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PolyGrid 2050:

Integrating hydrogen into the European energy transfer infrastructure landscape

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ENERGY TRANSITION

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Abstract

Development of a hydrogen economy will depend on adequate transportation infrastructure. Most discussion of hydrogen transportation to date has focused on adapting natural gas networks, but the issue is more complex. Hydrogen can also be transported by dedicated new pipelines as well as other transportation networks (e.g., truck, rail, and marine transport) and even produced on-site by transferring electrical energy instead of hydrogen. In future, end users' ability to switch from one form of delivery to another will result in new linkages between these diverse infrastructures in the sense that energy flows of different sectors will become more interdependent, and the widespread use of hydrogen is likely to strengthen this. This raises the fundamental question of how to prevent inefficiency (such as unnecessarily high hydrogen infrastructure costs or suboptimal utilization of gas and power networks) and redundancy in the future hydrogen transport infrastructure. This task is made more challenging by technological uncertainty, the unpredictability of future supply and demand for hydrogen, network externality effects, and investment irreversibility of grid-based infrastructures. Meeting these challenges entails coordinating investments in hydrogen transportation infrastructures across all modes in order to establish a cross-sectoral hydrogen polygrid. This paper analyses the strengths and shortcomings of three possible approaches—centrally coordinated, market-based, and regulatory—to this task. Finally, the paper offers policy recommendations on establishing a coherent institutional framework governing investment in the future hydrogen polygrid.

Keywords: hydrogen integration, cross-sectoral coordination, whole-system approach, integrated infrastructure planning, intermodal competition

Contents

Figures

Tables

1. Introduction

Hydrogen is expected to play an important role in helping European countries to achieve the net-zero carbon target (European Commission 2020a). In 2020 the EU Commission released the EU Hydrogen Strategy for a Climate Neutral Europe[1] as part of their European Green Deal. The strategy defines the goal of 1 million tonnes of clean hydrogen annually and an electrolyser capacity of 6 GW by 2024, rising to 10 million tonnes per year with at least 40 GW of electrolyser capacity by 2030. It also recognizes the importance of importing hydrogen from neighbouring regions, especially North Africa. By 2050, hydrogen could provide up to 24 per cent of total EU energy demand (Fuel Cell and Hydrogen 2019).

Given the role of hydrogen in European plans for climate neutrality, adequate hydrogen transport (and storage) infrastructure needs to be established to enable hydrogen penetration in the energy system. However, hydrogen transport infrastructures are costly and have a long lead time. There is also the issue of technology uncertainty and investment irreversibility.

Hydrogen can be transported as a gas or liquid or even converted to derivatives such as ammonia or methanol for long-distance transportation. It is also possible to transfer electrical energy instead of hydrogen and produce hydrogen in a decentralized way. Potential infrastructures for hydrogen transport include the following:

- repurposed gas networks
- power networks supplying power-to-gas/hydrogen facilities
- road, rail, river, and maritime transportation networks
- dedicated, newly built hydrogen pipeline networks.

These can be considered elements of a grand ‘polygrid’ that will be the backbone of 2050 decarbonized energy systems. The idea of a hydrogen polygrid implies that energy flows in infrastructures in different sectors are interdependent and the widespread use of hydrogen is likely to strengthen this interdependence.

The key question is how to ensure that there is no redundancy or inefficiency when the task of hydrogen transportation is dispersed across multiple sectors. The answer is cross-sectoral coordination of investment in energy transport infrastructures. In other words, to minimize new investments and their associated costs, an integrated approach to hydrogen transportation is needed. This, in practice, means integrating hydrogen into the available energy transfer infrastructure landscape such that infrastructures from several different sectors are utilized to deliver hydrogen to end users in an optimum way.

Achieving this is, however, not straightforward. The difficulty of the task stems from the current lack of an explicit mechanism to ensure cross-sectoral coordination. Some energy transport infrastructures (such as road, rail, and marine transport) are open to competition, whereas others (such as pipelines and electricity networks) are natural monopolies. Each infrastructure is subject to a sector-specific regulatory framework and has hence developed independently of the other sectors. Therefore, there is a risk of efficiency losses and consequent unnecessarily high infrastructure costs, which must be avoided when climate-neutral hydrogen is transported in large amounts from production sites to consumption centres (European Commission 2020a; 2020b; Ofgem 2021).

In Europe, the debate on how to optimize the integration of hydrogen in the energy transfer infrastructure landscape focuses on three key approaches: (1) putting a central agency in charge of coordinating investment in hydrogen infrastructures (2) working in a decentralized way through the market mechanism, and (3) relying on economic regulation. Each of these approaches reflects a different mode

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[1] Climate neutrality, among others, requires no net emissions of greenhouse gases by 2050.

of governance, as described in classical institutional economics—hierarchy, market, and network, respectively (cf. Powell 1990).

Using the coherence framework introduced by Finger et al. (2005), this paper analyses these approaches and the arguments raised for and against them to provide guidance on the institutional framework governing future cross-sectoral investment in hydrogen transport infrastructure.

The outline of this paper is as follows. Section 2 presents two challenges that integration of hydrogen brings to the existing sector-specific energy infrastructure planning process. Section 3 reviews the three approaches described above and analyses the alignment between the scope of institutional control under each approach and the technical boundaries of the future hydrogen system—the first of the two hydrogen-related challenges outlined in section 2. Section 4 presents arguments for and against these approaches and relates them to the findings from the academic literature. Building on the argument that the technical and institutional architectures of the future hydrogen system need to be aligned—the second hydrogen-related challenge—it offers guidance on the governance of future hydrogen-driven transport infrastructure investment. Section 5 concludes the paper.

2. Hydrogen as a game-changer for energy infrastructure

Hydrogen is expected to make a strong contribution to decarbonization efforts. However, it will require significant change in the current sector-specific planning for energy transport infrastructures in Europe. This section explains why that change is required, briefly reviews the current planning process, and defines the two key challenges that emerge when energy infrastructure expansion is planned for the purpose of hydrogen transport.

Currently the two primary European energy systems, power and natural gas, are network based. Electricity and gas networks are regulated natural monopolies with competition among generation plants as well as retail suppliers who all use the same grid to deliver energy to end users. Although consumer switching among retailers is common, the demand for the network infrastructure is not affected by that as end users do not switch network infrastructure provider.

Infrastructure switching often implies fuel switching—that is, it requires energy consumers to adjust or completely replace their equipment (e.g. replacing a gas boiler with a heat pump), and is hence associated with significant investment cost for the final consumer. For some purposes, especially in industrial sectors, fuel switching might not even be possible. In effect, this means that the demand for the capacity of a given monopolistic energy infrastructure, whether it is the power or gas network, is rather stable, regardless of developments in other sectors.

As a result of this, future infrastructure demand can often be reliably predicted using scenarios analysis within a centralized administrative planning process. Based on different investment requirements under different scenarios, so-called no-regret network expansion options are selected for future investment.

