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Establishing hydrogen hubs in Europe

An analysis of the European hydrogen landscape

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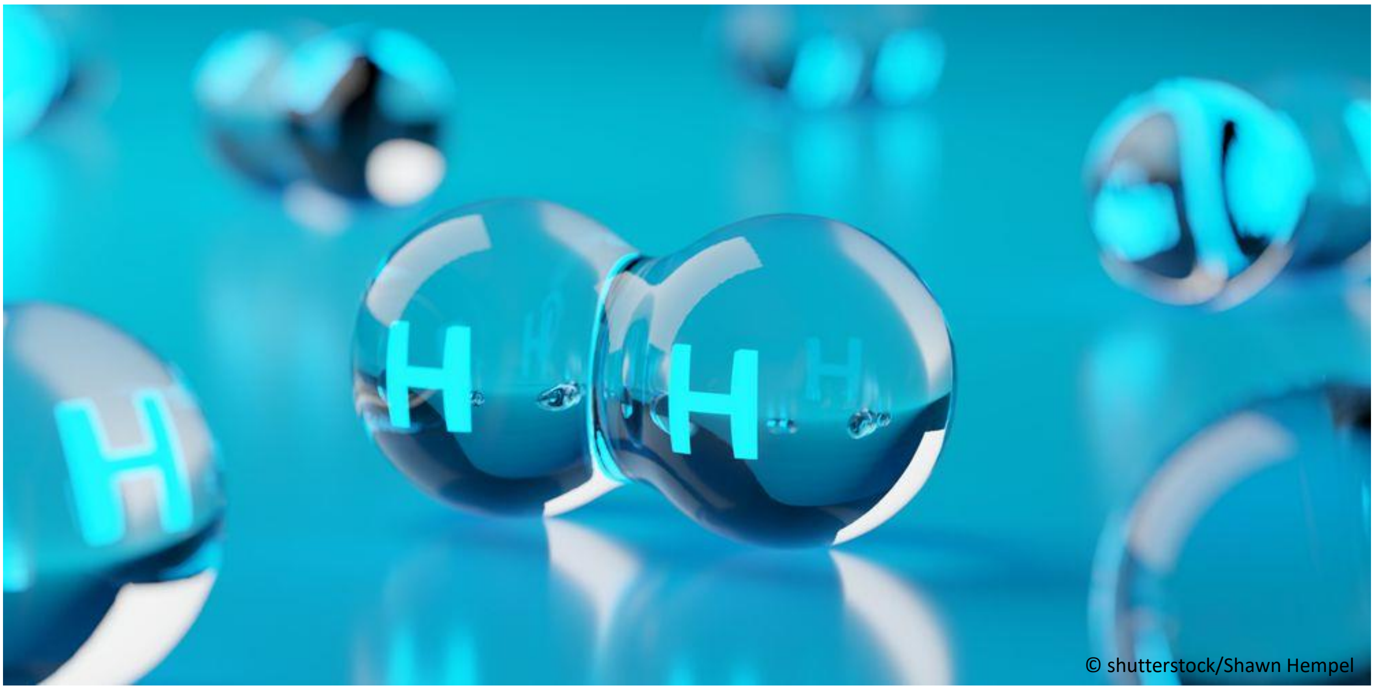

Green hydrogen has outgrown the testing stage: over the next few years, large consortia across Europe will be investing large sums to build the supply chains of tomorrow. This phase will determine our success or failure in the race for this technology. Europe as a whole will only be successful if it aligns the development of supply chains with the potential of its regions and exploits the advantages of a European division of labour. This cepInput, the first analysis of the geographical layout of a European hydrogen economy, provides food for thought.

Key propositions:

- In view of the diverse options for utilisation, the regional economic structure in Europe offers **great potential for a European division of labour** along hydrogen supply chains.
- This potential is not fully reflected in the geographical distribution of the major projects that are currently in the starting blocks.
- **Improving European coordination of funding channels** and ensuring that they are consistently aligned with regional economic criteria is important in the current start-up phase.
- The medium-term goal must be the **emergence of transregional markets** for green hydrogen in Europe. The conditions for this must start being created today with increased promotion of infrastructure development and by harmonising market regulation.

