DOI: 10.2478/ie-2023-0022

sciendo

Intereconomics, 2023, 58(2), 111-118

JEL: O14, Q42, R11

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The Spatial Evolution of a European Hydrogen Economy

Green hydrogen has outgrown the testing stage: over the next few years, consortia across Europe will be investing large sums to build the supply chains of tomorrow. However, Europe as a whole will only be successful if it aligns the development of supply chains with the potentials of its regions and exploits the advantages of a European division of labour. This article examines the spatial distribution of hydrogen frontrunner projects in light of regional heterogeneity. It reveals a pattern that exhibits clear core regions but is only partly consistent with the localisation of current production and usage potentials. For a rapid ramp-up of hydrogen markets, European policymakers should make greater efforts to incentivise capacity formation in regions with high potential, by harmonising national levies affecting hydrogen supply chains and promoting the build-up of a cross-regional hydrogen transport infrastructure. Moreover, public investment support provided by various institutions and programmes should be better aligned to the common target of capacity upscaling.

The goal of climate neutrality by 2050 is a central long-term challenge for the European economy. All sectors are under pressure to improve the greenhouse gas balances of their conversion processes. For this to succeed, sector coupling technologies must be implemented that extend the use of electricity from renewable energies beyond direct consumption to the areas of heat and mobility. The production of hydrogen from water molecules using renewable electricity, so-called green hydrogen, is one of these options. Its wide range of potential application fields in industry, mobility and the building sector make green hydrogen a suitable instrument for spreading cross-sectoral use of renewables. In the recent energy crisis, it has come even more into the spotlight as a contribution to breaking the dependence on fossil energy sources in hard-to-decarbonise sectors. As part of its REPowerEU plan, the European Commission has set a target of increasing domestic production of renewably generated hydrogen to 10 million tonnes by 2030 (European Commission, 2022a).

Achieving this goal requires not only a steep expansion of EU electrolysis capacities, but also a rapid build-up of hydrogen markets. In the early implementation stage, where an interregional transport infrastructure is largely missing, local scaling potentials in the producing regions will be key for market formation. In this respect, European regions differ considerably, both in terms of production (renewable energy capacities) and in terms of utilisation potential (e.g. industrial structure, mobility needs) of green hydrogen. Location decisions can thus be critical for overcoming economic barriers to hydrogen deployment.

This article examines the emerging spatial pattern of hydrogen capacity building in Europe based on the current project landscape. Ambitions of hydrogen hotspots are mirrored against their regional usage potentials and framework conditions. In this way, the technology- and cost-centered view dominating the literature is complemented by a regional economic perspective. Based on this, we discuss policy options for the EU and its member states to speed up the vision of a European hydrogen economy governed by the principle of comparative advantages.

Economic role of green hydrogen

Among the existing options in the field of sector coupling, technologies that convert renewable electricity directly into heat (heat pumps, electrode boilers) or mechanical energy (battery electric vehicles) tend to have the most favourable energy balance (Piebalgs et al., 2021). Due to the energy losses involved in the additional conversion step, the use of renewable electricity for the production of green hydrogen is energetically inferior. However, not all forms of energy use can be directly electrified in a meaningful way. By contrast, green hydrogen can be used directly as a gas, in many fields fully or partly replacing fossil natural gas. In addition to energy purposes, it can be used as a feedstock by

Open Access funding provided by ZBW – Leibniz Information Centre for Economics.

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the chemical industry for the production of fertilisers and synthetic fuels, as well as a reducing agent in steel production (Wolf and Zander, 2021). Thereby, it also contributes to a reduction in process emissions.

By now, there is a consensus that Europe cannot meet its future hydrogen demand from domestic production alone, given its limited renewable energy (RE) potential. However, own electrolysis capacities are indispensable as a supplement to hydrogen imports from third countries, in order to accelerate market development and prevent the emergence of new external dependencies. This is also made clear by the European Commission, which has set medium-term targets of 10 million tonnes of renewable hydrogen for domestic production and 10 million tonnes for imports by 2030, thus emphasising the equal importance of the two supply channels (European Commission, 2022a). Since many industries and energy forms will be involved in the implementation, new potentials for a European division of labour emerge.

