power grids and pipelines from exploiting their strong market position. Therefore, the liberalization packages led to a division of existing national

[15] Buchan and Keay (2015).
[16] Eising and Jabko (2001).
[17] Buchan and Keay (2015); Thaler (2016).
[18] Schmidt (1998); Biesenbender (2015); Schubert et al. (2016).
[19] Talus and Aalto (2017).
[20] Peng and Poudineh (2017).
[21] Biesenbender (2015).
[22] Schubert et al. (2016).
[23] FSR (2020).

champions into companies that had to compete in some areas of the energy business, while other regulated companies engaged in the transport and distribution of power and gas. As a result, the current landscape of the European energy sector and its regulation is based chiefly on liberalization reforms between 1996 and 2009, championed by the EC. The objective of these reforms was to break the strong market position of national and vertically integrated energy companies, create the internal market for energy, and enable consumer rights and transparency.

Following European policymakers' almost exclusive focus on liberalization in the 1990s, the two remaining objectives of European energy policy started to draw attention in the following decade. Spurred by Russian–Ukrainian gas disputes in 2006 and 2009, security of supply gained weight on the policy agenda, and was included prominently in the third liberalization package[24]. In addition, a majority of member states acknowledged the potential of a stronger European coordination of energy policy regarding security of supply and sustainability issues, as well as the existing synergies between the different goals[25]. The European gas crisis that started in 2021, and was greatly amplified by the Russian invasion of Ukraine in February 2022, strongly shifted policymakers' attention to security of supply, and resulted in reinforced political momentum for this particular energy policy objective[26]. Consequently, the potential conflicts and synergies between the three objectives in EU energy policy are reinforced.

Sustainability entered the energy policy agenda gradually in the late 1990s. With climate change becoming a pressing topic in policymaking and public discourses, sustainability considerations were eventually set to become a cornerstone of EU energy policy[27]. In its pioneering White Paper 'Energy for the Future: Renewable Sources of Energy'[28], the EC laid out benefits that could be achieved by increasing the share of renewable electricity in the EU, and highlighting, among others, the synergies with security of supply. Nevertheless, it was not before 2009 that the Renewable Energy Directive laid down the first set of comprehensive legislative rules to promote sustainability in energy policy[29]. The Renewable Energy Directive laid the foundation for a stronger focus on sustainability, and acted as the vanguard for numerous initiatives in energy policy and beyond by establishing ambitious sustainability goals at the European and national levels. In this context, notable policy packages are the Energy Roadmap 2050 (2011), the 2030 Energy Strategy (2014), the Energy Union Package (2015), the Clean Energy Package (2016), the European Green Deal (2019), and the Fit-for-55 Package (2021). Arguably, sustainability has taken on a central role in EU energy policy since the Renewable Energy Directive was established. Goals to decrease greenhouse gas emissions, to boost the share of renewable energy, and to increase energy efficiency have become common denominators for the ongoing Europeanization of energy policy. The European Commission, similarly to its role in liberalization, remains the main driver of policy initiatives at EU level. Nevertheless, member states put forward their own national initiatives to promote sustainability, and principally support European collaboration (to varying degrees) on climate change mitigation of energy policy and of other policies.

The historical excursion above describes the shifting priorities of EU energy policy: a strong focus on liberalization in the 1990s and early 2000s, with the liberalization packages (1996/98, 2003, 2009) as legislative foundations. These reforms resulted, among other provisions, in the vertical unbundling of large energy corporations, and the shaping of the European energy landscape until today. Security of supply entered the political agenda after the Russian natural gas supply disruptions in 2006/2009. With regard to sustainability, a gradual emergence of this policy objective as the core driving force of EU energy policy was noticeably kicked off by the Renewable Energy Directive in 2009, which was followed by a series of policy proposals on climate change mitigation. The chronological order of these shifting

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[24] Helm (2012).
[25] Thaler (2016).
[26] Birol (2022); Tubiana et al. (2022).
[27] Biesenbender (2015).
[28] European Commission (1997).
[29] The Renewable Energy Directive defined three goals for 2020: a 20 per cent reduction in greenhouse gas emissions (compared to 1990); a 20 per cent share of renewables in energy consumption; and reduction of total energy consumption by 20 per cent through efficiency gains (European Parliament and Council of the EU, 2009a).

priorities underlines the fact that EU energy sector policies on liberalization, security of supply, and sustainability were not developed simultaneously or cooperatively[30].

As a result, conflicts between the policy goals ensued, and still prevail. Here, friction between liberalization and sustainability is particularly visible. In the electricity sector, for instance, EU member states introduced numerous instruments to foster renewable power generation, such as investment subsidies and feed-in tariffs for renewable power generation. However, these instruments proved highly distortive to the market, resulting in considerably diverging wholesale and retail prices for electricity, and creating dissimilar investment conditions across Europe. The idea of creating an internal market for electricity (one of the EC's central instruments of liberalization in the energy sector) was based on a market design that in principle works for "conventional" power generation in the form of centralized, dispatchable, and large power plants. The new focus on sustainability, however, envisioned massive deployment of renewable power generation, which is typically decentralized and non-dispatchable. Consequently, the initial market design, as promoted by the Commission, cannot accommodate increasing amounts of renewable power in the European system. The results are market failures, incorrect price signals, and the introduction of new instruments such as national capacity mechanisms—which in turn further undermine the creation of a European market[31].

Nevertheless, synergies can be leveraged from the interplay of the three energy policy goals. In particular, security of supply is a policy goal that may benefit from the implementation of sustainability and liberalization instruments. To elaborate, a higher share of (domestically produced) renewable energy (both electricity and renewable gases) in Europe's energy mix reduces the need for imports of fossil fuels. A liberalized internal market that enables competition and consists of numerous market players may prove to be resilient against supply disruptions.

The current political focus on security of supply, evoked by Russia's invasion of Ukraine, opens up opportunities for synergies between the three objectives when it comes to the future European hydrogen economy, particularly in the medium to long term. For instance, switching from largely imported natural gas to in part domestically produced (green) hydrogen in industrial uses strengthens security of supply and cuts emissions at the same time. As green hydrogen could be used for seasonal storage of renewable power, overall stability of the electricity system can be improved, which in turn enables higher shares of renewable power (see section 5).

To conclude, regulation of the hydrogen supply industry will be subject to existing conflicts and synergies in European energy policy. Within Europe, hydrogen will be largely transported by pipeline (the most economical means of transport for high usage levels over medium to long distances)—so an infrastructure-based natural monopoly, similar to natural gas and electricity transmission, is likely to emerge. Therefore, hydrogen transport regulation will be subject to conflicts and synergies similar to those of gas pipeline infrastructure and electricity transmission grids. Consequently, future hydrogen transport regulation could in part be derived from existing regulation for gas and electricity infrastructure (see section 6). Nevertheless, the underlying political motivation for creating a European hydrogen economy and rules is quite different from the political driving forces that formed the natural gas and power markets as they exist today. As described above, in the 1990s liberalization and competition were the central elements for breaking up national electricity structures and creating a European market in the gas and power sector. This is reflected in a strong focus on unbundling rules, market access, and consumer protection. With regard to hydrogen, on the other hand, the political focus is arguably different. In tune with a wider trend in EU policymaking described above, the main political motivation for creating a comprehensive hydrogen economy is sustainability and decarbonization. Notably, hydrogen is to play a significant part towards achieving the EU's climate goals in 2030[32], and timely establishment of a European hydrogen economy is likely to be needed for hydrogen to deliver on this

[30] Buchan and Keay (2015).
[31] Peng and Poudineh (2017).
[32] European Commission (2020a).

ambitious goal. In turn, regulatory provisions that delay market ramp-up should be avoided in regulation of the hydrogen supply industry[33].

The Russian war against Ukraine and its grave implications for Europe's energy supply shifted policymakers' attention sharply towards security of supply[34]. Here, hydrogen can potentially play an important role in decreasing dependency on Russian energy imports. Any rules for the future hydrogen economy, including regulation of the hydrogen supply industry, will need to reflect the highlighted shift in policy priorities, if the energy policy goals of sustainability and security of supply are to be achieved.

4. Analytical framework

The structure–conduct–performance (SCP) paradigm, developed by Bain in 1959, provides a valuable framework for analysing the economics of energy sector reform. According to this framework, the performance of a specific industry is influenced by the conduct of the firms operating within it, which in turn is determined by the structure of the industry. The structure encompasses various aspects such as market concentration, barriers to entry, vertical integration, and diversification. Conduct involves operational decisions, pricing strategy, product strategy, research and development, and investment in new capacity. Ultimately, performance is measured by factors including cost efficiency, profitability, and technical progress.

A key insight from the structure–conduct–performance paradigm is that when firms in an industry exhibit poor performance, the government can intervene by restructuring the industry, rather than burdening the firms with additional regulations. By modifying the industry structure, the government can influence the behaviour of firms, thereby improving their conduct and subsequent performance. This approach recognizes that addressing the root causes of underperformance can be more effective than imposing regulatory constraints on individual firms.