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1 Context

The goal of climate neutrality by 2050 is the central long-term challenge for the European economic system and this by no means only affects the energy sector. All sectors of the economy are under pressure to decarbonise processes or make them emission-free through other measures. For this to succeed, the technologies deployed must extend the use of electricity from renewable sources (RES-E) beyond direct consumption to the areas of heat and mobility, i.e. contribute to sector coupling. The ability to produce green hydrogen using renewable electricity, and the diverse possibilities for its application in industry, mobility and the building sector, make it a suitable energy source for this purpose. In the recent energy crisis, it has increasingly gained attention as a possible means of breaking the dependence on fossil fuels. As part of its *RePowerEU plan*, the European Commission has set a target of increasing domestic production of renewable hydrogen to 10 million tonnes by 2030.[1] Achieving this goal will not only require a marked expansion in domestic electrolysis capacities, but also massive investment in hydrogen-based application technologies.

For a European hydrogen economy to succeed, it is essential to avoid the emergence of a patchwork of markets limited by region because European regions differ significantly in their potential, both in terms of production (RE capacities, technological know-how) and utilisation (e.g. industrial structure, mobility needs) of renewable hydrogen. In the future, therefore, a genuine European division of labour, based on the comparative advantages of the regions, will also be needed in the hydrogen trade. In addition to developing cross-regional infrastructure, this also requires an honest assessment of the extent to which the focus of project funding in Europe does justice to geographical advantages regarding specialisation.

This article explores the opportunities for regions to participate in a European hydrogen economy, and contrasts them with the emerging pattern of project activity. Unlike previous studies involving country comparisons, this one is not aiming to draw conclusions on cost or volume. Instead, we seek to identify the segments of future hydrogen supply chains in which European regions have potential, and how this potential corresponds to the local (infrastructure, knowledge, intermediaries) and national (funding policy) framework conditions. Thus, we want to contrast the usual techno-economic view with a regional economic perspective and, on that basis, we will investigate what instruments are available to the EU and Member States to support the increase in regional potential.

1 European Commission (2022a). REPowerEU: affordable, secure and sustainable energy for Europe. Communication COM(2022) 108 final