In order for a hydrogen economy to develop in competition with other energy sources, well-functioning markets are essential as allocation channels. The established system of emissions certificate trading in Europe (EU-ETS) already provides an important building block for rewarding the CO_2 savings of different technologies. But green hydrogen itself must also be priced by market forces, such that its total operational and economic costs are comparable with other forms of energy. Only through decentralised trading governed by market prices will funds be channelled into sensible investments contributing to overall energy efficiency. There are still hurdles to overcome for the establishment of such a price mechanism.

Economic barriers

The production and use of green hydrogen in Europe is currently still taking place in a conglomerate of more or less advanced pilot projects, most of which are regionally oriented. Trade across the borders of project networks and cooperative partnerships does not yet occur to any significant extent. There are reasons for this, mostly related to capacity and costs. First of all, the necessary superregional infrastructure is lacking. On the one hand, this concerns the possibility of affordable transport of green hydrogen. Large quantities of hydrogen will have to be transported within Europe primarily via pipelines. However, apart from a few regional pipelines that are not publicly accessible, there is still no hydrogen pipeline network in Europe. In principle, it is possible to inject hydrogen into the natural gas network, but technical limitations must be taken into account. In order to feed in large quantities of hydrogen, existing networks will have to be upgraded, and the construction of additional hydrogen pipelines will still be necessary for import corridors and important production regions (EHB Initiative, 2021). The second problem is the cost of electrolysis, especially the combination of high fixed costs and low efficiencies. Although newer generations of electrolysers have efficiency advantages, they also generate higher investment requirements (Ansari et al., 2022). In addition, in some regions there is a lack of usable renewable electricity, creating a supply-related problem.

Against this background, market formation can be delayed mainly for two reasons. One is the coincidence of economies of scale and regulatory uncertainty. For the profitability of private investments, the extent to which such economies of scale can actually be exploited is crucial. A significant uncertainty factor is governmental influence on the relative price of green hydrogen. This concerns the development of CO_2 certificate prices and related market regulation, but also the question of burdening hydrogen supply chains with government levies. Regulations in this area still vary widely from one member state to another. Investment restraint is a logical consequence in such an environment, and market development fails to materialise.

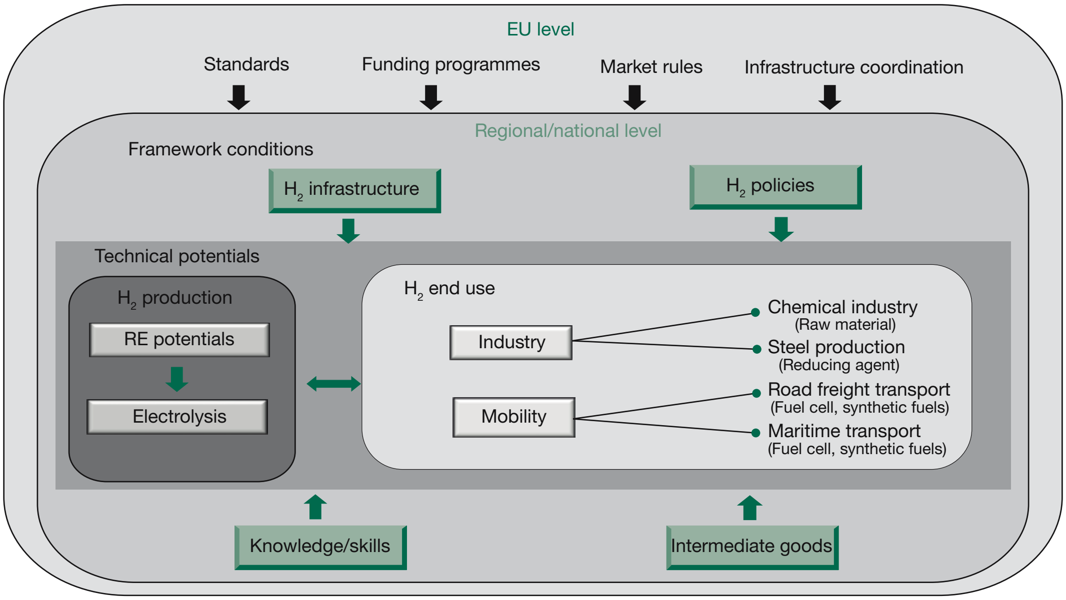
A second factor is the chicken-and-egg problem between markets and infrastructure. The formation of functioning markets requires flexible and non-discriminatory access to transport and storage infrastructure. Conversely, the development of a public infrastructure network only becomes profitable with the prospect of continuously high hydrogen flows. The European Hydrogen Backbone Initiative, an association of European energy network operators, estimates the cost of building a pan-European pipeline network to be in the order of €80-€143 billion by 2040 (EHB Initiative, 2022). This coordination problem can ultimately only be resolved through political impetus.