Given the monopoly setup, infrastructure planning and proposed investments are subject to strict regulatory examination and approval. Approved investment cost is directly translated into network charges which, given the absence of alternatives, are always borne by the final consumers independent of their choice of retailer. Hence, it is the task of regulatory oversight to make sure that the planning process leads to the lowest-cost solution and an efficient implementation.

Hydrogen, on the other hand, can be delivered to end users by various means, and thus presents a different set of challenges for transport infrastructure planning. As mentioned previously, it can be transported by a dedicated new pipeline, a repurposed gas network, or existing transportation networks (e.g., truck, rail, and marine transport) or even produced on-site by transferring electrical energy instead of hydrogen. As a result, hydrogen as an energy carrier can establish new linkages between existing power and gas networks, new infrastructures in different sectors, and decentralized renewable hydrogen generation.

In the future, end users are expected to be able to switch from one infrastructure to another for delivery of hydrogen or even decide to produce hydrogen on-site (cf. ACER & CEER 2021; European

Commission 2020b). Hydrogen as an energy carrier represents a technological change that connects power and gas networks with infrastructures from other sectors and with decentralized renewable hydrogen generation.

This means that future hydrogen-driven investment in established energy networks should not be solely governed by sector-specific supply and demand, but also be coordinated with production, consumption, and infrastructure development in other sectors. This will require an adjustment to current energy infrastructure planning processes, which are all sector-specific. Otherwise, efficiency losses—such as unnecessarily high hydrogen infrastructure costs or suboptimal utilization of gas and power networks—are likely to occur when hydrogen is transported in large amounts.

A change in technology implies a governance adjustment and vice versa—that is, a coevolution of governance and technology is necessary. A suitable mode of governance is one that is aligned with the technological development of hydrogen transport. More specifically, an infrastructure delivers good economic, social, and technical performance when (1) the scope of institutional control corresponds to the technical boundaries of the system and (2) the institutional and technical architectures—whether centralized, decentralized, or peer-to-peer/relational—are aligned (cf. Finger et al. 2005).

Transport of hydrogen in large quantities is likely to introduce two misalignments that the existing planning process cannot address:

1. *Technological misalignment*—Power and gas networks will become part of a broader hydrogen transport network whose technical boundaries exceed their administrative ability for network planning. Therefore, existing sector-specific energy infrastructure planning processes will need to be enhanced with new cross-sectoral mechanisms that allow coordination of hydrogen-driven energy infrastructure expansion with the development of hydrogen generation, consumption, and transport in other sectors.
2. *Institutional misalignment*—For power and gas networks, both the architecture and the planning process tend to be centralized due to their natural monopoly characteristics. This stands in strong contrast to the decentralized architecture of some hydrogen delivery options, notably in the transportation sector (e.g. road and marine) and peer-to-peer character of present-day hydrogen sector. Thus, new cross-sectoral coordination mechanisms will be needed to account for hydrogen-related investment outside the natural monopoly setting.

Clearly, if power and gas networks are to be adapted to transport large quantities of hydrogen by the middle of the 21st century, cross-sectoral coordination mechanisms capable of addressing these two challenges must be developed quickly. This paper analyses three such mechanisms proposed by European stakeholders and suggests ways these could complement each other in developing a broader institutional framework for the integration of hydrogen into the energy transfer infrastructure landscape.

3. Three approaches to cross-sectoral coordination of hydrogen infrastructure

Addressing the first challenge—misalignment between the technical boundaries of hydrogen transport infrastructure and the institutional boundaries of the existing energy infrastructure planning processes in electricity and gas networks—this section reviews approaches to cross-sectoral coordination of investment in hydrogen transport infrastructure that have been proposed by European stakeholders. Broadly speaking, there are three such approaches, each reflecting a different classical mode of governance. These are the centrally coordinated, market-based, and regulatory approaches, reflecting the *hierarchy*, *market*, and *network* governance modes (cf. Powell 1990). The remainder of this section discusses these approaches in turn.

3.1 Centrally coordinated approach

The first approach calls for a central planner who coordinates infrastructure expansion across different sectors. This central planner can be either a new, neutral institution or a common information platform that promotes exchange among the stakeholders from different sectors. Given its authoritative character, with individual transactions managed by clearly defined roles and administrative procedures, the centrally coordinated approach corresponds to the classical *hierarchy* governance mode.

Within the energy sector, the interlinked model of ENTSO-G and ENTSO-E (European Network of Transmission System Operators for Gas and for Electricity, respectively) is the most prominent European example of this approach. Initiated by European regulation (EU 2013b) and applied in practice since 2018, it uses integrated scenario planning for the power and gas sectors when developing 10-year network development plans for the respective transmission network associations (ENTSO-G & ENTSO-E 2018). As soon as 2022, the model is expected to be further extended to consider the interactions of the power and gas sectors not only in the scenario development phase, but also when assessing specific investment projects (ENTSO-G & ENTSO-E 2021).

At the national level, the German Energy Agency's *Systementwicklungsplan* (system development plan) provides another example of this approach. Based on a stakeholder exchange platform, it includes the heat and hydrogen sectors as well as the power and gas sectors and covers both distribution and transmission. The plan is not intended to evaluate specific investment projects. It remains at the scenario planning level but aims to define the design of the overall future energy system, including its policy and market framework and eventually the necessary policy adjustments (dena 2020).

Another example is the ongoing discussion of the 'energy future system operator' in the UK. The independent electricity system operator, which currently belongs to National Grid, is proposed to become a completely neutral stakeholder. This is to be achieved either by selling it, so that it becomes independent of any energy sector interests, or defining it as a new, independent public agency. This future neutral system operator would take over not only the electricity and gas network planning, but also additional roles and functions that are necessary for whole-system optimization. As in Germany, these include (but are not limited to) design of energy markets, data management, and competition in energy networks. Furthermore, in addition to power and gas, the future system operator in the UK is envisioned to cover the hydrogen, heat, and transportation sectors as well as both transmission and distribution (BEIS & Ofgem 2021).

In this approach, while each implementation context varies, the central principles are identical and follow a strongly hierarchical architecture. In all mentioned examples, there is an institution that coordinates energy infrastructure expansion in different sectors as one system—i.e. a central planner—who forecasts the energy transport needs of the overall system within several different scenarios. Put differently, the total energy generation and demand within the national economy, and therewith the total expected production of and demand for different energy carriers, are predicted. Given the locations of the expected energy production and demand, future energy transportation needs are identified.

In the next step of the planning process, the identified overall transportation need is allocated to different sectors by the central planner. This decision is guided by the available infrastructure and sector-coupling capacities, congestion, sector-specific infrastructure, sector-coupling investment costs, and potential cross-sectoral synergies. The resulting sector-specific demand for infrastructure and sector-coupling expansion serve as an input for planning for infrastructure investment in the different sectors and in the existing energy network. If the provision of the desired sector-specific or sector-coupling capacity is expected to be difficult, a policy or market design adjustment is put forward by the central planner to promote private investment.