While the structure–conduct–performance paradigm offers insights into the economic aspects of energy sector reforms in the past century, it is important to note that reforms have not been driven solely by economics. Various other factors have played a decisive role in the pioneering countries that undertook the restructuring of their energy industry. For instance, in the case of the United Kingdom, the motivations for power sector reform were multi-faceted. Key objectives included reducing government involvement in the sector, enhancing the operational and investment efficiency of utility companies, decreasing public sector borrowing, curbing trade union power through fragmentation, promoting wider share ownership, and gaining political advantage for the incumbent government at the time. These motivations highlight that the rationale for reform extended beyond economic considerations alone.

The components and objectives around gas and electricity sector reform continued to evolve, and were further institutionalized in 2009 with the EU's introduction of the Third Energy Package. The package encompassed five main components aimed at promoting a more competitive and transparent energy market. These components included unbundling energy suppliers from network operators, strengthening regulatory independence, fostering increased cross-border cooperation between transmission system operators (TSOs) to ensure non-discriminatory network access, and establishing transparent wholesale and retail markets.

The principles of power sector reform in the 1990s were guided by certain initial conditions that shaped the restructuring process. First, it was argued that liberalization would lead to welfare enhancement only if average costs exceeded marginal costs, allowing competition to drive down average system costs and potentially to reduce prices. In cases where average costs were lower than marginal costs at the outset, rising prices were more likely. Thus, the economic objectives of reform were more likely to be met when there was excess capacity in the system rather than capacity shortages.

[33] Piebalgs and Jones (2021).
[34] Tubiana et al. (2022).

Second, wholesale and retail competition relied on non-discriminatory open access to the transmission and distribution network. During the time of power sector reform (as well as the natural gas reform), a well-established transmission and distribution system was already in place, and access to it played a critical role in ensuring the smooth functioning of the newly established electricity markets. The existing infrastructure of transmission lines and distribution networks formed the backbone of the electricity supply chain, enabling the efficient and reliable delivery of electricity from generation sources to end consumers. Access to this established system was vital for facilitating market competition, as it allowed multiple suppliers to connect and transport their electricity to customers. The reliable and widespread network infrastructure served as the cornerstone for the successful implementation and operation of the reformed electricity markets, fostering competition, innovation, and efficient allocation of resources throughout the industry.

In contrast to the gas and electricity sectors in the 1990s, the hydrogen industry faces a different set of conditions today, primarily due to its nascent stage of development. Unlike the established gas and electricity industries, the hydrogen sector lacks the initial conditions necessary for reform to take place. First, there is no existing excess capacity that would allow hydrogen users to benefit from the difference between average and marginal costs. Without surplus production capacity, there is limited potential for competition in the market to drive down costs and prices.

Furthermore, there is currently no well-established infrastructure for the transportation and storage of hydrogen. Unlike the transmission and distribution networks that already existed for gas and electricity, the hydrogen industry lacks a comprehensive system for efficiently moving and storing hydrogen. This absence of infrastructure presents a significant challenge in establishing a functioning hydrogen market. Without a reliable transportation and storage network, the efficient flow of hydrogen from producers to consumers is impeded.

Consequently, the objective of reform in the hydrogen supply industry is not to “restructure” an already established industry, but rather to create both the market and the necessary infrastructure from scratch. The focus is on building a new industry structure in which hydrogen producers and consumers respond to market incentives. The disparity in the objectives of regulating the future hydrogen supply industry versus the existing electricity and gas sectors means that not all components of power and gas sector reforms will apply to facilitating the initiation of the hydrogen industry. Consequently, regulatory bodies must meticulously select and adapt elements that align with the overarching goal of “creating” an industry, rather than restructuring an already established one.

Designing a regulatory framework for the future hydrogen supply industry requires a deep understanding of its unique characteristics and challenges. As a nascent industry, hydrogen presents distinct technical, economic, and environmental considerations that need to be carefully addressed. By considering these unique features, a robust regulatory framework can be devised to foster the growth and development of the hydrogen industry, enabling it to become a reliable and viable energy solution in the future.

The following sections present a comprehensive analysis of the distinctive characteristics of the hydrogen supply industry, and examine their profound implications for the regulatory framework governing the hydrogen sector. We explore the vital considerations for regulators as they navigate the task of selecting relevant components from the existing regulatory framework of the gas and electricity supply industries to effectively govern the future hydrogen industry.

5. Unique features of the hydrogen supply industry

Drawing from existing regulations in the natural gas and power sectors, which share similarities with hydrogen infrastructure, can provide a blueprint for future regulation. This includes considering anticipated transportation via pipelines as the most economical option in most applications, leading to a natural monopoly. Additionally, provisions from the European network codes[35] in the natural gas and power sector can inform the creation of a European hydrogen market.

However, despite the similarities with existing regulatory regimes, there are additional unique factors and constraints specific to the future European hydrogen economy. These factors need to be carefully considered when formulating rules and regulations for hydrogen infrastructure. This includes addressing the non-existent market for green hydrogen, exploring technological aspects related to hydrogen transport options, considering the decentralized production nature of hydrogen, and identifying the anticipated demand sectors for green hydrogen. In this section, we analyse these features and highlight their implications for regulation of the future hydrogen supply industry.

5.1 Non-existent market

A European hydrogen market and a pipeline network do not exist yet. While hydrogen is currently a vital commodity in the chemical industry, it is largely produced on-site at chemical plants. Currently, around 95 per cent of hydrogen in the EU is produced via steam methane reforming (SMR) or autothermal reforming (ATR) using natural gas[36]. The grey hydrogen produced is then typically transported via small, privately owned pipeline systems such as a business park. A market where large quantities are traded and transported, similar to that for natural gas, does not exist. For the future, policymakers envision a mature hydrogen market that largely resembles the existing one for natural gas and features similar rules[37]. Until a mature hydrogen market has materialized, however, simply mirroring the gas market rules and their evolution will not suffice. This is because when the current regulatory framework for natural gas was developed[38], a European cross-border natural gas pipeline network already existed. The goal of the three energy packages was to improve, Europeanize, and partly reorganize a functioning market with stable demand and supply[39]. Addressees of these provisions were well-established market players such as the previously described national champions and existing natural gas users.

Currently, significant demand and supply for green hydrogen and a European hydrogen infrastructure do not exist, and there are no well-established market participants. Hence, the primary objective of hydrogen regulation would be to foster the development of a market. First, this would entail encouragement for the uptake of green hydrogen production and demand. In an early phase, this could possibly include public support schemes, such as the European Commission's Important Projects of Common European Interest[40] and/or national programmes. Subsequently, demand for green hydrogen will largely be driven by the need of industries to decarbonize their production and to avoid rising CO_2 costs.

Second, hydrogen regulation will need to encourage the build-up of a European infrastructure that allows the physical transportation and trading of hydrogen to materialize. As discussed in more detail below, transporting hydrogen via pipelines is the most economical mode of transport for large-scale applications and long distance, but it creates a natural monopoly. It is likely that the majority of future hydrogen transport pipelines will be repurposed existing natural gas pipelines. Hence, regulation needs to address this aspect of hydrogen transport infrastructure, which would possibly lead to discrepancies with existing unbundling rules (see section 6). Additionally, hydrogen infrastructure would need to accommodate the transport requirements of a mature market in their lifetime, as pipeline assets typically have a long economic lifespan and high economy of scale.[41] As a result, initial transport infrastructure

[35] https://www.acer.europa.eu/gas/network-codes
[36] European Commission (2020b).
[37] European Commission (2020a).
[38] Regulation (EC) No 715/2009 (European Parliament and Council of the EU, 2009c) and Directive 2009/73/EC (European Parliament and Council of the EU, 2009b).
[39] Piebalgs et al. (2021).
[40] European Commission: 'IPCEIs on hydrogen': https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/ipceis-hydrogen_en
[41] In the EU, the average regulated lifetime of natural gas pipelines is 40 to 50 years. The expected commercial and technical lifetime of hydrogen pipelines is not determined as of now (Grote et. al, 2022).

would be oversized with regard to the still nascent transport volumes during the ramp-up phase of a European hydrogen market[42]. As discussed in section 6, this feature of the future hydrogen market needs to be reflected in its financing and investment schemes, and it could entail a funding structure quite different from existing models in the natural gas and power sectors. Moreover, existing EU funding and financing models, such as Projects of Common Interest (PCIs), could be updated and aligned with the requirements of a nascent hydrogen market. And thirdly, hydrogen regulation needs to encourage new players to join the market. Therefore, features of existing natural gas and electricity regulations can act as blueprints, for example with regard to third-party access (TPA) to the pipeline system[43].

5.2 Hydrogen transport

The second unique factor to consider when developing future European hydrogen transport regulation is closely linked to the previous section. Since a physical hydrogen market—in which the gas is sold, bought, and transported over long distances—does not exist, the technological aspects of its mode of transportation are somewhat undetermined. This differentiates hydrogen from natural gas, for which a pipeline-based cross-border infrastructure network already existed in Europe when a true European market was devised in the 1990s, rendering the question of transportation irrelevant.