With a combination of regulatory market incentives and government start-up financing, policymakers can promote scaling and thus accelerate market development. For this, the heterogeneity of economic structures, but also differences in centrality and topographic-climatic characteristics of the European regions entail very different starting conditions at the regional level. The goal of a hydrogen economy thus becomes a spatial economic problem: for the European hydrogen market of tomorrow, local potentials must be identified today and exploited in a targeted manner. So far, this aspect has hardly been discussed in the debate, which has focused on technological parameters.

Location criteria for green hydrogen production

Due to its versatile use, it is difficult to determine general criteria for an ideal production site for green hydrogen.

Figure 1
Interplay of location criteria for green hydrogen production



Note: RE stands for renewable energy.

Source: Author's representation.

One essential location criterion is the availability of sufficient local RE potential for electrolysis purposes. Spatial proximity of electrolysers to renewable electricity generation plants helps to limit further cost pressure on electricity network expansion, and to facilitate the integration of electrolyser activities into the balancing management of network operators. Kakoulaki et al. (2021) have estimated the maximum potential of renewable electricity generation for European NUTS 2 regions. Against the background of costly hydrogen transport, those locations offer the best conditions for a rapid market development where high RE opportunities meet an equally high local demand potential. To illustrate regional demand potentials, we focus on four application sectors of green hydrogen that are considered key for the forthcoming roll-out (Hydrogen Council, 2020): the chemical industry, steel production, road freight transport and maritime transport. In these areas, the distribution of regional usage potentials is assessed by means of available indicators on regional employment (chemical industry), production capacities (steel production) and transport intensity.

In addition to these technical potentials, the local framework conditions likewise have an influence on the suitability of a location. We consider the physical infrastructure (transport networks, refuelling stations), the regional presence of producers of important inputs, and the availability of knowledge and skilled workers in the region. Figure 1 presents our analytical scheme and the interplay of location criteria. Not all of these conditions can be assessed based on official regional statistics, but platforms like the Fuel Cells and Hydrogen (FCH) Observatory offer a range of detailed geoinformation on the location of infrastructure, input suppliers and the offer of H_2training programmes. This geoinformation was aggregated by us to the regional level.

Regions are defined according to the NUTS 2 classification, the most disaggregate level at which comparative economic indicators for the application fields are available. Table 1 lists the set of indicators used for the analysis.

The roll-out of green hydrogen in Europe

The application of green hydrogen in Europe has now moved beyond the phase of purely technical testing. Current implementation projects focus on the creation of so-called hydrogen valleys. This essentially means the development of regional markets for hydrogen production and use, where use is not limited to individual consumers but is designed to be cross-sectoral. The recent hydrogen valley progress report by Weichenhain et al. (2022) defines the four constituent characteristics: significant scale of investment (at least tens of millions), supply to multiple sectors, coverage of wide ranges of value chains, and clear spatial delineation. In particular, hydrogen valleys are distinguished from pure pilot and demonstration projects: the focus is on upscaling under real market conditions and the establishment of economically viable supply chains.