3.2 Market-based approach

In the debate about decarbonization of the hydrogen and gas markets, arguments have been raised in favour of most hydrogen transport infrastructure being delivered by unregulated private investors, who would decide where and when to build based on purely commercial considerations. In such an environment, cross-sectoral coordination would be decentralized, and its optimization would be ensured by individual stakeholders in response to price signals at energy markets. This approach corresponds to the classical *market* governance mode.

The market-based approach has been proposed by European energy network regulators in response to calls by policymakers and stakeholders for a regulated hydrogen network development model similar to that for gas and electricity networks (cf. CEER 2021a; European Commission 2021a, 2021b; Gas for Climate 2021). Regulators who advocate this approach highlight the possibility of cross-sectoral infrastructure competition when regulated infrastructures, such as existing power and natural gas networks or new pipelines, are expanded for the purpose of hydrogen transport. They are critical of any setup where hydrogen infrastructure investment is decided by the regulated power and gas network operators using the existing energy infrastructure planning processes.

Instead, they argue that these operators should only monitor market developments. If this monitoring results in a proposal for additional hydrogen-driven investment, regulators reserve the right to weigh the cost of the proposed investment against alternatives from other sectors and to reject the proposal on these grounds. Hence, in the market-based approach, the outcome of the established energy infrastructure planning process with respect to hydrogen-driven infrastructure investment is only a proposal that competes against other options (ACER & CEER 2021; CEER 2021a).

The concept of market-driven energy infrastructure development is not new. It has been intensely discussed across the globe in the context of power networks as the so-called merchant transmission investment. However, in practice, the attention given to this discussion has never been met by a corresponding level of private power sector investment (cf. Joskow 2005). In contrast, it is more common in the gas sector.

The so-called open season—a process of marketing commercial infrastructure in which potential shippers are invited to contract capacity of the planned project on a long-term basis— which has been applied to some high-pressure natural gas pipelines in the US and Canada, today represents a common step in the development of new liquefied natural gas terminals. Similarly, the complete dedicated hydrogen pipeline network in Europe, consisting of 1,600 kilometres, has been developed and is operated in an unregulated commercial regime (ACER 2020; Perrin 2007). Similar setups can also be observed with respect to other commercial gases, such as oxygen and nitrogen.

How can a market-based approach align the boundaries of institutional control with the technical boundaries of the hydrogen transport infrastructure system? The merchant transmission investment model assumes private investors will develop infrastructure projects along the congested power lines to arbitrage price differences between the newly connected congestion regions. In practice, most private infrastructure projects, whether power or gas, are backed by long-term contracts between infrastructure investors and commodity shippers (cf. Joskow 2005; NERA 2002) in order to forestall the price convergence that results from investing in infrastructure capacity between congested regions. As a result, private infrastructure investment is driven by the common expectation of the stakeholders—infrastructure investors and commodity shippers—regarding the price and the future supply of and demand for the given energy carrier. This demand and supply in turn depend on the development of energy markets in other sectors (i.e. supply and demand for substitution fuels in alternative markets).

The mechanism of cross-sectoral links for the power and gas sectors has already been elaborated in detail elsewhere (see e.g. Gil et al. 2003; Peng & Poudineh 2015; Rubio-Barros et al. 2012). These can be roughly summarized by two economic concepts. First, the *substitution effect* implies that the demand for a given energy carrier depends on the relative prices of all energy carriers. For example, lower electricity prices can motivate some gas consumers to electrify their energy consumption processes and hence reduce the gas demand in the medium to long term. Second, the *arbitrage effect* refers to the motivation of market parties to interlink two sectors with differing energy market prices by sector-coupling technologies in order to benefit from the price difference. This effect has traditionally been implemented by gas power plants that convert 'less valuable' natural gas into 'more valuable' electricity. New market coupling technologies, such as electrolysis, contribute to this effect as well.

Both substitution and arbitrage effects emerge as a result of optimization by individual market participants in reaction to prices at energy markets in different sectors. Hence, these extend beyond gas and power to other energy sectors and allow energy markets to exert institutional control beyond the boundaries of the established energy sectors. Cross-sectoral coordination with respect to hydrogen transport infrastructure occurs using this highly decentralized market-based institutional architecture.

An important point here is that the market-based approach does not imply complete abandonment of the administrative energy infrastructure planning processes for the regulated power and gas networks. As explained in section 4.2 below, a degree of administrative planning might be necessary for the efficient operation of this approach. Furthermore, European regulators propose applying the market-based approach only to hydrogen-related investment in the regulated energy infrastructures. Other investment plans for these infrastructures, that are not subject to cross-sectoral infrastructure competition, should remain within the sector-specific planning framework. Potential cross-sectoral benefits with respect to these investments should be realized by means of the centrally coordinated approach (CEER 2021a). Unfortunately, a decision rule that allows new investment in regulated infrastructure to be defined as hydrogen-related or business-as-usual has not been clearly specified yet.

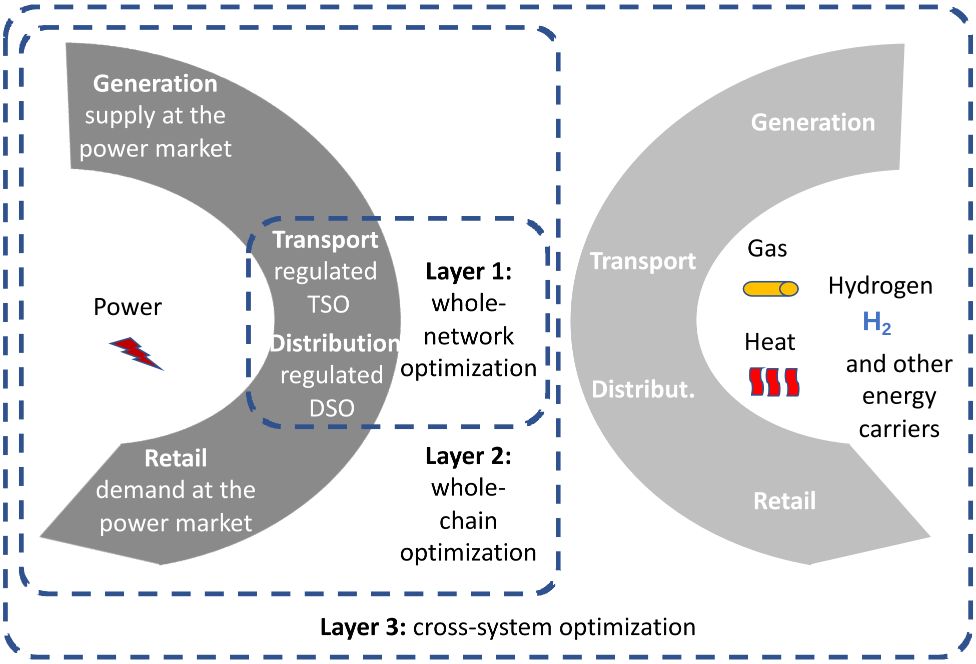
3.3 Regulatory approach

The regulatory approach proposes adjustments to network regulation that motivate operators of regulated infrastructures to make hydrogen-driven investments based on the social benefit to the entire system, not just their own grid. Network operators should abstain from expanding their networks if other modes of transport are found to be socially more preferrable, and should coordinate with providers of these alternatives to achieve socially optimal solutions. Given the focus on the complementarity of resources and the resulting degree of interdependence between the operators of established energy networks and providers of alternative hydrogen infrastructures, this approach corresponds to the classical *network* governance mode.