2 Establishing a European hydrogen economy

2.1 Benefits for climate policy and the economy

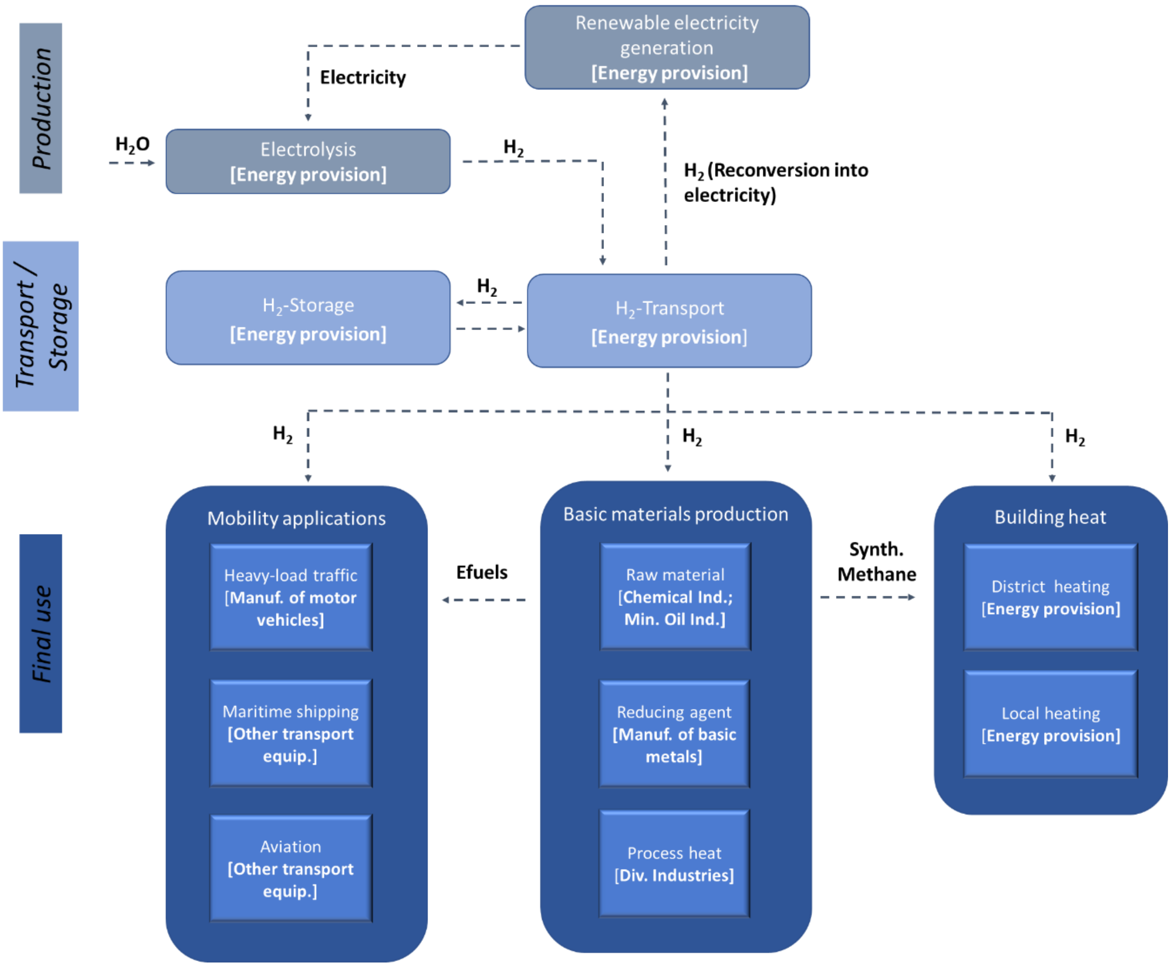
Among the existing options in the field of sector coupling, technologies that directly convert RES-E into heat (heat pumps, electrode boilers) or mechanical energy (battery electric propulsion) generally have the best energy balance. However, not all forms of energy use can be electrified directly in a viable manner. Nor is electrification a means of reducing non-energy greenhouse gas emissions, especially emissions from industrial processes. For this reason, methods of making renewable electricity usable in other ways will also be necessary in the future. The use of RES-E to produce hydrogen through the electrolysis of water molecules, so-called green hydrogen, is one such process. Although this technology is energetically inferior to electrification due to the loss of useful energy that this conversion step entails, it scores points on the variety of possible applications. Green hydrogen can be used directly as a gas, in many cases thereby replacing natural gas, either entirely or in part. However, it can also be used to produce synthetic heating and motor fuels. In addition to energy use, it can also be used as a raw material in the chemical industry and as a reducing agent in steel production, and can thus help to decarbonise industrial processes.[2] Figure 1 shows potential supply chains schematically according to economic sectors.

From an economic perspective, this potential diversity of supply chains also raises hopes for a significant effect on value creation and employment, especially for industrial regions under great pressure to transform. There is now a consensus that Europe cannot meet its future hydrogen requirement from domestic production alone, given the limited RE potential. However, Europe's own electrolysis capacities will be 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 status of the supply routes.[3] As potentially many sectors and forms of energy will be involved in the implementation, there is new potential for division of labour in Europe.