Table 1
Overview of location criteria for green hydrogen production

Indicator	Explanation	Unit	Source
Renewable energy potential			
Potential renewable electricity	Annual generation potential	Terawatt-hour	Kakoulaki et al. (2021)
H_2 usage potentials			
Chemical industry	Employees chemical industry	No. employees	Eurostat (2022)
Steel production	Annual production capacities	Tonnes	EUFOR (2022)
Road freight transport	Average loaded/unloaded road freight	Million tonne-kilometres	Eurostat (2022)
Maritime transport	Loaded and unloaded freight at harbours	Kilotonnes	Eurostat (2022)
Framework conditions			
Scientists and engineers	Regional employment of scient. and eng.	No. employees	Eurostat (2022)
H_2training programmes	Existence of H_2-related training offers	Yes/No	FCH Observatory (2022a)
Suppliers of fuel cell stacks/systems	Presence in the region	Yes/No	FCH Observatory (2022b)
Suppliers of electrolyser stacks/systems	Presence in the region	Yes/No	FCH Observatory (2022b)
Suppliers of stack components	Presence in the region	Yes/No	FCH Observatory (2022b)
Dedicated hydrogen pipelines	Presence in the region	Yes/No	FCH Observatory (2022c)
Hydrogen refuelling stations	Number of stations	No. stations	glpautogas (2022)

Source: Author's representation.

In her State of the Union address in 2020, European Commission President von der Leyen highlighted the development of hydrogen valleys as an important purpose for the means of the NextGenerationEU fund (von der Leyen, 2020). In February 2021, the Clean Hydrogen Partnership (CHP) as a new funding source for hydrogen projects was presented. A first call for proposals in May 2022 came up with a tender volume of €300 million (CHP, 2022). These funds are to be used to launch at least five hydrogen valleys. Moreover, 22 EU member states and Norway committed themselves in a manifesto to the development of European value chains in the field of hydrogen systems and technologies and announced the initiation of Important Projects of Common European Interest (EU Countries/Norway, 2020). As a first technology wave called Hy2Tech, 41 such cross-border projects were approved by the European Commission in July 2022. A second wave of Hy2Use projects with a total volume of over €5 billion, focusing on application technologies and infrastructure, was approved just a short time later in September 2022 (European Commission, 2022b).

The rapid expansion of funding channels has promoted the formation of project consortia in almost all parts of Europe. The current project plans and ambitions are as complex as the possible uses of green hydrogen. They range from the creation of local electrolysis capacities for individual industrial customers to the conception of pan-European supply chains, including the required transport infrastructure. Especially the large-scale projects currently envisaged will most likely shape the spatial structure of a European hydrogen economy over the next decades. They will decide on the emergence of hydrogen flagship regions in Europa, which, in turn, can help to incentivise supraregional market integration through infrastructure expansion.

Currently, there exists no official central register of publicly funded green hydrogen projects in Europe. However, some platforms maintain more or less comprehensive project databases. By far the most comprehensive database is the Hydrogen Projects Database of the International Energy Agency (IEA). According to its own statements, it includes almost all projects announced since 2000 to date that serve to generate hydrogen as an energy source and/or as a means of combating climate change (IEA, 2022). In addition to numerous completed micro-projects, the list also contains recently announced large-scale projects, including information on the timeframe and scope of the planned generation capacities as well as the intended utilisation purposes. We cross-checked this project list with two other up-to-date databases: the project overviews of the Mission Innovation (MI) Hydrogen Valley Platform (CHP/MI, 2022) and the Hydrogen Project Visualisation Platform of the Association of European Network of Transmission System Operators for Gas (ENTSOG, 2022). After a clean-up procedure,[1] a list of a total of 262 project entries was

1 Only projects that envisage the creation of capacities for the electrolytic production of hydrogen and have set clear volume targets and timeframes are considered. Among these, micro-projects (< 1 MW electrolysis capacity) as well as projects that exclusively provide hydrogen for reconversion to electricity were excluded. Future offshore electrolysis capacities were excluded due to the lack of allocation options.