The regulatory approach was originally discussed at the European level due to increased use of decentralized renewable power generation, storage, and flexible power loads for electricity network services. Given the location of such distributed resources in the distribution networks, network-servicing adjustments to the output of these facilities affected not only the supply–demand balance of the entire electricity system, but also the power flows in the networks operated by several different network operators. Existing regulation of electricity networks incentivizes the cost-efficiency of the individual electricity network operator (cf. Joskow 2005). In the presence of external effects associated with the network-servicing use of distributed resources, such an incentive might, however, promote situations where different network operators purchase conflicting grid services (cf. CEER 2016, 2020; European Commission 2020b).

To prevent such outcomes, the Council of European Energy Regulators (CEER) proposed the ‘whole system approach’ to electricity network regulation—a set of regulatory measures that promote cooperative behaviour among the operators of these networks (CEER 2016, 2017). This initiative has been positively received by diverse European stakeholders (CEER 2018) and has motivated CEER to expand its whole-system approach beyond ‘whole-network’ optimization in the electricity sector. As shown in Figure 1, the whole-system approach also covers regulatory action to utilize power generation, consumption, and storage as substitutes for traditional network expansion (‘whole-chain’ optimization, introduced in CEER 2018) as well as instruments that make it possible to consider resources from other sectors for power system optimization (‘cross-system’ optimization, introduced in CEER 2020). The latter is particularly important in the context of this paper, as hydrogen integration is planned to become the focus of the work on cross-system optimization in the upcoming years (CEER 2021c). Similar initiatives can also be observed outside of Europe; New York Reforming the Energy Vision” (REV) is one of the earliest and most prominent examples (cf. NYS DPS 2014).

Figure 1: The Council of European Energy Regulators whole-system approach



Source: (CEER 2020, authors' illustration).

The basic idea behind the regulatory approach is rather simple. The cost-minimization incentive promoted by traditional network regulation drives operators of regulated infrastructures towards socially optimal behaviour as long as the consequences of their decisions are fully priced in their actions. Given that there are situations where such a cost transfer does not fully occur—i.e., external effects are insufficiently internalized—individually rational action by an infrastructure operator might not benefit the overall system. As a result, efficient coordination of infrastructure operators within and across different sectors will not be achieved. It is thus the task of network regulation to identify such situations and prevent possible misalignments between individually optimum actions by the infrastructure operator and those measures that would lead to socially optimum outcomes (CEER 2018).

The implementation of the regulatory approach proves to be complex, though (see also section 4.3). CEER in this context traditionally emphasizes improved information exchange among the stakeholders in order to prevent unintentional external effects from emerging. Furthermore, network regulation should motivate network operators towards whole-system optimization by introducing an additional incentive for collaboration on top of the established cost-minimization incentives (CEER 2016, 2018). In practice, such an incentive can be implemented by defining activities promoting information exchange and cooperation as a new output in the network regulation (cf. Brunekreeft et al. 2020; Poudineh et al. 2020).

Given that existing network regulation incentivizes infrastructure operators to minimize their expenditures (input) per pre-defined output, such as per-kilometre length of the network, the newly defined outputs can be used by infrastructure operators to justify additional expenditures, and can motivate additional expenditures by the infrastructure operators on these newly defined activities. Apart from such adjustments to network regulation, countries are also encouraged to harmonize their regulatory frameworks along the three layers depicted in Figure 1 (whole network, whole chain, and cross-system) and to remove regulatory barriers that limit system optimization efforts by the infrastructure operators (cf. CEER 2020).

The regulatory approach is primarily directed at natural monopoly infrastructure operators such as electricity and gas grids. Stakeholders from competitive sectors and even potential investors in new hydrogen pipelines are currently not explicitly addressed in this approach. Although this focus might at first appear constraining, it is sufficient to coordinate investment in hydrogen transport infrastructure across different sectors and stakeholders (cf. CEER 2021c). There is no central entity that decides on the hydrogen transport infrastructure investments by investors from different sectors. This process is decentralized—regulated network operators are free to cooperate with any other hydrogen infrastructure investor or expand their own network and vice versa. The incentive to minimize costs, whether in a regulated infrastructure or an investment in competitive sectors, promotes a competition-like environment where hydrogen transport infrastructure investors search, independently of each other, for the most socially optimal solution out of their own commercial interest. As is common in the network form of governance, these stakeholders are free to decide whether competition against or coordination with others best serves their interest.

Clearly, a perfectly functioning market for unregulated stakeholders must be assumed for such a system to work. Therefore, apart from introducing adjustments to network regulation, it is also the task of the regulatory authorities to account for the potential market distortions in competitive sectors. For this purpose, a centralized infrastructure planning process can be implemented. This process should consider external effects in the system as well as additional criteria that are important for the stable operation of infrastructures, such as congestion, storage, resilience, and quality of service. It should also be technologically neutral and intend only to identify the overall system transportation needs. In other words, the result of the planning process should be a common scenario that is used by the regulatory authorities in approving the investment decisions of hydrogen infrastructure investors and as a foundation for further adjustments to network regulation.

3.4 Summary of coordination approaches

European stakeholders have proposed three approaches that align the scope of institutional control with the technical boundaries of the emerging hydrogen transport infrastructure. These approaches—summarized above as centrally coordinated, market-based, and regulatory—reflect the modes of governance known from classical institutional economics as hierarchy, market, and network, respectively (cf. Powell 1990). Theoretically, each of these approaches is capable of addressing the challenge of misaligned institutional and technological boundaries, as each introduces a degree of cross-sectoral coordination with respect to hydrogen transport infrastructure development. While the three governance modes behind these approaches are typically understood as alternatives (cf. Powell 1990), there seems to be no convergence emerging at the European level with respect to hydrogen integration into the energy transfer infrastructure landscape.

4. Critiques of the three approaches to cross-sectoral coordination

Which of the three above-mentioned approaches to developing a cross-sectoral hydrogen polygrid should policymakers adopt? This question is presently intensely discussed in Europe. This section presents arguments raised by European stakeholders, relates them to arguments in the academic literature, and provides guidance on institutional design for the future hydrogen polygrid.

4.1 Arguments regarding the centrally coordinated approach

Section 2 suggested that infrastructure will deliver a good overall performance when its institutional architecture corresponds to its technological architecture (cf. Finger et al. 2005; Künneke et al. 2021). The difficulty of aligning these two architectures stems from the fact that hydrogen can be produced locally, in clusters or on site or transported in larger quantities by a monopolistic energy network (e.g. gas network) or competitive transportation options (e.g. trucking). Each of these transportation options is characterized by a different technological architecture and requires a different institutional framework.