Principally, hydrogen can be transported in different forms, for example via truck or ship in liquid form, in its gaseous state via pressurized pipelines, or as a chemical derivative such as ammonia, methanol, or methylcyclohexane (the latter is also known as liquid organic hydrogen carrier, LOHC). These modes of transport require a varying amount of energy intake for conversion, cooling, or pressurization, and are associated with transport energy losses (particularly transport of liquefied hydrogen) and transport costs (particularly high in trucks). They also require significant upfront infrastructure investments (pipelines). The infrastructure cost of each mode of transport results in a matrix of distances, in which the respective transport option is the most economical. For instance, for short distances up to 200 km and small quantities of up to 10 t/day, transport by truck seems to be the most cost-efficient option[44]. But for larger quantities and longer distances of up to around 3000 km, transport by pipeline appears to be the most economical mode, particularly when repurposed gas pipelines are used. A conversion into derivatives and subsequent transport via ship pay off when hydrogen is being transported over longer distances and across oceans, and where pipeline costs are too high[45].

Hence, for a cross-border hydrogen transportation system within Europe, pipelines are principally an economical mode of connecting supply and demand[46]. Therefore, if the principal mode of shipping hydrogen in a future European market will be via pipelines, rules and regulations for this evolving market will need to consider the specific characteristics of pipeline-bound transportation.

While policymakers and industrialists strive to ramp-up domestic hydrogen production, the EU will be a major importer of hydrogen in the future. The World Energy Council expects the EU to import as much as 80 per cent of its green hydrogen demand in 2030 and 50 per cent in 2050[47]. The above options for transporting hydrogen are also applicable to imports into the EU. Imports via pipelines, for example, could be an economical option for neighbouring regions such as North Africa and Eastern Europe, in cases where an existing natural gas pipeline connection can potentially be repurposed. With regard to long-distance imports from regions in which conditions for producing green hydrogen are more favourable than in Europe, ship-based transport of hydrogen in the form of derivatives (such as ammonia or methanol) seems to be the most economical mode.[48] Considering that part of hydrogen imports will arrive in the form of such derivatives, regulation needs to address related implications. For

[42] Piebalgs et al. (2021).
[43] Directive 2009/73/EC, Art. 32 (European Parliament and Council of the EU, 2009b).
[44] ACER (2021).
[45] Ortiz et al. (2021); ACER (2021).
[46] There are arguments that, if majority of future hydrogen pipelines will be repurposed natural gas pipelines that exist today, investment costs will be reduced (Piebalgs et al. 2021).
[47] European Commission (2021).
[48] For a detailed discussion of options for global hydrogen trade, see Patonia and Poudineh (2022).

example, clear definition and certification is required to ensure that derivatives are included in the calculation of European and national hydrogen import targets[49]. If the imported derivatives are re-converted into hydrogen, the legal status of converting facilities and operators could be aligned with unbundling and TPA rules in the case of market failures. Here, existing rules for liquefied natural gas (LNG) terminals could act as blueprint, but they would need to be adjusted and extended to hydrogen. Lastly, in situations where these derivative imports are not converted back into hydrogen, it remains to be determined whether the existing and future TPA rules and unbundling provisions should be extended to cover these derivatives. Implementing such measures would guarantee market players' access to these imports and align with the existing regulations governing LNG import terminals.

5.3 Nature of hydrogen production

Hydrogen, unlike natural gas which needs to be extracted, is a manufactured good. Hydrogen is produced from primary and other resources such as natural gas (grey, blue, and turquoise hydrogen); water and renewable electricity (green hydrogen); and more (e.g. waste and biogas). Its domestic production in the EU will be characterized by decentralization. This is particularly true for green hydrogen, for which the key primary resource—renewable power—will be even more widely available in the future. Despite the assumption that there will be considerable green hydrogen imports (see above), and a number of large-scale European production centres where conditions for renewable power production are most favourable (North and Baltic Seas, Mediterranean), small-scale and decentralized production will be spread all over Europe[50]. Already today, the plethora of planned production projects suggests distributed small-scale production sites in almost all EU countries[51].

The characteristics of European hydrogen production will somewhat resemble developments in the power sector over the past few years. With the increased harnessing of renewable energy sources, in particular via solar photovoltaic and wind parks, European power production is gradually shifting away from large and centralized power plants (such as coal combustion and nuclear) towards a decentralized system[52]. Domestic hydrogen production will most likely mirror the developments described. As noted above, currently, hydrogen is almost exclusively produced via SMR and ATR in industrial clusters. This concentrated production landscape will diversify substantially in the coming years. With increasing shares of green hydrogen production based on renewable power, smaller and distributed production sites are expected to emerge across Europe. However, large-scale green hydrogen projects (above gigawatt-sized) will materialize particularly where renewable power generation is most efficient, namely around the North and Baltic Seas and in southern Europe. Electrolysers will likely be located in areas either where renewable power is already being produced, or where conditions (wind, sun, space, local support) are favourable. As several anticipated electrolysis projects indicate, investors regard renewable power and hydrogen production as mutually reinforcing investments[53].

How should the nature of hydrogen as a manufactured good, and its likely decentralized production, be reflected in future regulation of a European supply industry? Two aspects come to mind: a precise TPA framework, and transparent and inclusive network planning.

A detailed TPA is crucial as it allows distributed producers and other network users to be connected to the future hydrogen grid. Taking as a starting point existing provisions in the European gas market regulations[54], TPA rules for the hydrogen grid need to effectively take into account the decentralized production landscape. In this context, elements of existing national regulations on network access for biomethane production could be used as a starting point. Biomethane is produced mainly in small-scale

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[49] See e.g. REPowerEU (European Commission, 2022b).
[50] ACER (2021).
[51] See the list of projects at 'Project pipeline of the European Clean Hydrogen Alliance': https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance/project-pipeline_en
[52] Crisan and Kuhn (2017).
[53] For example, see the planned Andalusian Green Hydrogen Valley project, for which 3 GW renewable power and 2 GW green hydrogen production investments are foreseen: https://www.cepsa.com/en/press/cepsa-will-invest-3-billion-euros-in-green-hydrogen
[54] cf. Regulation (EC) No 715/2009 and existing European network codes (European Parliament and Council of the EU, 2009c).

facilities in rural areas, and it can be injected in gas distribution and transmission grids. A number of EU member states[55] have in place provisions that guarantee biomethane producers access to the gas grid, for example via obligations for TSOs and distribution system operators (DSOs) to provide a connection point[56]. Similar rules at the European level can be implemented to ensure the future injection of distributed hydrogen production into the hydrogen grid.

The second aspect to reflect the characteristics of hydrogen production is transparent and inclusive network planning. If hydrogen producers know when and where hydrogen pipelines will be located and what costs to expect, they can take appropriate investment decisions. At the same time, the absence of enough hydrogen production facilities makes the investment in expansive hydrogen distribution networks uneconomical. This chicken-and-egg problem can be addressed through a combination of policy measures, strategic investments, research, collaboration, and market-driven approaches: for example, with regional or local hydrogen hubs where production, distribution, and consumption occur in close proximity. These hubs can be expanded or interconnected over time.

From the perspectives of both business strategy and overall efficiency, electrolysers should ideally be located in areas where renewable power is available, but also relatively close to existing hydrogen pipelines that connect import infrastructure with demand centres, for instance. The network planning processes at both national and European levels should be transparent and open to stakeholders. Once again, existing planning tools could be facilitated, further developed, and implemented in national and European regulation. In particular, existing national network development plans—the European Ten-Year Network Development Plan (TYNDP) and the Projects of Common European Interest (PCI) process—could be adapted to hydrogen. The difference from existing network planning processes in natural gas infrastructure is due to the decentralized feature of hydrogen production, to the expected wider range of stakeholders, and to a significantly higher degree of uncertainty. These aspects need to be firmly reflected in regulation from the beginning. Finally, hydrogen network planning should be closely aligned with electricity and, in a transitional phase, gas network planning to maximize synergies and reflect interdependence[57].

5.4 Demand sectors for hydrogen

The fourth unique factor to consider when creating hydrogen supply industry regulation is hydrogen demand structure. Since a current hydrogen market does not exist in Europe, organization of supply and demand is largely uncertain. As described above, hydrogen supply is likely to feature degrees of decentralization and small-scale production. In terms of demand, an initial concentrated consumer structure is likely to materialize in existing industrial hubs, which will subsequently and gradually diversify. Hydrogen will be used chiefly in hard-to-abate sectors and applications where a switch from fossil fuels to electricity-based solutions is not possible or economical[58].

The lead market for hydrogen in the EU will be the chemical industry, where blue and green hydrogen can have an immediate and significant decarbonization effect by replacing fossil-based hydrogen used in refineries, and by providing feedstock for ammonia and methanol production[59]. From a technological point of view, using green or blue instead of grey hydrogen is relatively straightforward, and does not require significant investments for the customer; the largest roadblock is the currently high price for green and blue hydrogen. Similarly, clean hydrogen is paramount for decarbonizing the European steel sector, which represents the fourth largest usage of hydrogen after refining and producing ammonia and methanol[60]. By applying the direct-reduced iron (DRI) method[61], fossil feedstock (coal, natural gas)

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55 Among them Germany, France, Hungary, Poland, and Ireland.
56 ACER (2020a).
57 Piebalgs et al. (2021).
58 IEA (2019).
59 European Commission (2020a).
60 European Commission (2020a).
61 Other production methods, such as blast furnace-basic oxygen furnace (BF-BOF) with hydrogen injection, also offer CO_2 savings. But if the EU's goal of climate neutraility by 2050 is to be achieved, the DRI method for steel making is considered the only viable long-term option (European Commission, 2020b; Wang et al. (2021).

can essentially be replaced with green or blue hydrogen, potentially extensively reducing CO_2 for steel making[62]. In turn, hydrogen demand for steel making is expected to increase sharply over the coming decades. According to one study, hydrogen demand for steel making will nearly triple from 2030 to 2040[63]. Therefore, the chemical and steel-making industries represent the largest sectors for the growing hydrogen demand in Europe, and will thus drive production, import, and transportation architecture.