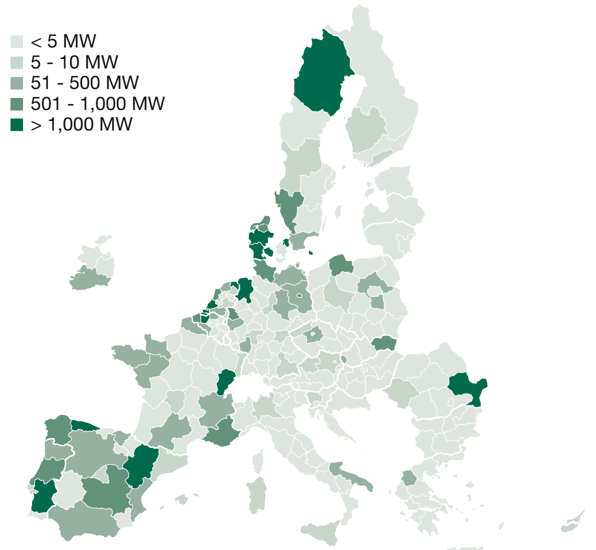
created, which we subsequently assigned to individual NUTS 2 regions on the basis of their electrolysis location (according to available project information).

Figure 2 shows the distribution of the total regional capacities determined for the planning period up to 2030. Due to the upscaling activities of the coming years, it is decisively influenced by the major projects currently in the planning phase. Of course, it cannot provide any information on the technical feasibility of individual projects. In this respect, it should be read primarily as a map of ambitions. It reveals a Europe with widely differing speeds. Distinctive regional centres of production can be identified, which are at the same time widely distributed throughout the EU. The Iberian Peninsula and the North Sea Region are the most prominent centres. Overall, coastal regions play an important role in planning. In a country comparison, the low presence of Italy, central parts of France and southern Germany on the project map is striking. This involves industrial core regions such as Île-de-France (FR) and Lombardia (IT). Planned capacities for the eastern member states are also comparatively modest, with the exception of a few large-scale projects.

The outstanding position of some regions in planned electrolyser capacity deserves a separate analysis. For this purpose, we consider the subgroup of those NUTS 2 regions for which electrolysis capacities of more than 1 GW are planned by 2030, henceforth termed "focus regions". This applies to 14 of 241 EU regions. These 14 regions exhibit a total planned capacity of 55.3 GW. This alone would account for more than half of the EU-wide 90-100 GW that, according to the European Clean Hydrogen Alliance, will be needed to meet the 10-million-tonnes target by 2030 (ECH, 2022). Three each of the focus regions are located in Denmark (Hovedstaden, Midtjylland, Syddanmark) and the Netherlands (Groningen, Zeeland, Zuid-Holland), two in Spain (Aragón, Principado de Asturias), and one each in Belgium (Oost-Vlaanderen), France (France-Comté), Germany (Weser-Ems), Portugal (Alentejo), Romania (Sud-Est), and Sweden (Övre Norrland). A comparison of their specific potentials with the rest of the EU provides information on how their local conditions can contribute to the market ramp-up in Europe.

According to the estimates of Kakoulaki et al. (2021), some of the focus regions possess very high area potentials for renewable electricity generation in comparison with the rest of the EU (see Figure 3). In relation to the size (in square kilometres) of the regions, this is especially true for the North Sea regions, due to their high wind power potentials. However, this by no means holds for all focus regions. Figure 4 maps the relationship between planned electrolysis capacities and the distribution of hydrogen