In order for such a division of labour to develop in competition with other energy sources, functioning markets are needed as steering instruments. The established system of emissions allowance trading in Europe already provides an important device for rewarding the CO_2 savings of different technologies. Green hydrogen itself must also be priced according to market forces thus making its total operational and societal costs comparable with other forms of energy. Only through decentralised regional and cross-sectoral trading controlled by market prices will funds be channelled into viable investments that will ensure that the European energy system is cost effective and energy efficient. There are still hurdles to overcome in the establishment of such a price mechanism.

[2] Wolf, A. (2022). How green hydrogen will make Europe more independent. cep**Input** No. 6 / 2022.
[3] Cf. European Commission (2022a).

Figure 1: Overview process chains



Source: Own illustration

2.2 Economic barriers

The production and use of green hydrogen in Europe is currently still taking place in a consortium of more or less advanced pilot projects, mostly with a regional focus. There is, as yet, no significant amount of cross-border trade taking place, beyond the bounds of project alliances and cooperation partnerships. This is due to reasons of both capacity and cost. Firstly, the necessary trans-regional infrastructure is lacking. This concerns, on the one hand, the possibility of transporting green hydrogen economically. Larger quantities of hydrogen will have to be transported within Europe primarily via pipelines. However, apart from a few pipelines that are not publicly accessible, there is as yet no hydrogen pipeline network in Europe. Although, in principle, there is the possibility of incorporating hydrogen into the natural gas grid, technical limitations must be taken into account in this respect. In order to supply large quantities of hydrogen, existing grids will certainly have to be converted; the construction of additional hydrogen pipelines will also be necessary for import corridors and intra-European production regions.[4] The second problem is the cost of electrolysis, particularly the combination of high fixed costs and low levels of efficiency. Although newer generations of

[4] EHB Initiative (2021). Analysing future demand, supply, and transport of hydrogen. Report – June 2021. European Hydrogen Backbone Initiative.

electrolysers have efficiency advantages, they also give rise to higher investment requirements.[5] In addition, in some regions, there is a lack of usable renewable electricity as a capacity-related problem.

High costs and infrastructure barriers are not in themselves specific to green hydrogen, but are typical of the early stages of many young technologies. This alone does not indicate the need for state support. Two additional factors are relevant. One factor is the **concurrence of economies of scale and regulatory uncertainty**. Economies of scale here mean a decrease in production costs per kg of green hydrogen as production volume increases. This cost reduction results from improved coverage of the fixed costs of capacity expansion (static economies of scale) and, in the medium term, also from efficiency gains through lessons learned (dynamic economies of scale). The extent to which such economies of scale can actually be exploited is crucial for the profitability of private investment. Governmental influence on the relative price of green hydrogen are a major factor for uncertainty. This concerns the development of carbon allowance prices and related market regulation, but also the issue of imposing government levies on hydrogen supply chains. Regulations in this area still vary widely from one Member State to another (see Section 3.3.4). Reluctance to invest is the logical consequence in such an environment, and market expansion 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, however, the construction of a public infrastructure network only becomes profitable with the prospect of continuously high hydrogen flows. The *European Hydrogen Backbone Initiative*, a group of European energy network operators, estimates the cost of building a pan-European pipeline network by 2040 to be in the order of € 80-143 billion.[6] Ultimately, a solution to this coordination problem requires political impetus.

With a combination of regulatory market incentives and governmental start-up financing, policy can support scaling and thus accelerate the market build-up. The emergence of price signals then enables users to weigh up the costs and the potential of different climate-neutral forms of energy in a transparent manner, which favours the realisation of cost-efficient decarbonisation pathways.

The heterogeneous nature of the economic structure, as well as differences in centralisation and in the topographical-climatic characteristics of the regions, provide for very different starting conditions within Europe. In view of the short time available, funding should focus on those regions that will enable rapid scaling due to their particular generation or utilisation potential. The goal of a hydrogen economy thus becomes an issue of regional economics: for the European hydrogen market of tomorrow, local potential must be identified today and exploited in a targeted manner. Not only the success of the transformation, but also the economic potency of Europe as an industrial location, will depend on it. This aspect has received little coverage in the debate so far, which has focused on technological and business parameters. In this cep**Input**, we are devoting an in-depth analysis to it.