At present, the most widely recommended ways to transport hydrogen are as a compressed gas via road for low volumes and distances, as a liquid via road for midsize volumes and middle to long distances, and by pipelines for large volumes at any distance. (For transoceanic transportation, one option under consideration is to convert hydrogen into a hydrogen-rich substance with higher energy density and lower thermodynamic losses, such as ammonia or methanol.) However, given the early stage of the hydrogen economy, future hydrogen demand and supply—and consequently the volume of future hydrogen transport needs—are highly uncertain.

Furthermore, with the general transport sector in transition to climate neutrality and the expected advances in truck and pipeline technologies, the borderlines between different modes of hydrogen transport are going to shift. The direction and size of the shift are difficult to predict, as these depend not only on the pace of technological developments, but also on the local circumstances of the implementing country (Owen 2009). As a result, the technical architecture of the future hydrogen transport infrastructure is highly uncertain and context-dependent.

Given this uncertainty, an academic argument in favour of the more hierarchical centrally coordinated approach might be raised. Hierarchical economic organization has been suggested for environments characterized by uncertainty, small numbers of prospective market participants, and costly information asymmetries. Pairing these environmental factors with the corresponding human factors, such as bounded rationality, strategic behaviour and opportunism is likely to lead to poor market performance or even market failure (Williamson 1975).

Investment in hydrogen transport infrastructure is without a doubt associated with uncertain technological development, monopolies in at least some sectors, and information asymmetries between sectors. It is beyond the scope of this paper to evaluate whether prospective hydrogen infrastructure investors are characterized by the abovementioned human factors, but these seem to be implicitly assumed by the stakeholder arguments that are presented below. Hence, this centrally coordinated approach appears in theory to be advantageous.

However, European energy network regulators, who are familiar with the centrally coordinated approach from the existing energy sectors, have been rather critical of using this approach to cross-sectoral coordination of hydrogen transport infrastructure investment. They have raised two concerns in particular, regarding potential bias and inefficiency.

The first concern is that, when regulated infrastructure operators administratively decide on the development of hydrogen infrastructure, they might distort or preclude potential competitive hydrogen transport activities, and the centrally coordinated approach may be unable to prevent this (CEER 2021a; European Commission 2020c). Aware of this criticism, proponents of the approach have proposed countermeasures to secure an objective and informed decision by a central planner and thus prevent any sector, technology, or stakeholder bias. In practice, the neutrality of the central planner is ensured either by separating the planner's tasks from infrastructure ownership, as proposed in the UK, or by introducing an inclusive platform that promotes exchange among the stakeholders, as discussed in Germany and in the interlinked model of ENTSO-G and ENTSO-E.

Separating planning from infrastructure ownership might happen by delegating the system planner role to private entities who own no infrastructure that can transport hydrogen in their area of operation. Perverse incentive might still occur, though, as this solution allows for a setup in which the decisions of the central planner might alter or intensify competition in the planner's home market. This argument is known from the US debate on the independent power system operators who do not have physical assets in their state of operation but do have assets elsewhere. Owners of regional utilities were advised to strategically withhold network investments when the new network capacity would intensify retail or wholesale competition in their home market (cf. Balmert & Brunekreeft 2010). Likely to be familiar with the problem, BEIS and Ofgem (2021) have suggested that the central planner should be 'independent of energy sector interests' (p. 12).

Even though this requirement goes in the right direction, it might be too short-sighted with respect to the home market argument. When hydrogen becomes one of the major energy carriers in a climate-neutral economy, the central planner's decision on hydrogen infrastructure will in effect define the local availability of green hydrogen. Markets for different products that utilize hydrogen in their production process might be affected as a result. Thus, the impact of the central planner's decision might easily go beyond the borders of the energy sector.

An alternative to private ownership is to organize the central planner as a public agency (BEIS & Ofgem 2021). In this approach, perverse incentives are unlikely. However, potential synergy losses stemming from separating ownership from the task of infrastructure planning remain possible. Furthermore, moving any task from the private to the public domain should typically be justified by one of the common market failures—market power, external effects, or public good. From a purely theoretical perspective, perverse investment incentives might not suffice as a justification for public ownership in this context.

Another alternative is to design the central planner as a common stakeholder platform. A well-designed platform would allow exchange among the stakeholders to weigh different interests and prevent the decision bias that could occur with a central planner. However, designing such a platform is challenging in practice (Brandstätt et al. 2017; Buchmann 2016). The interlinked model of ENTSO-G and ENTSO-E takes a first step towards implementing such a platform by being open to consultation by any interested party (ENTSO-G & ENTSO-E 2018, 2020). The German system development plan goes further and allows for a degree of stakeholder participation in decision-making—for example, by defining the optimization criteria for the planning process in a stakeholder discussion (dena 2020).

Other elements of a common stakeholder platform design, such as dispute settlement (cf. Brandstätt et al. 2017), have not been addressed in the current proposals by practitioners. In addition, as the share of hydrogen in the energy mix increases, it is likely to attract increasing numbers of stakeholders to such platforms. This is likely to make the platform operation more difficult and thus more costly. In other words, the transaction costs of this solution are likely to rise with the increasing use of hydrogen.

The second concern that energy network regulators have raised about the centrally coordinated approach relates to the efficiency with which it coordinates hydrogen integration across sectors. For example, regulators have criticized the interlinked model of ENTSO-G and ENTSO-E for insufficiently modelling the linkage between the electricity and gas sectors, especially with respect to market-related interactions relating to price formation, their respective infrastructures, and the impact of specific investment projects (ACER 2017). At the time of writing (October 2022), improvements provided by the network operators have not yet been accepted by the regulators as sufficient (ENTSO-G & ENTSO-E 2021).

The difficulties already encountered in modelling the linkages between these two regulated, monopolistic networks (power and gas) and their respective markets highlight the problems that are expected to emerge when such models are extended to the competitive, decentralized transport sector and the relational framework of the current peer-to-peer hydrogen production system.

The problem is also well demonstrated by experience in the transportation sector. Whereas coordinated infrastructure planning appears innovative in the context of the energy sector, it has been practiced in Europe in the transportation sector for two decades. The latter sector recently entered a transition away from fossil fuels and is expected to undergo rapid and transformational technological change. At the same time, multimodal transport infrastructure development is still governed by a hierarchic planning process like those used in the power and gas sectors (cf. European Commission 2001, 2011). The recent 5-year review of the European 10-year transport infrastructure development strategy evaluated the performance of the planning process and concluded (European Commission 2016, p. 35):

> Since the 2011 White Paper strategy some genuinely new trends in the sense of societal developments and quicker than anticipated technological advances have been materialized. These trends will without doubt shape the views on transport policies in the years to come, even if many of them cannot yet be measured or accurately predicted by means of statistics.