Figure 2
Planned electrolysis capacities in EU NUTS 2 regions until 2030

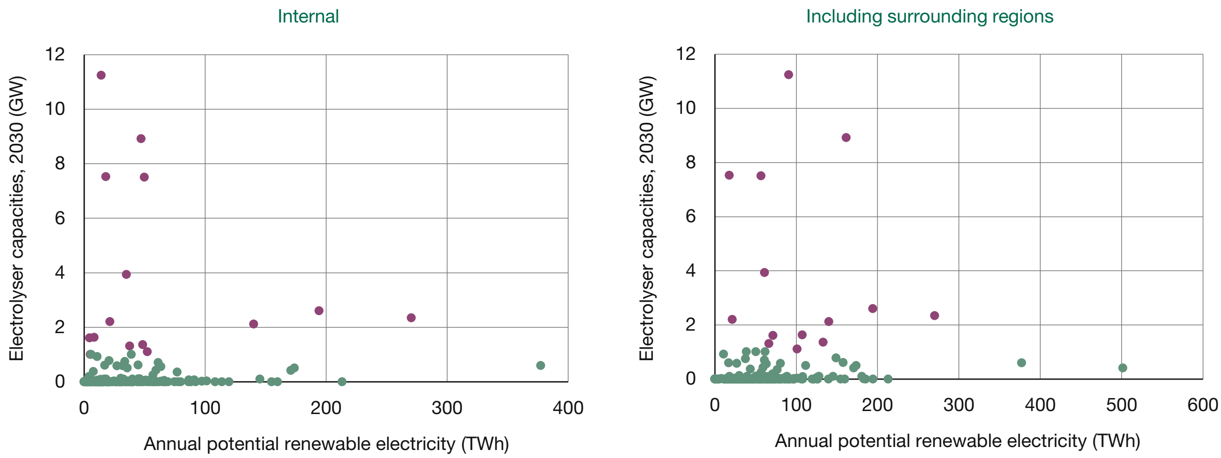


Sources: CHP/MI (2022); ENTSOG (2022); IEA (2022); author's calculations.

demand potentials across regions. Here again, the picture is very heterogeneous. When viewed in relation to region size, only one of the 14 focus regions (Zeeland (NL)) exhibits above-average potentials compared to the rest of the EU in all of the four investigated application fields. Within each single field, only a small minority of the focus regions exhibits exceptionally high concentrations of usage potentials. For instance, with respect to steel production, this only holds for Asturias (ES) and Ost-Vlaanderen (BE), while in maritime transport Zuid-Holland (NL) stands out. In the majority of focus regions, above-average potentials can only be noticed for individual fields, if at all. In five of the regions, they are predominantly below average (Alentejo (PT), Aragón (ES), France-Comté (FR), Övre Norrland (SE), Sud-Est (RO)). This picture remains basically unchanged if the potentials of the surrounding regions are included.

Regarding the regional framework conditions, the focus regions as a whole hardly appear to be exceptional (Table 2). The most favourable conditions are observed for regional upstream capacities and the physical infrastructure. At least half of the focus regions are home to manufacturers of stack components, and at least a quarter are home to manufacturers of electrolysis stacks/systems – figures that are well above average in an EU comparison. The focus regions also feature a slightly higher average density of hydrogen refuelling stations than the rest of the EU, and more often already host dedicated hydrogen pipelines. Regarding the availability of skilled workers, the focus regions as a group do not stand out from the rest of the EU.