[5] IEA (2022). Electrolysers – Tracking report. September 2022. International Energy Agency.

[6] EHB Initiative (2022). Estimated investment & cost. European Hydrogen Backbone Initiative. https://ehb.eu/page/estimated-investment-cost

3 Location analysis for EU regions

3.1 Analysis criteria

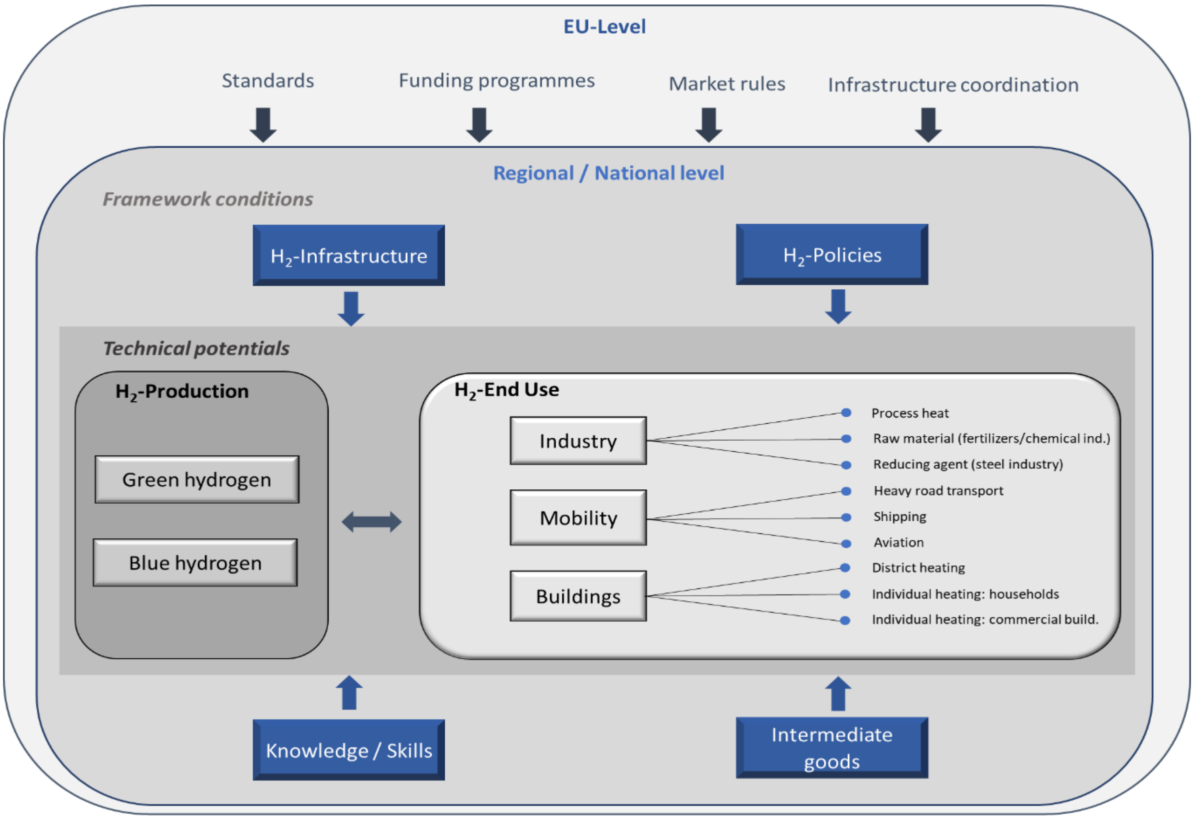
It is difficult to determine general criteria for an ideal green hydrogen production site because its versatility also means that regions with very different conditions can be equally suitable as a location. The crucial thing is that the regions exploit the potential for use that is appropriate to their geographical location and economic structure. Conventional systems of location analysis, based on a consideration of the competitive conditions, such as Porter's diamond model, are unsuitable for the description, as the markets for green hydrogen are only just emerging. In the following analysis, we therefore apply our own set of potential indicators to the European locations.