The adoption of a hierarchical architecture like the one used in the centrally coordinated approach has been recommended in the academic literature for environments where problems such as those raised by the European energy network regulators—including stakeholder opportunism and uncertainty due to dynamic technological and societal changes—are expected to emerge. However, stakeholders who will have to take the lead under the centrally coordinated approach (cf. CEER 2021a; European Commission 2020c) tend to have reservations about this approach, in particular due to concerns about technological change.

This becomes especially apparent in the reluctance of European energy network regulators to approve costs associated with repurposing gas pipelines to carry hydrogen, even if these projects emerge out of the established energy infrastructure planning processes on many occasions as a cost-effective solution for hydrogen transport. Regulators' concerns about stranded infrastructure investments and technological lock-in are too big to allow them to make this decision (ACER & CEER 2021; European Commission 2020b).

4.2 Arguments regarding the market-based approach

As explained in section 3.2, European energy network regulators have suggested addressing the technological uncertainties of the future hydrogen polygrid by leaving infrastructure planning open to competition (cf. CEER 2021a, 2021b). Competition is expected to identify not only the most efficient modes but also the required extent of hydrogen transport (cf. ACER & CEER 2021). In this approach, competition is used as a discovery mechanism instead of assigning the final decision to the energy network regulator. However, can the market-based approach to hydrogen infrastructure investment outperform the efficiency of the centrally coordinated approach? Two main objections to this approach have been raised by practitioners: regarding its ability to harmonize the complex new system and regarding its robustness.

First, the market-driven approach has been criticized for forgoing benefits from harmonization (cf. European Commission 2021a; Gas for Climate 2021). Although practitioners often refer to this problem as it relates to infrastructure planning procedures and standards (cf. ENTSO-G & ENTSO-E 2018), the argument also emphasizes the role of external effects that occur between the different hydrogen transporting infrastructures. These are difficult to address within a market-based approach.

External effects for energy infrastructures were first academically documented in the context of *merchant transmission investments*—market-driven private investments in US electricity networks (Bushnell & Stoft 1996). Introducing a new power line is known to affect the physical power flows in the entire network and hence impact the stability of the overall system. If a new investor does not consider these external network effects, e.g. due to missing market signals, a privately profitable investment might easily be socially inefficient. More specifically, the social benefits of the new line might not be sufficient to compensate the losses of other network users caused by the changes in power flows. The opposite case, where socially efficient investment is not profitable for an investor, is also possible. A welfare loss from the social perspective occurs in both cases.

The idea of a hydrogen polygrid assumes that energy flows in infrastructures in different sectors are interdependent, even if to a lesser degree than within a single network (cf. Gil et al. 2003; Rubio-Barros et al. 2012). Therefore, widespread use of hydrogen is likely to strengthen the interdependence of the infrastructures from different sectors and therewith the external network effects between the sectors. The risk of socially inefficient investment increases as a result.

Energy network regulators, as proponents of cross-sectoral hydrogen transport infrastructure competition, emphasize that network tariffs, which are responsible for coordination under competition, should promote a level playing field for comparable activities within an integrated energy system. This means that network tariffs should be cost-reflective, technology-neutral, and free of any subsidies, distortive taxes, or levies (CEER 2021a). Furthermore, infrastructure projects by unregulated investors should be assessed in line with network plans developed by regulated network operators, and energy network regulators should have the final decision power—that is, the ability to reject planned projects or propose new projects. With this approach, in their view, external network effects would be sufficiently addressed. This might nevertheless raise the question whether regulators can convince their critics by simply stating that they are fit to identify and correct for external network effects (cf. CEER 2021a, p. 5).

Hierarchical (centrally coordinated) solutions should be expected to outperform markets as long as external network effects are unknown and hence difficult to internalize (Williamson 1975). Externalities associated with cross-sectoral coordination of hydrogen transport infrastructure are thus far only poorly understood and the subject of ongoing academic research (see section 4.3 below). Therefore, the problem of external network effects seems in theory better managed by central coordination than by the market-based approach.

Indeed, in the European transport sector, utilization of synergies between different transport infrastructures—that is, internalization of positive external network effects—is one of the central elements in network planning. In what is referred to as multimodal travel, infrastructures from different sectors are intentionally combined to reduce the cost, environmental impact, and travel time of freight and passenger transport (cf. European Commission 2011; EU 2013a).

Proposals for a centrally coordinated approach from the UK and Germany, as well as the planned extension of the interlinked model, intend to apply this concept to energy transport (cf. ACER 2017; BEIS & Ofgem 2021; dena 2020). Furthermore, negative external network effects can be addressed by including additional criteria, such as system resilience and environmental impact, in the optimization by the central planner (cf. BEIS & Ofgem 2021). Using these measures, the centrally coordinated approach makes it possible not only to minimize the overall system cost of hydrogen transport, but also to promote other socially desirable goals, such as CO_2 emissions reduction, acceleration of infrastructure construction, increase in the system resilience, and better congestion management (European Commission 2020b).

A second common criticism of the market-based approach often raised by practitioners is that it is likely to provide slower infrastructure creation and weaker coverage than the centrally coordinated approach (European Commission 2021a; Gas for Climate 2021). This common argument might be questioned, though. When discussing the market-based approach to hydrogen transport infrastructure, the telecommunications sector often serves as a point of reference for European energy network regulators (cf. ACER & CEER 2021; CEER 2021a). In this sector, it is striking that European countries that originally promoted the development of next-generation glass-fibre telecommunication networks by administrative processes instead of competition, such as the UK and Germany, currently aim to reduce their deficits against other European countries by promoting market-driven glass-fibre investment (cf. Bundesnetzagentur 2021; Cave 2014; Hutton 2021). Clearly, the two sectors and their setup conditions differ. Nevertheless, the telecommunications sector might be understood as providing a ‘lesson learned’ that can be applied to hydrogen transport infrastructure investment.

Nevertheless, an academic argument might be raised that market-driven investment in grid-bound hydrogen transport infrastructures is likely to become distorted. Investment in grid-bound infrastructure has a high degree of asset specificity. A wrong investment decision could lead to sizable stranded infrastructure assets, which makes the cost of failure high (ACER & CEER 2021; EHB 2021). This might distort hydrogen-driven investment in grid-based infrastructure in competitive settings (McDonald & Siegel 1985). For such irreversible investments, a project must not only cover its costs (including interest on capital) but also exceed the value of investing in the same project at another time in the future. Given that the investment is irreversible while the decision to defer the investment is reversible, the value of waiting might easily become significant, especially when the future is uncertain.

The waiting problem is exacerbated by the lumpiness of the investment[2] (cf. McDonald & Siegel 1985). As explained in section 4.1, the future hydrogen transport infrastructure architecture is still highly uncertain. Furthermore, practitioners argue that the investment in hydrogen and repurposed methane pipelines is lumpy (cf. EHB 2021; Gas for Climate 2021). As a result, market-driven investment in grid-based hydrogen transport infrastructures is likely to be suboptimal when no further countermeasures or market adjustments are introduced. Clearly, the waiting problem does not emerge under the centrally coordinated approach, as this provides investors of grid-bound infrastructures with a secure investment environment through regulatory commitment (cf. European Commission 2021a; Gas for Climate 2021). Suboptimal hydrogen transport infrastructure investment is, however, possible due to failures in the planning process.