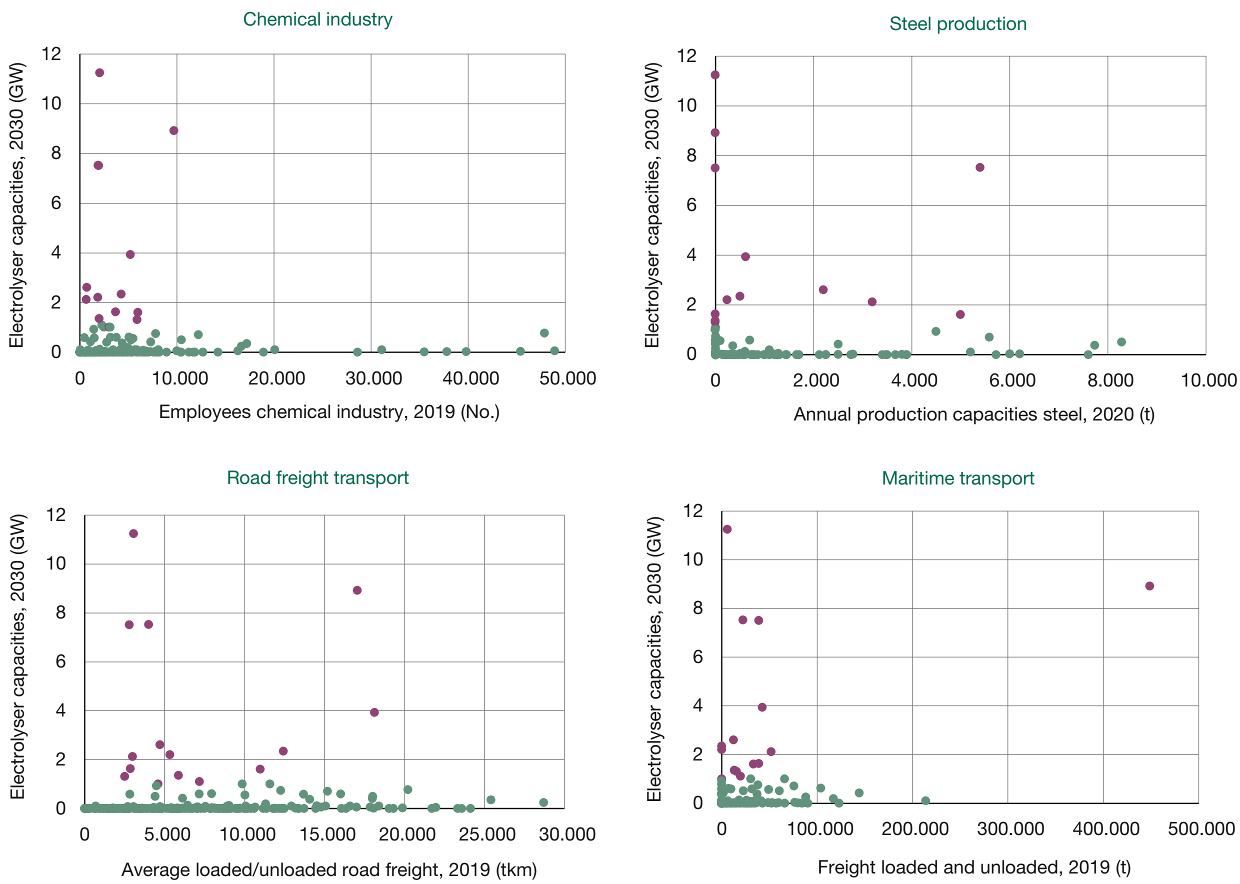
Figure 3
Planned electrolysis capacities vs. renewable energy potentials



Notes: Pink: focus regions. Surrounding regions: regions within 100 km radius of regional centre.

Sources: Kakoulaki et al. (2021); CHP/MI (2022); ENTSOG (2022); IEA (2022); author's calculations.

Figure 4
Planned electrolysis capacities vs. hydrogen usage potential indicators



Note: Pink: focus regions.

Sources: CHP/MI (2022); ENTSOG (2022); Eurostat (2022); Eurofer (2022); IEA (2022); author's calculations.

Implications for EU hydrogen policies

From a European perspective, the regions currently selected as important locations for hydrogen production are thus only partially predestined for their role. In particular, in some cases there is a gap between the elevated position as a production site and the expected importance as a consumer region, even when taking into account the potentials of the region's surroundings. For many implementation projects, the interregional distribution of the generated hydrogen will therefore have to be part of the economic plan already in the early stages. At the same time, in many of those European regions characterised by favourable potentials, hardly any significant project activities have been observed so far. In the absence of a pan-European transport infrastructure, there is a risk that existing scaling potentials will not be exploited in a timely manner, and that the chicken-and-egg problem in infrastructure development will remain unsolved. This threatens to delay the development of hydrogen supply chains in Europe. However, the EU cannot afford to lose time here. The development of import channels from third countries is being driven forward in parallel. Although green hydrogen imported from regions such as North Africa or South America is costly due to the time-consuming transport, this can be offset on the production side by higher RE potentials (Hydrogen Council, 2020).

This threatens to create new external dependencies in the course of decarbonisation. The decision-makers in the EU are therefore well advised to align the promotion policy in the field of green hydrogen even more consistently with the goal of competitiveness. This includes the encouragement of integrated projects in spatial proximity to future European utilisation centres: only if the spatial-economic advantages of short distances can really be exploited will hydrogen valleys live up to their name.