Nevertheless, other sectors will further increase hydrogen demand. For instance, the EC expects the transport sector, particularly heavy-duty vehicles, to benefit from clean hydrogen's decarbonization potential[64]. In the medium term, hydrogen as an energy source presents a decarbonization pathway for industrial high-temperature demand, for example in glass, ceramics, bricks, and paper production[65]. Hydrogen will play a key role in the EU's electricity system. Increasing shares of intermittent and season-dependent renewable generation in Europe's power mix are necessary to achieve the EU's climate goals. Dispatchable and base load-capable electricity generation in the form of natural gas and other fossil fuel power plants will have to be gradually phased out. Both developments create a demand for hydrogen in the power sector. This is because hydrogen can offer efficient seasonal electricity storage, which directly or indirectly compensates seasonal renewable production (particularly solar photovoltaics). Additionally, hydrogen can be combusted in highly versatile turbines similar to existing gas power plants, providing balancing services and generation flexibility as well as baseload for the electricity system[66].

Another potential demand sector for hydrogen in the EU could be the heating of buildings[67], although it is subject to huge uncertainty. In its 2016 heating strategy, the EC prioritizes heat pumps, solar and geothermal as renewable sources for heating. This is largely due to these technologies' high energy efficiency[68]. The Commission aims to install an additional 10 million individual heat pumps from 2022 to 2027, and 30 million by 2030[69]. Already, between 2019 and 2021 the pace of installing heat pumps across the EU has reached a level that would achieve this goal[70]. Nevertheless, heat pumps work best in well-insulated buildings[71]. In older and not well-insulated buildings, efficiency advantages of heat pumps over different renewable heating solutions may dwindle. This is why a number of EU member states, in their respective national hydrogen strategies, consider hydrogen as an option for heating buildings to varying degrees. The German government, for instance, foresees a rather limited role for hydrogen in heating, for example in district heating[72]. The Dutch and Polish national hydrogen strategies, on the other hand, envision a substantial role for hydrogen in decarbonizing the heating of buildings[73]. As a result, future demand for hydrogen in the EU heating sector will vary from one member state to another, and will be characterized by a substantial degree of uncertainty. For 2050, demand scenarios for hydrogen in the heating sector range from virtually zero[74] to 600 TWh.[75]

To sum up, the future demand sectors for hydrogen will differ from the current natural gas demand sectors. Remarkably, steel-making and heavy-duty transport will represent higher shares of hydrogen demand than they currently demand from natural gas. The heating sector, in contrast, will play a less prominent role in future hydrogen demand. In terms of hydrogen transport infrastructure, the described demand structure will have an impact on infrastructure requirements. The sectors primarily driving

[62] IEA (2019); Patisson and Mirgaux (2020).
[63] From 55 TWh/year in 2030 to 143 TWh/year in 2040 (Wang et al., 2021).
[64] European Commission (2020a).
[65] IEA (2019).
[66] European Commission (2020a); Wang et al. (2021).
[67] European Commission (2020a).
[68] European Commission (2016).
[69] European Commission (2022b).
[70] Lyons et al. (2022).
[71] European Commission (2016).
[72] BMWI (2020).
[73] Government of the Netherlands (2020); Ministry of Climate and Environment Poland (2020).
[74] Agora Energiewende (2021).
[75] Wang et al. (2021).

demand in the coming years up to 2030—chemical industries and steel making—are typically large-scale and concentrated facilities. As a consequence, a hydrogen pipeline network, partially based on repurposed natural gas pipelines, would initially connect these relatively few demand centres with hydrogen production clusters and import points, resulting essentially in a rather centralized European grid. From 2030 to 2040, hydrogen demand is expected to diversify to the other sectors discussed above, leading to decentralization of hydrogen infrastructure[76]. Despite the temporal aspect of European hydrogen transport infrastructure, a robust regulatory framework would need to be established during the market ramp-up. This is mainly because of the particular cost recovery issues the hydrogen grid faces, as discussed in section 6.

This section has outlined a number of factors and constraints that are particular to the future European hydrogen market. The analysis presents a set of features that needs to be considered when creating a regulatory framework for hydrogen transport infrastructure. To begin with, a hydrogen market is non-existent. Hence, the ramp-up of both production and demand needs to be facilitated by infrastructure investments. As noted above, it is likely that the most economical mode of transporting hydrogen across Europe will be via pipelines. As a result, natural monopolies will emerge, and they need to be regulated. Similarities to existing European natural gas and electricity regulation do exist. Since hydrogen is a manufactured good, European domestic production will be partly decentralized. Notwithstanding significant hydrogen imports and large-scale production in the EU's periphery, the expected emergence of small-scale hydrogen production requires stringent TPA rules and oversight of monopolies in grid and storage infrastructures. Hydrogen network planning requires high levels of transparency and participation, as well as close links to planning processes in electricity and natural gas. Yet, existing institutions and instruments, such as the TYNDP and PCI process, can be used as a blueprint. Finally, hydrogen demand will initially be driven by the steel and chemical industries. Subsequently, heavy duty transport and power generation will present considerable demand sectors. This particular demand structure may have an impact on required hydrogen infrastructure investments. The following section scrutinizes how these elements, together with existing conflicts in European energy policy in the light of shifting political driving forces, can be reflected in a future hydrogen supply industry regulation.

6. Regulatory considerations for the future hydrogen supply industry

The previous section outlined the particular environment and unique conditions under which an EU hydrogen supply industry regulation is to be created. To recall, the central political motivations behind the establishment of a European hydrogen economy are sustainability and security of supply. To that end, the conditions and parameters for conceiving a functioning, physical hydrogen market in the EU differ substantially from the circumstances that characterized the establishment of current gas and power markets. To elaborate, the reforms that almost took two decades to mould the regulated parts of gas and power markets into their current form have been chiefly driven by the EU's overarching strategic goal of liberalization and the associated creation of a European market[77]. In the case of hydrogen, sustainability and security of supply are policy goals that require swift realization: the EU's target of being climate-neutral in 2050, in which hydrogen is to play a central part, demands a steep reduction in greenhouse gas emissions until 2030[78]. Additionally, Russia's invasion of Ukraine in February 2022 has invoked in policymakers an unparalleled urgency for improving security of energy supplies[79].

The analysis above has also shown that a set of unique factors has to be considered when creating regulation for the hydrogen supply industry. For instance, a hydrogen market does not exist yet, and future domestic production in the EU will be partly decentralized. Additionally, the future hydrogen market will be closely intertwined with its electricity counterpart, so close coordination is required.

[76] van Rossum et al. (2022).
[77] McGowan (1993); Schmidt (1998); Schubert et al. (2016).
[78] European Commission (2021).
[79] Tubiana et al. (2022).

This section explores different regulatory provisions that emerge from the observations above. On one hand, a number of principles of existing natural gas and electricity regulations can be adapted or taken as a blueprint for hydrogen. On the other hand, new elements are necessary that particularly reflect the adjusted EU policy goals and unique aspects of regulating the hydrogen supply industry. After discussing both sets of regulatory aspects, we combine them and summarize the implications for future hydrogen regulation.

6.1 Elements of existing regulations

As outlined in section 5, a number of differences exist between the European gas and electricity markets and the future hydrogen market. However, despite these differences, given the network-based nature of the hydrogen industry, it is possible to utilize some elements of natural gas and electricity networks' regulations for the future hydrogen market's regulations. Here, two principal concepts and their respective sets of rules and institutions stand out in terms of their significance for a successful hydrogen ramp-up. First, the concept of network access; second, what is termed here European coordination. Elements of the future hydrogen supply industry that are not subject to natural monopolies are discussed at the end of this subsection.

6.1.1 Network access

Non-discriminatory access to networks is a policy instrument to counter the adverse effects of natural monopoly, which evolves in grid-based energy transport systems such as power grids and natural gas pipelines. To that end, network access rules were, and still are, a cornerstone in the EU's ambition to liberalize the natural gas and electricity market[80]. In the context of hydrogen, this is important because it is likely that the economical means of transporting hydrogen within the EU would be via an interconnected pipeline system, implying that a large portion of future hydrogen transport infrastructure will constitute a natural monopoly. In this context, network access is relevant for the future hydrogen market and should be guaranteed for market participants such as producers, consumers, and shippers. As the domestic hydrogen production landscape will be characterized by a high degree of decentralization (see 5.3), it is crucial that small-scale producers gain access to the EU hydrogen grid. This will foster the ramp-up of production in the EU and thus help achieve the underlying goal of sustainability by creating green hydrogen production capacity. Shippers of hydrogen, too, require non-discriminatory access to hydrogen infrastructure as they are market players who guarantee effective trading across Europe, thus matching supply and demand. Network access provisions need to apply not only to transport infrastructure, but also to storage and import infrastructure. In this regard, existing framework rules on TPA, in the form of EU regulations that govern access to gas and electricity networks[81], can be applied to hydrogen. Moreover, the respective concrete rules that have been manifested in natural gas and electricity network codes, may be extended to hydrogen. For natural gas and electricity, these rules have been developed by the European Network of Transmission System Operators for Gas (ENTSOG) and the European Network of Transmission System Operators for Electricity (ENTSO-E)[82]. A similar European network for hydrogen TSOs is needed to establish technical rules for the European hydrogen market, such as network access. The potential design of such an institution is discussed below. Existing rules for biomethane at member state level could be used as a starting point for hydrogen network access: hydrogen network operators could be obliged to provide a network connection point to hydrogen producers (if technically feasible and economically reasonable).