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[2] Lumpy investment means it is characterized by large infrequent movements, rather than continuous adjustment.

4.3 Arguments regarding the regulatory approach

The regulatory approach offers a compromise between the competition of the market-based approach and the coordination of the centrally coordinated approach. Adopting a network form of governance, the regulatory approach should in theory be particularly suitable for situations where there is a need for efficient and reliable information exchange. A networked structure provides more flexibility than a hierarchical structure, and is as capable of coping with complex and uncertain environments, but is better at handling demand fluctuations and unexpected changes (Powell 1990).

However, CEER, the main organization that promotes the regulatory approach, has thus far neither specified measures to promote technology-neutral competition across different sectors nor provided any examples. Indeed, CEER (2020, 2021c) has characterized the application of the whole-system approach to cross-sectoral integration of hydrogen transport as new and challenging. At the time of writing, CEER (2021c) has only promised to addressing the implementation issues and providing guidelines by the end of 2025.

Academics are a step ahead and suggest implementing this approach by making adjustments to existing incentive regulation of energy networks. Several difficulties have been identified in this approach (cf. Brunekreeft et al. 2020). First, external network effects, and hence situations where the individual and social optimums diverge, are difficult to identify. For example, current studies of the electricity sector indicate that interactions among different electricity network regions and services—that is, external network effects within a single sector—are not conclusively understood (Grøttum et al. 2019). Hydrogen, which will interlink infrastructures from multiple sectors, introduces another layer of complexity. The external effects likely to result from this additional layer have hardly been explored, and there is no consensus on this issue. Therefore, adjustments to network regulation on the grounds of external effects are difficult to justify.

Second, promoting system-wide efficient behaviour by network regulation is not straightforward. For example, operators of electricity transmission networks in the international Nordic power market were shown to minimize their costs, when confronted with network congestion, by shifting the congestion into regions managed by other network operators (Bjørndal et al. 2003; Glachant & Pignon 2005). Palovic (2022) takes this argument further and predicts that external network effects will turn regular power network operator interactions into noncooperative game-theoretical problems that are repeated in endless random order. This makes such coordination problems hardly solvable.

Integration of hydrogen is likely to also introduce these problems in the cross-sectoral context. It might be questioned whether promoting information exchange and cooperative behaviour—common activities under the regulatory approach—would automatically improve the outcome in this setting. Indeed, even short-run noncooperative behaviour has been shown on occasions to promote the long-run efficiency of the overall system (cf. Axelrod 1984). Hence, behaviour to be promoted by network regulation can be defined only when the external effects and associated infrastructure operator strategies are properly understood. As stated above, this is at present not the case.

Third, hydrogen-related investment by regulated network operators has a different risk profile than other traditional activities. Given that network regulation promotes cost reduction in business-as-usual activities, the incentive for hydrogen investment is likely to be suboptimal (cf. Poudineh et al. 2020). Therefore, operators of regulated infrastructures need an additional incentive in order to optimally invest in hydrogen transport. However, promoting innovative behaviour by a network operator by defining a new output is a challenge. Once the desirable behaviour is defined, the output indicator capable of measuring it must be defined and the optimal level of penalties or rewards selected. Promoting a given output too strongly or weakly might distort the incentives of the infrastructure operator away from the social optimum and hence miss the desired effect. In this context, additional factors, such as risk, might also play a role and need to be identified and accounted for (Poudineh et al. 2020).

All these aspects depend on an accurate understanding of the problem. A consensus on the necessary regulatory action is currently unlikely given the limited knowledge on cross-sectoral hydrogen infrastructure optimization, the associated external effects, network operator strategies, and systemoptimizing remedies. Hence, any network regulation adjustments on these grounds are likely to be difficult to justify and might appear arbitrary and become a subject of political and academic controversy.

4.4 Strengths and weaknesses of the three approaches

Table 1 summarizes the three approaches to cross-sectoral optimization of hydrogen transport discussed above, along with their key strengths and weaknesses.

Given these options, what should the cross-sectoral institutional framework for a future hydrogen polygrid look like? The analysis presented here yields the following important lessons.

First, each of the three approaches described above provides an advantage for a certain technical architecture, is driven by implicit assumptions about that architecture, and only partially accounts for other options. Therefore, different countries are likely to opt for different approaches depending on their local conditions. Further research is needed on how to map these local contextual factors to the most appropriate approach to cross-sectoral optimization (cf. Scholten & Künneke 2016).

Second, there is a degree of complementarity between the three approaches at the European level. Limiting consumer choice with respect to alternative modes of hydrogen transport, or constraining decentralized renewable hydrogen production, is difficult to imagine in Europe at this early stage of hydrogen adoption. Given the resulting uncertainty about the future hydrogen supply, demand, and respective transport technology cost—that is, the technical architecture of future hydrogen transport infrastructure—one would in theory expect the adoption of hierarchical administrative planning processes (described here as the centrally coordinated approach). On the other hand, European energy network regulators have made clear that they feel uneasy taking the lead in this uncertain environment. Such a lead, however, is necessary in order to provide hydrogen transport infrastructure investors with the regulatory commitment that the centrally coordinated approach is based on.

The alternative is to use a market-based or regulatory approach, in which competition and market mechanisms are assumed to determine not only the most efficient future modes of hydrogen transport but also the extent of hydrogen transport needs. However, two problems are associated with these competition-based solutions.

One is that external network effects among infrastructures from different sectors are expected to emerge with the widespread adoption of hydrogen. These effects are so far only poorly understood and thus difficult to internalize by market mechanisms. The risk of socially inefficient hydrogen transport infrastructure investment increases as a result. Administrative planning processes associated with the centrally coordinated approach address these issues well. Therefore, market-based and regulatory approaches need to adopt similar additional instruments to address external network effects—that is, implement them in the form of regulatory oversight, instead of attempting to internalize external network effects directly through the markets. Thus, combining these solutions with the centrally coordinated approach currently represents one option for addressing the problem of external network effects in Europe.

The other issue is that hydrogen-driven investments in grid-bound infrastructures, whether they are regulated or not, are irreversible, with the associated risk of stranded assets. As a result, these infrastructures differ from other technical solutions with less hydrogen-specific infrastructure assets. In an environment where the whole hydrogen infrastructure investment is driven solely by optimization carried out by individual stakeholders in response to price signals from decentralized energy markets, investment in grid-bound infrastructures is likely to be suboptimal. The centrally coordinated approach can address the problem by providing a regulatory commitment for the cost recovery of high-risk investments.