Simultaneously, the current project landscape forces decision-makers to address the development of the infrastructure and the harmonisation of regulatory framework conditions for the formation of transnational markets even more decisively. On the one hand, this presupposes the existence of sufficient investment incentives for infrastructure operators. In hydrogen transport, this concerns both the retrofitting of parts of the natural gas network and the supplementary construction of new hydrogen pipelines. In order to shorten planning and approval procedures and save construction costs, retrofitting existing gas networks should be made possible wherever this is technically feasible. Financing barriers related to unbundling requirements should be kept as low as possible in the interest of affordable transport costs, without ignoring the risk of supplier concentration. At the same time, regulatory barriers to cross-border transport should be removed and non-discriminatory access for all suppliers of sustainable hydrogen should be ensured. In addition, the competitive conditions for hydrogen supply chains should be harmonised as far as possible throughout Europe. This concerns the tax-related burden on electricity purchases of electrolysers, but also the question of discounting fees for network use in hydrogen transport by electrolysers and storage operators. The long-term goal should be the creation of a European division of labour, which is characterised as little as possible by the activities of individual lighthouse projects, and as much as possible by the real comparative advantages of the regions.

Table 2
Regional framework conditions in focus regions and EU average

Indicator	Unit	Focus regions	EU NUTS 2 average
Average density of scientists and engineers*	No. workers per km^2	14.93	16.39
Regions with H_2 training programmes**	%	28.57	23.08
Regions hosting suppliers of fuel cell stacks/systems**	%	21.43	12.82
Regions hosting suppliers of electrolyser stacks/systems**	%	28.57	25.64
Regions hosting suppliers of stack components**	%	50.00	36.75
Regions with dedicated hydrogen pipelines in place**	%	14.29	6.84
Average number of hydrogen refuelling stations***	No. stations	1.07	0.74

Sources: * Eurostat (2022); ** FCH Observatory, author's region assignment based on location information; *** glpautogas.info, author's region assignment based on location information.

Conclusion

The rapid development of markets for green hydrogen is essential for the entry into a European hydrogen economy. For this to succeed, economies of scale in hydrogen production must be exploited and barriers to infrastructure development must be overcome. Regional production and utilisation potentials play a key role: in the absence of a supraregional transport infrastructure, they provide the economic impetus for capacity expansion in all parts of the supply chain, and thus for the future emergence of interregional markets. The success of the transformation is thus not only determined by technology and business optimisation, but also crucially by the spatial economic conditions in Europe. Hydrogen generation, infrastructure and application technologies must not only be expanded in parallel, but the expansion must be spatially synchronised.

This article shows that in the spatial distribution of hydrogen valleys currently materialising, a few regions stand out with planned electrolysis capacities exceptionally high. However, this outstanding position is not always accompanied by above-average regional generation or utilisation potentials, even if surrounding regions are included. For the upcoming decisive phase of capacity expansion, there is a risk that the path towards economic viability will be slowed down in part by supraregional infrastructure restrictions. Since a considerable amount of public money is invested in hydrogen projects, European policy should fulfill its monitoring competencies. Better spatial coordination and more consistent alignment of the projects currently funded through a variety of channels is necessary.

The integration of the emerging regional markets represents the next step in the development of a European hydrogen economy. It is a prerequisite for the establishment of an efficient spatial division of labour in the production and use of green hydrogen. Only in this way will European H_2 supply chains become competitive with hydrogen import channels. The right political impetus is needed today to accelerate this process. Here, too, a value chain-oriented approach is required: regulatory incentives should focus equally on production, utilisation and infrastructure. European harmonisation is important to avoid distortions in allocation. This applies to the levy-based charging of electrolysers and storage operators as well as to the regulation of future hydrogen networks. The European Commission has already made some proposals in this direction, but in many areas there is still a need for specification and coordination.

For the future, improved spatial management also requires an expansion of the information base. This concerns the estimation of regional production costs and volume forecasts as well as the costs of interregional hydrogen transport. First, detailed bottom-up analyses of small-scale potentials as a supplement to official regional data is necessary. Second, the planning of the intra-European hydrogen transport infrastructure should be concretised, to allow for determining the costs resulting from spatial distance in sufficient detail.

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