Clear and transparent rules for network access enable a wide range of players to participate in the European hydrogen market. As a result, the strategic policy goal of increasing security of supply is also strengthened. This is because the easier it becomes for small-scale distributed hydrogen producers in

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[80] De Hauteclocque and Talus (2011).

[81] Regulations of the European Parliament and of the Council 715/2009/EC and 714/2009/EC, respectively.

[82] A process for which the Agency for the Cooperation of Energy Regulators (ACER) established binding framework guidelines, see Regulation (EC) No 715/2009, Art. 6.

the EU to participate in the market, the fewer hydrogen imports are required. With regard to hydrogen demand, network access rules give off-takers the chance to source hydrogen from grid infrastructure. In combination with increasing production capacities and, thus, greater volumes of tradable hydrogen, a wide array of consumers are able to decarbonize their processes. In turn, this contributes to the strategic policy goal of sustainability. A diversified stakeholder landscape across hydrogen production, shipping, trading, and demand boosts system resilience against market disruptions.

Consequently, guaranteed non-discriminatory network access not only strengthens a functioning hydrogen market by allowing a wide array of players to compete, it also creates synergies with sustainability and supply security goals.

6.1.2 European coordination

Establishing the European hydrogen economy is a European project. Hence, when policymakers think about the distinctive elements of the future hydrogen economy, including the creation of a functioning market, taking a European perspective from the start is imperative. As discussed above, the energy sector in the EU has undergone a remarkable Europeanization over the past 30 years[83]. Core policy instruments in this development were the EU's three liberalization packages for electricity and natural gas. It is argued here that a number of existing provisions on European coordination should be utilized to foster the establishment of a European hydrogen economy as well.

A central element of the EU's 2009 third liberalization packages for electricity and natural gas was the creation of the European Networks for Transmission System Operators, ENTSO-E (for electricity) and ENTSOG (for natural gas). Essentially, these associations' task is to foster the functioning and competition of European markets for electricity and gas. They do so by means of enabling physical interconnections between member states, and by developing technical and commercial rules, for example with regard to network access[84]. A fundamental tool used by both ENTSO-E and ENTSOG is network planning via scenario development. In their two-yearly TYNDP, the two associations analyse future infrastructure needs. Since 2018, this exercise has been conducted jointly between the two organizations in order to develop a holistic projection of the future European energy system[85]. These associations are central actors with regard to liberalization and Europeanization in the electricity and gas sectors. Due to the close collaboration between the two organizations, the TYNDP also provides a general picture of the infrastructure requirements of Europe's future energy system. Based on regulation regarding trans-European networks for energy[86], the TYNDP also forms the basis for EU funding and financing of European energy infrastructure. PCIs, defined in the TEN-E regulation, are one of the EU's most powerful tools to foster cross-border infrastructure investments in electricity and gas. By providing financing and funding to project promoters as well as a streamlined permitting process, PCIs ought to accelerate European network integration and the functioning of electricity and gas markets[87]. In order for infrastructure projects to receive PCI status, they first have to be included in the TYNDP's project list that identifies the infrastructure investments that are essential for achieving the EU's energy policy goals[88].

Although set up by EU legislation, neither ENTSO-E nor ENTSOG is an EU institution. Instead, they are member-based organizations that bring together TSOs in electricity and gas from EU member states as well as from European neighbourhood countries[89]. As such, they pool technical expertise and, as consultative committees[90], support the European Commission (the principal actor in EU energy policy) in its pursuit of energy policy goals[91]. Consequently, ENTSOG and ENTSO-E are institutionally well

[83] Buchan and Keay (2015).
[84] Schubert et al. (2016).
[85] ENTSOG and ENTSO-E (2018).
[86] TEN-E Regulation No. 347/2013, European Parliament and Council of the EU (2013).
[87] Buchan and Keay (2015).
[88] Scheibe (2018).
[89] ENTSOG: https://www.entsog.eu/members; ENTSO-E: https://www.entsoe.eu/about/inside-entsoe/members/
[90] Richardson (2006).
[91] Buchan and Keay (2015).

embedded in European policymaking. Processes in both organizations feature transparency and stakeholder participation, for example in the scenario development process.

The existing institutions, protocols, and rules concerning European coordination and network planning for electricity and natural gas present an invaluable foundation upon which a European hydrogen market can be built. Given the intricate interrelations among electricity, natural gas, and hydrogen, capitalizing on the aforementioned processes and existing organizations can be instrumental in crafting a coherent and effective European hydrogen market.

There are undeniable parallels between the natural gas industry and the emerging hydrogen sector, especially considering that a significant portion of future hydrogen pipelines may likely evolve from repurposed natural gas pipelines[92]. However, it is imperative to recognize that while many of today's natural gas TSOs might transition into hydrogen network operators due to evident synergies, the landscape remains open for various new players and non-traditional entities to have significant roles. Thus, while ENTSOG currently unifies gas TSOs to pinpoint infrastructure necessities and establish technical guidelines for an efficient market, its future role in the hydrogen domain is not set in stone.

There are multiple reasons for this. First, the scale and makeup of the future hydrogen network remain uncertain, and its evolution might witness a multitude of players from diverse sectors. Second, while there are indeed synergies, the technical, regulatory, and market dynamics of hydrogen are unique and may demand specialized knowledge and strategies.

Nevertheless, should ENTSOG transition into managing future hydrogen transport infrastructure, it could utilize its established processes, such as data collection, modelling, and expertise in network codes, to expedite the adoption of regulations and network planning tools for hydrogen. Such a proactive approach could be beneficial, especially in the early stages of establishing a European hydrogen market, identifying cross-border infrastructure necessities, and formulating market rules.

Regardless of the entities that eventually own and operate hydrogen infrastructure, insights from the joint network planning of gas and electricity networks by ENTSOG and ENTSO-E can provide valuable lessons and best practices to ensure efficient coordination, stakeholder engagement, and effective market operation.

6.1.2.1 Network planning

When it comes to network planning of future hydrogen transport infrastructure, close coordination with ENTSO-E is necessary. This is because strong interdependencies between electricity and hydrogen will emerge that require integration of the two systems. Green hydrogen production in the EU via electrolysis will represent a considerable part of overall renewable electricity demand. For example, replacing the Union's current (predominantly grey) hydrogen production with green hydrogen would require approximately 10 per cent of the EU's total electricity production[93]. Already by 2030, hydrogen demand in the EU is expected to increase significantly, and will continue to do so until 2050[94]. Hence, it is key to establish close collaboration between the electricity and hydrogen sectors, particularly with regard to electricity supply from renewable sources and demand from electrolysers. Integrated network planning, therefore, presents a powerful tool to increase overall energy system efficiency and resilience. In this context, the TYNDP process could be used a starting point for an overarching energy system modelling tool featuring electricity, natural gas, and hydrogen. Common scenarios of a future integrated European energy system can provide essential information on infrastructure needs and present a tool to cope effectively with high levels of uncertainty, particularly at the early stage of a hydrogen market ramp-up. Consequently, integrated network planning and financial instruments could be based on these integrated scenarios. In fact, European policymakers already recognize the value of integrated network planning for a future hydrogen grid: the 2022 revision of the TEN-E regulation includes hydrogen

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[92] Piebalgs et al. (2021).
[93] Kakoulaki et al. (2021).
[94] See e.g. Blanco et al. (2018); Kakoulaki et al. (2021).

infrastructure and electrolysers, and aims to leverage synergies[95]. Thus, also the PCI-process, which offers funding, financing, and permitting benefits, is accessible for hydrogen infrastructure projects[96]. The TYNDP and PCI processes could act as enablers of integrated energy infrastructure investments.

At the same time, it is essential to address the inherent uncertainty associated with forecasting supply and demand for hydrogen. Building an extensive hydrogen network without sufficient assurance of future hydrogen production and consumption could result in underutilized infrastructure. Conversely, a lack of network coverage could impede the development of a future hydrogen economy. Striking the right balance is crucial to avoid both scenarios. Therefore, uncertainty needs to be explicitly considered in hydrogen network planning to ensure that infrastructure investments are robust and aligned with actual market needs.