Table 1: Three approaches to cross-sectoral optimization of hydrogen transport

	Method of coordination	Key features and examples	Advantages	Disadvantages
Centrally coordinated approach	A central planner (a new neutral institution or a common information platform) coordinates infrastructure expansion across different sectors.	A hierarchical economic organization oversees cross-sectoral hydrogen infrastructure investment. Examples: • interlinked model of ENTSO-G and ENTSO-E[a] • *Systementwicklungsplan* (system development plan) proposed by the German Energy Agency • energy future system operator proposal in the UK.	Better addresses investment risks. Better addresses network externality effects.	Challenge of neutrality of the central planner; risk of sector, technology, or stakeholder bias. Informational disadvantage of the central planner.
Market-based approach	Unregulated private investors decide where and when to build hydrogen infrastructure based on purely commercial considerations.	The cross-sectoral coordination of hydrogen transport infrastructure is ensured in a decentralized fashion by individual stakeholders in response to price signals at energy markets. Examples: • high-pressure natural gas pipelines in the US and Canada and LNG terminals, the so-called open season • existing 1,600 kilometres of dedicated unregulated and commercial hydrogen pipeline network in Europe • merchant transmission investment model in the electricity sector.	Better deals with technological uncertainty. Is decentralized. Competition identifies the most efficient modes and the extent of future hydrogen transport.	Difficult to account for external effects. Difficult to address investment risks. Suboptimal hydrogen-driven investment in grid-based infrastructure.
Regulatory approach	Network regulation is adjusted to motivate operators of regulated infrastructures to decide their hydrogen-driven investment based on the net social benefit for the entire system instead of only for their own grid.	Network operators are incentivized to abstain from expanding their networks if other modes of transport are found to be socially preferrable, and to coordinate with providers of these alternatives to achieve a socially optimal solution. Example: incentive given to distribution networks to integrate distributed generation, storage, and demand response to address grid issues and defer the need for grid reinforcement.	Is decentralized—no need for a central entity. Promotes a competition-like environment. Handles technological uncertainty.	External effects might be insufficiently internalized. Implementation is complex. A perfectly functioning market for unregulated sectors is assumed.

[a] European Network of Transmission System Operators for Gas and European Network of Transmission System Operators for Electricity

In theory, the regulatory approach can also address this issue by introducing an add-on. It can also promote competition between regulated and unregulated energy infrastructures by encouraging targeted regulated infrastructure operators to consider all available hydrogen transportation modes when planning their investments. In this way, the regulatory commitment securing hydrogen investment in grid-bound infrastructures can be provided, while a coordinated cross-sectoral hydrogen transport infrastructure investment is incentivized at the level of the individual infrastructure investor instead of staying solely in the hands of the regulator. Using the regulatory approach, however, necessitates an ongoing mechanism that continuously identifies distortions occurring among infrastructures in different sectors, a requirement that makes its implementation challenging.

All in all, there is no silver-bullet solution to the problem of cross-sectoral coordination of hydrogen transport infrastructure. This depends on contextual factors and the sector's development stage. Given that hydrogen is in the early stage of development, the centrally coordinated approach seems to be a reasonable way to coordinate hydrogen transport infrastructure investment across different sectors. This would not only provide the regulatory commitment that is necessary for hydrogen infrastructure projects to take off quickly, but also make it possible to address cross-sectoral external effects when such effects are not well understood and the social consensus is missing.

However, the centrally coordinated approach should not be considered final. As the hydrogen industry evolves, the coordination of the cross-sectoral hydrogen transport infrastructure should evolve too. This is because the understanding of this coordination and its challenges is likely to develop over time. Furthermore, the centrally coordinated approach is expected to perform well with respect to clear-cut projects in terms that are socially optimum, but to reach its limit in situations where defining the most socially efficient mode of hydrogen transportation is difficult. As long as there is only a limited understanding of cross-sectoral coordination, the centrally coordinated approach should be used to launch clear-cut hydrogen transport projects while postponing the less clear cases. Those less well-defined projects can be addressed at a later point by decentralized regulatory or market-based approaches after the first experience with cross-sectoral coordination has been made.

5. Conclusion

Integrating hydrogen into the energy transfer infrastructure landscape represents a challenge for sector-specific energy network planning processes because there are various means of delivering hydrogen to end users. Hydrogen can be transported by a dedicated newly built hydrogen pipeline, a repurposed gas network, or existing transportation networks (e.g. truck, rail, and marine transport), or even produced on-site by transferring electrical energy instead of hydrogen.

As a result, hydrogen as an energy carrier establishes new linkages between existing energy networks and new infrastructures in different sectors, as in the future end users are expected to be able to switch from one infrastructure to another for delivery of hydrogen. This is different from existing energy networks (e.g. gas and electricity), which have traditionally been considered natural monopolies. Thus, future hydrogen-driven investment in these networks should no longer be solely governed by sector-specific supply and demand, but also be coordinated with production, consumption, and infrastructure developments in other sectors.

In Europe, there are three key approaches to the integration of hydrogen into the energy transfer infrastructure landscape. Each of these approaches results in a different institutional framework. For example, under the centrally coordinated approach, a newly introduced central planner—either a new institution or a common stakeholder platform—coordinates infrastructure expansion across different sectors. In contrast, under the market-based approach, most of the hydrogen transport infrastructure is delivered by unregulated private investment, and cross-sectoral coordination is ensured in a decentralized fashion by individual stakeholders in response to price signals at energy markets. Finally, under the regulatory approach, network regulation would be adjusted to motivate operators of regulated infrastructures to coordinate with providers of alternative hydrogen transport modes in order to achieve socially optimal solutions.

These three approaches reflect three modes of governance—hierarchy, market, and network, respectively—conceptualized in classical institutional economics. The most suitable approach will be the one that is aligned with the technological aspects of hydrogen transport. Some hydrogen transport infrastructures are natural monopolies (e.g. gas networks), whereas others are potentially competitive (e.g. trucking). Each of these technological scenarios requires a different institutional framework to coordinate actions within and across sectors. The choice of institutional framework in this context needs to consider the pace of development of the different energy transfer technologies and local circumstances in the implementing country, both of which are highly uncertain.

Given multiple characteristics of the hydrogen sector—its technological uncertainty, investment irreversibility, the risks associated with grid-based infrastructures, the issue of network externality effects, and the fact that hydrogen is at the early stage of development—the centrally coordinated approach is likely to be more effective in coordinating hydrogen transport infrastructure investment across different sectors. It can provide the regulatory commitment that is necessary for hydrogen infrastructure projects to launch swiftly while making it possible to address cross-sectoral external effects which are not well understood.

The centrally coordinated approach should not, however, be considered final or permanent. Institutions governing the cross-sectoral coordination of hydrogen transport infrastructure should evolve over time, as the industry evolves and with it our understanding of its potentials and challenges. Furthermore, the centrally coordinated approach may not work well in situations where it is difficult to define the most socially efficient mode of hydrogen transportation. Therefore, this approach should be used to facilitate sharply defined and efficient system-wide hydrogen transport projects. Less well-defined projects can be addressed, at a later point, by decentralized regulatory or market-based approaches, after the first experience with cross-sectoral coordination has been made.

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