One approach to address uncertainty in hydrogen network planning is through scenario analysis. By developing multiple plausible scenarios of hydrogen supply and demand, taking into account different technological, economic, and policy factors, network planners can gain insights into potential future outcomes. These scenarios can be used to assess the range of infrastructure requirements under different conditions, helping to identify flexible and scalable solutions. Sensitivity analysis can also be conducted to test the robustness of infrastructure plans against varying assumptions and market conditions. The TYNDP framework constitutes a possible blueprint for conducting such complex scenario analysis, and could be leveraged to address uncertainty in European hydrogen network planning.

Another solution is to adopt a phased and adaptive approach to network development. Instead of building a vast network all at once, infrastructure can be deployed incrementally based on the evolving market dynamics and technological advancements. This phased approach allows for course corrections and adjustments as new information and market developments emerge, minimizing the risk of overbuilding or underinvestment.

Close engagement and collaboration with stakeholders is vital in addressing uncertainty in hydrogen network planning. By involving a wide range of actors, including decentralized hydrogen and electricity producers, storage operators, consumers, import infrastructure operators, shippers, as well as NGOs and civil society groups, the planning process can benefit from diverse perspectives and insights. Stakeholder participation fosters transparency, knowledge sharing, and a better understanding of the evolving market dynamics, leading to more informed decision-making and infrastructure development that aligns with the needs of all stakeholders. Ultimately, the direct involvement of EU member states could create a platform for strategic planning. Bearing in mind the creation of an EU-wide hydrogen market, such a platform could address potentially diverging national interests as well as cross-border collaboration at a political level. The described modes of stakeholder participation, including at member state level, could conceivably be integrated and further developed in existing formats within the TYNDP framework to achieve comprehensive stakeholder participation in hydrogen network planning.

In summary, uncertainty plays a significant role in hydrogen network planning. Striking a balance to avoid both overinvestment and underinvestment requires robust methodologies, scenario analysis, adaptive planning, and stakeholder engagement. By incorporating these elements into the planning process, the development of a future-proof hydrogen infrastructure can be achieved, facilitating the growth and integration of hydrogen into the broader European energy system. Integrated network planning featuring effective stakeholder participation will offer a holistic view on a future European hydrogen market, thus fostering a fit-for-purpose infrastructure development.

6.1.2.2 System integration and market mechanisms

Another aspect to be considered is system integration and stability. Beyond green hydrogen production being a significant demand sector for renewable electricity in the future, hydrogen can act as a seasonal

[95] European Parliament and Council of the EU (2022).

[96] For instance, Fluxys and Gascade, two natural gas TSOs, have applied for PCI-status for an off-shore hydrogen pipeline project (Fluxys, 2023).

storage vector for renewable electricity and also provide network services. By producing hydrogen from renewable electricity, this electricity essentially can be stored at a large scale and over long periods of time. Using hydrogen or ammonia as energy carriers can offer certain advantages over battery storage for medium- to long-term energy storage. Additionally, natural salt caverns in Europe present a potential option for large-scale hydrogen storage[97]. When renewable electricity production is low (in winter), the stored hydrogen can be re-converted into electricity, either in a combined-cycle gas turbine (CCGT) or via fuel cells, thus providing electricity[98]. Alternatively, the stored hydrogen can be used to satisfy hydrogen demand, thus replacing ongoing hydrogen production elsewhere and decreasing electricity demand (for example at times when renewable power generation is low).

The second aspect concerns grid services. Hydrogen can provide dispatchable electricity generation via hydrogen-fired power plants, and thus can play a role in renewable peak load generation and electricity network balancing[99]. Moreover, hydrogen production capacity can be deployed to avoid curtailment of renewable power generation[100]. This increases overall energy system efficiency as renewable power waste is minimized, also contributing towards the overall policy goal of sustainability. In order to mitigate risks and exploit synergies stemming from the interdependencies between electricity and hydrogen, resilient European market mechanisms for both electricity and hydrogen need to be established. In this context, close collaboration and coordination between ENTSO-E and the future European network of hydrogen system operators will be key. The two institutions ought to commonly address challenges and opportunities at the European level, starting from an early stage of the hydrogen ramp-up.

To sum up, European coordination, close alignment, and (where possible) integration of European network planning for natural gas, electricity, and hydrogen will be needed. Beyond that, common goals, as well as commonly developed market mechanisms and rules that address all three sectors, will foster the establishment of a European hydrogen market and overall system integration. The development of hydrogen infrastructure should be institutionally embedded at the European level. Here, ENTSOG can be utilized as a blueprint. Harnessing the synergies of comprehensive system integration at European level will essentially support the overall policy goal of sustainability: they enable a quick market ramp-up for hydrogen and foster the further roll-out of renewable power generation (for example through curtailment prevention). Ultimately, an integrated European energy system will be more resilient against disruptions and will thus boost security of supply, the second strategic European energy policy goal[101].

6.1.3 Liberalization of non-monopoly elements

The three past liberalization packages for natural gas and electricity established market principles in the European energy sector. Liberalization efforts were focused on those parts of the energy value chain where competition, in principle, is possible and economical. Most notably, this includes production, demand, trading, and sales. Notwithstanding these aspects, the grid-bound transport of both electricity and natural gas presents a natural monopoly (the same is likely to be true for large-scale natural gas storage). Hence transport, rather than being liberalized, is subject to regulation and oversight. Many of the aspects discussed above, including network planning and the requirement for transparency, are elements of this regulatory framework. As discussed above, a number of existing instruments can also be applied to hydrogen transport infrastructure.

Similarly, those aspects of a future hydrogen market that are not connected to natural monopolies could conceivably be liberalized. Once again, mirroring existing provisions for electricity and natural gas could be a starting point. Production, demand, trading, and sales of hydrogen could be subject to European competition rules. This is in line with the Union's conviction that competition in liberalized energy

[97] IEA (2019).
[98] However, the overall efficiency of turning electricity into hydrogen and back into electricity amounts to approximately 40 per cent, meaning that 60 per cent of the initially produced electricity is lost (IEA, 2019).
[99] IEA (2019).
[100] Ruggles et al. (2021).
[101] Varro and Zinglersen (2021).

markets increases efficiency and drives down prices for consumers[102]. Nevertheless, this is notwithstanding public support schemes at both the national and European level to boost hydrogen production and demand. Potential instruments are discussed below.

6.1.4 Elements of existing regulations—summary

The provisions described above are directly derived from existing EU natural gas and electricity regulations. They have a clear focus on market liberalization and Europeanization. First, guaranteed network access prevents potentially discriminatory practices of monopolistic hydrogen network operators. Second, comprehensive European coordination fosters the build-up of a functioning European hydrogen market and physical cross-border interconnections. And third, non-grid elements of the hydrogen value chain (production, demand, trading, sales) could conceivably be liberalized. Although aiming primarily at the policy goal of market liberalization, all three elements also foster both security of supply and sustainability. This is because of direct and indirect synergies between the three strategic goals of EU energy policy. To elaborate, network access, European coordination, and competition reinforce the future hydrogen economy's resilience—through enabling more actors to partake in business activities, and through a physically interconnected market. Thus, security of supply is strengthened. Additionally, the three elements described above favour the timely progress of a European hydrogen economy. In particular, guaranteed network access enables decentralized production and consumption, thereby increasing overall supply and demand. Establishing an interconnected European hydrogen grid helps to link hydrogen production (for example, in the European periphery) with demand centres in central and western Europe. Finally, competition ought to lower hydrogen end-use prices. In turn, consumers will have a greater incentive to decarbonize via use of hydrogen, directly contributing to the EU's sustainability goal.

These provisions should arguably be included in hydrogen infrastructure regulation as they contribute to all three strategic goals of EU energy policy, and are key for the development of a hydrogen market within the timeframe required to meet net zero carbon objectives.

6.2 New regulatory elements—departure from the standard form of liberalization?

The liberalization and regulatory reforms that transformed the European gas and electricity markets in the 1990s and 2000s addressed mature (national) markets with established actors. In this context, the far-reaching reforms aimed to allow new players to enter the market, enable European competition, and provide transparency for consumers. Arguably, unbundling and network infrastructure financing through regulated tariffs are among the sternest elements of the liberalization packages. Highly contested, a political agreement on these regulations could only be reached after almost two decades of decision-finding between the European Commission, European Parliament, and member states[103]. Central among unbundling rules was that vertically integrated energy companies were obliged to separate their transmission business from generation and retail operations[104]. The EC's goal was to prevent established energy companies from using their natural monopoly status in transmission to shut out competitors and undermine competition. As a result, TSOs became independent companies (to varying degrees, see below) which were subject to EU regulation[105].

Another crucial aspect introduced by the liberalization packages was the cost recovery of transmission infrastructure via dedicated network tariffs. Essentially, TSOs finance their infrastructure through transparent tariffs that are subject to oversight by the national regulatory authority[106]. The goal of this provision was to provide transparent and non-discriminatory pricing for transmission network users.

[102] Schubert et al. (2016).
[103] Schubert et al. (2016).
[104] European Parliament and Council of the EU (2009b), Art. 9.
[105] Buchan and Keay (2015).
[106] European Parliament and Council of the EU (2009c), Art. 13.

The unbundling and financing reforms in the gas and electricity sectors were driven primarily by the political/economic objective of promoting liberalization and establishing a unified European energy market [107]. However, it remains uncertain whether the existing provisions on unbundling and infrastructure financing in the gas and electricity sectors can be directly applied to regulate hydrogen transport infrastructure. This is because the hydrogen industry does not enjoy the same level of user base and infrastructure as the gas and electricity sectors. This raises the question of whether copying and implementing these rules for hydrogen infrastructure could potentially compromise the reinforced considerations of sustainability and security of supply that are closely associated with the timely expansion of the hydrogen economy.

It is argued that a cautious approach is necessary when adapting unbundling and financing rules from the gas and electricity sectors to the regulation of hydrogen infrastructure. Simply replicating the existing provisions without considering the unique characteristics and requirements of hydrogen could undermine the objectives of sustainability and security of supply, which are essential for a successful and smooth transition to a hydrogen-based energy system. Therefore, regulations specifically tailored to hydrogen infrastructure should be developed, taking into account the strategic goals of sustainability and security of supply, as well as the specific factors discussed in section 5.

6.2.1 Unbundling

The development of future hydrogen networks presents an opportunity for creating an independent infrastructure that may or may not evolve from existing natural gas networks. While there are economic and technical reasons to consider the existing natural gas network operators as potential future operators of hydrogen transport infrastructure, alternative options also exist. For example, new independent entities could emerge to operate the hydrogen networks. These could range from new commercial ventures to public or community-owned utilities.

If a significant portion of European future hydrogen transport infrastructure is expected to utilize repurposed existing natural gas pipelines[108], the involvement of today’s natural gas network operators may be a practical strategy in driving hydrogen infrastructure investments and operations. However, it is essential to emphasize that other models could also be viable and effective. New operators, potentially arising from various sectors and not necessarily from the natural gas industry, could bring fresh perspectives, innovation, and competition into the hydrogen infrastructure landscape.

Furthermore, it is important to highlight that careful consideration must be given to the necessary adaptations and regulatory frameworks required for safe and effective hydrogen transport, given the specific characteristics of hydrogen as an energy carrier. For any entity, whether a natural gas TSO or a new independent operator, to leverage potential synergies, and thereby contribute to both EU sustainability and security of supply ambitions, appropriate unbundling provisions need to be in place.

Unbundling refers to the separation of energy production, transport, and distribution within an energy supply chain. In essence, it means that the entities responsible for producing the energy are different from those responsible for transporting and distributing it to the end-users. This is to address market failures, related information asymmetry, and market power of natural monopolies. In the established industries, such as natural gas and electricity, the primary aim of unbundling is to increase competition, reduce market power, provide transparency, and stimulate innovation.

However, for a nascent industry like that of hydrogen, unbundling might need to take a different form. Especially in the early stages, setting up a hydrogen infrastructure is capital-intensive. Allowing for less stringent unbundling could help entities benefit from economies of scale, lowering the financial barriers to entry, spreading the risk across the supply chain, and consequently encouraging initial investment and speeding up implementation.

[107] Barnes (2023).
[108] Piebalgs et al. (2021); Wang et al. (2021).

Therefore, unbundling rules for hydrogen would need to encompass two key aspects. First, to the extent that future hydrogen infrastructure will be repurposed gas pipelines, existing gas network operators that are eligible need to be authorized to transition into hydrogen TSOs and, at least for a transitional period, potentially need to be able to operate natural gas grids and hydrogen grids simultaneously (horizontal unbundling). Second, future hydrogen TSOs, whether evolved from natural gas TSOs or newly formed entities, might need to be permitted, under strict transparency rules and at least during the transition, to be part of vertically integrated energy companies (vertical unbundling).

6.2.1.1 Horizontal unbundling

The journey towards a robust hydrogen infrastructure is multi-faceted and poses diverse possibilities for TSOs. While traditional TSOs with a natural gas background could leverage their deep-seated expertise, a notable regulatory hurdle exists for natural gas TSOs to also become hydrogen network operators. Current EU energy transport regulations do not permit the simultaneous management of multiple grid-bound energy carriers under one TSO[109]. Rooted in the principles of liberalization, this stance primarily aims to deter monopolistic structures and their undue influence[110].

Yet, considering the nascent stage of the European hydrogen economy, arguments can be provided for allowing dual management of both natural gas and hydrogen infrastructures by a single TSO, under conditions where it makes sense for natural gas TSOs to transition to hydrogen network operators. Such an adaptive regulatory approach might hasten the maturation of the hydrogen market. It could also foster more integrated national and European network planning, harmonizing diverse energy carriers. In this scenario, TSOs, along with a broader consortium of stakeholders, could formulate a comprehensive transition strategy that aligns the establishment of European hydrogen transport infrastructure with the larger goals of European energy transformation.

However, joint operation is not without its complexities. While it offers system efficiency advantages, it is vital to ensure fair competition. It necessitates rigorous transparency rules, safeguarding against any monopolistic tendencies or discriminatory practices. In this context, national regulatory authorities, alongside institutions like the Agency for the Cooperation of Energy Regulators (ACER), could refine existing mechanisms, such as TSO reporting guidelines, to ensure compliance.

Although existing natural gas TSOs have a wealth of experience that could be tapped into for a seamless evolution from natural gas to hydrogen transport systems, the European landscape could benefit from the introduction of new, specialized hydrogen TSOs or other entities. These fresh players might bring innovative strategies, technological advancements, or unique operational models that could accelerate the development and adoption of hydrogen infrastructures.

Overall, the pivot towards establishing a hydrogen economy from scratch in the EU signifies more than just technological transformation. It echoes a broader strategic shift—from a purely liberalization-driven approach to unbundling rules, to one that is also in line with sustainability and security objectives. Embracing alternative models to horizontal unbundling could be key to navigating this transformative period effectively.

6.2.1.2 Vertical unbundling

As discussed above, in the three energy liberalization packages the European Commission pushed for strict separation of different elements of the value chain through vertical unbundling[111]. As the EC's ambitions were contested by a number of member states, the final compromise resulted in three different unbundling options for vertically integrated energy companies: the ownership unbundling model (OU, the EC's preferred model in terms of liberalization); independent system operator model

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[109] Notable exceptions include the national TSOs of Luxembourg (Creos) and Denmark (Energinet), which both operate electricity and natural gas transmission grids.

[110] In the United Kingdom, however, establishment of a public future system operator (FSO) is being discussed by policymakers and regulators. The FSO would have responsibility across electricity, gas, hydrogen, and CO_2 networks. The underlying idea is that such an operator could leverage existing synergies and effectively coordinate strategic systems planning (Ofgem, 2023).

[111] Schubert et al. (2016).

(ISO); and independent transmission operator model (ITO), for which member states had pushed. Essentially, the three models describe varying degrees of unbundling from which member states could choose. The OU model features the strictest rules, where an investor that owns majority rights of a TSO might not be engaged in undertakings that operate in different parts of the energy value chain (such as sales or distribution). Ownership unbundled TSOs are often state-owned[112]. The ISO model demands strict separation between ownership and operation of the grid. Finally, TSOs unbundled according to the ITO model are independent companies, own the grid they operate, and are autonomous in their business decisions. However, they may be owned by companies and investors that are engaged in other parts of the value chain and are subject to compliance programmes and oversight[113]. In the natural gas sector today, all these unbundling models are represented in the EU, with OU and ITO being the majority. According to the Council of European Energy Regulators (CEER), all three unbundling models are deemed to be largely successful in their ambition to increase competition and transparency in electricity and natural gas markets[114].

It is argued here that for successful deployment of a physical European hydrogen market, the existing unbundling models should also be applied to future hydrogen transmission operators. This becomes particularly important if it is found that leveraging synergies between natural gas and hydrogen transport infrastructure can reduce investment costs. In this context, the ITO model is of particular interest. To elaborate, almost half (44 per cent) of European natural gas TSOs are certified as ITO[115]. Companies and investors that own these TSOs are typically also engaged in other parts of the gas value chain. Therefore, it is plausible to assume that owners will also engage in the future hydrogen value chain. For instance, as discussed in section 5, hydrogen is a manufactured good, and it can be expected that the production landscape in the EU will be largely decentralized. As result, owners of TSOs may conceivably aim to invest in decentralized hydrogen production. Under the current ITO model this would be authorized, as long as independence of the TSO and oversight is guaranteed.

However, if an ITO certification for hydrogen TSOs were not feasible, the discussed synergies between natural gas and hydrogen might not be facilitated. To elaborate, if the owner of a natural gas TSO invests along the hydrogen value chain, it would not be feasible for that TSO to repurpose its natural gas assets for the transport of hydrogen and become a hydrogen transmission operator (see discussion above). Instead, hydrogen transport infrastructure would need to be sold to an investor outside the vertically integrated energy company of which the gas TSO is part. Consequently, the incentive for this particular TSO to invest and transform its assets for hydrogen transport is eliminated[116]. This issue concerns 19 ITO-TSOs, of which 11 are located in Germany. Arguably, if an ITO certification for hydrogen transport operators is not feasible, these TSOs would be unlikely to invest in hydrogen infrastructure.

In the case of gas and electricity unbundling rules, the European Commission initially favoured strict ownership unbundling in line with its liberalization goals[117]. The choice of an appropriate unbundling approach necessitates a delicate balance between coordination and competition. In the gas and electricity sectors, given the industry's developmental stage, competition was deemed paramount. However, in the case of hydrogen, greater emphasis should be placed on the scaling-up of production and infrastructure, which demands a higher degree of coordination. Consequently, the ITO model should form an integral part of the future hydrogen unbundling regime. This approach is likely to provide a better balance between coordination and competition, given the stage of the hydrogen supply industry.

[112] Nationaler Wasserstoffrat (2022).
[113] For a detailed description of unbundling models, see European Commission (2010).
[114] CEER (2019).
[115] CEER (2016).
[116] Nationaler Wasserstoffrat (2022).
[117] Opposition from member states resulted in creation of the ITO model as a compromise (Buchan and Keay, 2015).

6.2.2 Cost-recovery of hydrogen infrastructure

The unique condition of a virtually non-existent market for hydrogen poses a challenge for financing transport infrastructure. At the core of this challenge lies the fact that, during the market ramp-up, the number of hydrogen customers will be small and infrastructure investment needs will be uncertain. In this context, the existing regulated cost-recovery regime for natural gas pipelines is insufficient. Today, gas network tariffs are the main instruments for cost allocation and recovery of transport infrastructure. They have to be cost-reflective, transparent, and non-discriminatory[118]. Essentially, network users pay for the network costs: in simplified terms, a TSO's costs for operating and maintaining the grid, plus a determined regulatory profit, are added up and then allocated to all network users. Monitored by national regulators, all cost parameters and resulting network tariffs are reviewed regularly. This principle was introduced in the EU's liberalization packages[119] and applied to mature natural gas markets featuring existing infrastructure and an established customer landscape. In contrast, in the case of a hydrogen, neither transport infrastructure nor suppliers and customers exist yet. Hence, a similar regulatory cost-recovery regime cannot be applied to a nascent hydrogen market. Taking into consideration the decarbonization potential and ensuing demand in the coming decades, a European hydrogen grid would need to be designed from the beginning so as to meet this future demand[120]. As a result, few early customers would potentially face extremely high network tariffs, as they would essentially pay for a large future grid. Thus, potential customers would be dissuaded from using hydrogen, effectively delaying market ramp-up[121]. Ultimately, TSOs and investors would also hesitate to invest in hydrogen infrastructure as remuneration is uncertain.

How, then, to sufficiently finance infrastructure for ramping up the EU hydrogen market? Different cost-recovery mechanisms, in principle, qualify for triggering sufficient investment in order to swiftly build up a European hydrogen grid. Nevertheless, all models part with the concept of cost-reflectivity and/or require different degrees of public intervention.

One approach is to fully or partially merge gas network tariffs with hydrogen network tariffs. By aggregating network costs for natural gas with costs from building up hydrogen infrastructure, the resulting tariffs for hydrogen users would be significantly lower than in a cost-reflective approach[122]. As a consequence, the financial burden on early-stage hydrogen users is reduced, and more potential customers would regard hydrogen as a financially attractive decarbonization option, in turn boosting market ramp-up. Moreover, existing gas network operators can leverage their infrastructure, expertise, and customer base to transition into hydrogen transport, reducing the need for creating an entirely new network. Ultimately, merging natural gas and hydrogen tariffs allows customers a gradual transition from natural gas to hydrogen use. On the other hand, there are disadvantages to merging the two tariff types. To begin with, natural gas users would subsidize hydrogen infrastructure. As a result, these users would face higher tariffs which could discourage their participation in the transition to hydrogen. For those gas customers that will not demand hydrogen in the future, merged tariffs will potentially cause even greater resistance. Another challenge when devising merged tariffs is an accurate cost allocation between natural gas and hydrogen customers. This is particularly critical in an early market phase, when the number of hydrogen customers is expected to be small. Here, a transparent and detailed cost allocation mechanism would be required, characterized by constant revision. Lastly, merging the tariffs of two distinct energy sources would potentially raise complex regulatory issues. Consequently, adjustments of existing regulatory frameworks at the EU and national levels would become necessary, involving all relevant stakeholders. The issues of cost-allocation and regulatory adjustments become even more pressing when considering allocating the costs for hydrogen transport across all energy vectors, an approach that would acknowledge the energy system value of hydrogen (storage and demand-side response).

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[118] ACER (2020a).
[119] European Parliament and Council of the EU (2009c), Art. 13.
[120] Piebalgs et al. (2021).
[121] Boltz (2021).
[122] Boltz (2021).

As the financial risks associated with the hydrogen scale-up are significantly higher than during the liberalization of gas markets, risk mitigation by member states and/or the EU are conceivable approaches. For instance, potential options include government grants for infrastructure investments, or co-financing via the EU's Connecting Europe Facility (already used for electricity natural gas infrastructure). Another possibility is the direct subsidization of hydrogen tariffs at national or EU level using general tax money, driving down prices for potential hydrogen customers[123]. This would allow for broader socialization of costs and can provide a more equitable funding mechanism, as all taxpayers contribute regardless of their direct use of hydrogen or natural gas. Additionally, subsidization of hydrogen tariffs enables governments to actively support the nascent hydrogen industry, promoting its development and growth. Hydrogen tariffs could initially be capped at a level acceptable for customers, subject to approval by national regulatory authorities or ACER. The difference between the capped tariff and the actual tariff required to recover the costs for investments would then be covered or hedged by member states or the EU. As more customers connect to the hydrogen grid, this difference would shrink and, eventually, disappear[124]. Nevertheless, involvement of governments via subsidization may lead to resistance from taxpayers who do not directly benefit from or have an interest in the hydrogen industry. Governments may also face competing priorities for allocating tax revenue, and the availability of funds for hydrogen infrastructure could be subject to budget constraints. Finally, there may be a lack of direct incentives for private sector investment and innovation in hydrogen infrastructure, as the funding is predominantly reliant on government support.

Regardless of which approach (or combined approaches) is most practical, the discussion above indicates a central requirement for hydrogen infrastructure cost-recovery. If the 2030 policy goals of sustainability and security of supply are to be achieved via timely establishment of a European hydrogen market, as envisioned by the EC[125], the financing of transport infrastructure will likely have to feature elements that, for some time, depart from the EC's former strict focus on liberalization and market principles. In particular, during the transition period, the concept of cost-reflective network tariffs may need to be revised, and state interventions on pricing mechanism may become necessary. Nevertheless, existing high standards on transparency and the non-discriminatory character of network tariffs should be upheld.

7. Conclusions

Crafting a robust regulatory framework for the emerging hydrogen supply industry is at the crux of the EU's energy policy discourse. Amidst the policy tension of balancing market liberalization, environmental sustainability, and energy security, the nascent hydrogen economy presents its own set of unique challenges and opportunities. Among these are the lack of a mature hydrogen market, technological nuances associated with hydrogen transport, and the need for different models for the future structure of the hydrogen supply industry. This paper argues that future regulation must carefully navigate the intricate balance between market liberalization and sustainability objectives, while also accounting for the distinctive features of hydrogen as an energy carrier.

Our analysis reveals that the push for sustainability, which mandates expedited development of a European hydrogen market, may be at odds with traditional market liberalization mechanisms, known for their risk-averse nature and potential to delay grid-related industries. Nonetheless, specific aspects of liberalization can synergistically bolster both sustainability and energy security. This paper thus proposes a hybrid approach that amalgamates existing regulatory principles with innovative provisions tailored to the hydrogen sector.

To lay the groundwork, we advocate repurposing certain tried-and-true regulatory tenets from the natural gas and electricity sectors. First, ensuring non-discriminatory access to the hydrogen network can serve as a cornerstone in developing a functional hydrogen market. This provision not only

[123] Piebalgs et al. (2021).
[124] Dena (2022).
[125] European Commission (2020a).

encourages market participation by diverse stakeholders, but also advances sustainability and energy security by stimulating supply and demand, and enhancing system resilience. Second, we should capitalize on existing European coordination mechanisms, extending them to encompass hydrogen-related concerns such as network planning, cross-border collaboration, and the integration of hydrogen and electricity systems. Finally, as hydrogen moves toward commercial viability, existing liberalization rules for non-grid elements of natural gas could serve as a template, with the understanding that they inherently bolster both security and sustainability.

However, the hydrogen sector's unique characteristics demand bespoke regulatory elements. For example, unbundling rules need to be designed to accommodate hydrogen's strategic role in promoting sustainability and enhancing energy security. This could be achieved by providing a framework that allows for various stakeholders—including but not limited to existing natural gas network operators—to contribute to the development of hydrogen infrastructure. In the case of natural gas TSOs, while this dual ownership could introduce efficiencies, it necessitates stringent transparency regulations to avert anti-competitive behaviour. Moreover, the embryonic state of the hydrogen market complicates investment recovery for transport infrastructure. Consequently, regulators may need to deviate temporarily from conventional cost-reflective tariff models, contemplating alternative cost-recovery mechanisms and possibly blending tariffs across various energy vectors. Public interventions, such as grants, subsidies, and tariff caps, may be indispensable to stimulate adequate infrastructural investment.

In conclusion, this paper posits that a regulatory framework synthesizing both conventional regulatory elements and novel provisions can effectively catalyze the growth of the European hydrogen industry. This multi-faceted approach aims to reconcile the often-conflicting objectives that characterize the EU's energy policy, laying the foundation for a resilient, sustainable, and market-friendly hydrogen economy.

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