An important location criterion with regard to market development is the local availability of renewable electricity for electrolysis. This is because the level of capacity utilisation necessary for economic viability can only be achieved if there is the prospect of sufficient electricity being purchased over extensive periods during the operating hours that are theoretically possible. Geographical proximity to the power plants is also very important with regard to system integration. In principle, this criterion would support focusing electrolysis in a few locations characterised by particularly large RE potential. This would enable the optimum exploitation of economies of scale in hydrogen production and, at the same time, the large-scale cost reductions would drive market development on the demand side through falling prices. However, the importance of transport costs and capacity militates against such a geographical concentration. The low weight and - related to this - the high volatility of hydrogen molecules poses the risk of large energy losses. The high reactivity also means that attention must be given to the issue of keeping the hydrogen free of impurities. Where hydrogen is incorporated into existing grid infrastructure, there could also be a risk of the hydrogen diffusing into pipeline walls and thereby damaging them.[7] To avoid this, there is a need for retrofitting - or alternatively investment in new hydrogen networks. Thus, hydrogen transport will in either case be associated with significant fixed and variable costs. This perspective tends to support locating electrolysers near centres of consumption.

Based on this cost trade-off, the best conditions for rapid market development is offered by locations where significant RE generation opportunities meet equally significant local demand potential. In the next section, as is customary in the literature, we differentiate the demand potential according to sector, i.e. industry, heat/buildings and transport. Within the sectors, we consider those areas of application in which green hydrogen is classified as a sensible alternative to electrification when it comes to meeting the goal of decarbonisation. In addition to this technical potential, the local framework conditions also have an influence on the suitability of a location. This includes the physical infrastructure (transport, storage, application) as well as the regulatory conditions for marketing green hydrogen. The presence of producers of key upstream products in the region must also be taken into account when assessing the location. Ultimately, the availability of knowledge and qualified employees is also an important factor when it comes to developing a regional hydrogen economy. Figure 2 is a diagram of the structure of our analysis and the features considered. A summary of the origin and calculation of the indicators used can be found in the Annex in Table A1.

[7] ALPIQ (2021). Wasserstoff – Herausforderungen an die Infrastruktur. Energieforschungsgespräche Disentis, 22 January 2021.

Figure 2: Analysis structure



Source: Own illustration

As the regional indicators necessary for the analysis are only available in the NUTS classification[8], an official classification of territorial units in the EU, this is what we have relied upon for the geographical definition of the regions in our analysis. The NUTS classification is divided into a hierarchy of four levels (NUTS-0 to NUTS-3). There is a trade-off between geographical precision and data availability when choosing the NUTS level. NUTS-1, for example, is geographically relatively low resolution and characterised by particularly large differences in size. NUTS-3 is much higher resolution but does not offer sufficient relevant indicators. For our purposes, we have therefore chosen to use NUTS-2, which has medium resolution.[9] At this level, too, there are differences in size between the regions because of the non-uniform distribution of population and economic power, and due to the varying administrative divisions within the Member States. To measure the geographical concentration of potential in a region, the available regional key figures are therefore set in relation to the size of the area. At the same time, it should be borne in mind that, due to interregional exchange, regions can also draw some of their locational advantages from the potential of their neighbouring regions. This applies in particular to NUTS 2 regions consisting of urban conurbations. In the latter part of the analysis, we therefore look at the external potential that can be measured in the vicinity of a region.

[8] Eurostat (2022). NUTS - Nomenclature of territorial units for statistics.
[9] In Germany, this corresponds to the level of the administrative districts of a federal state (in larger federal states) or the federal state as a whole (in smaller federal states).

3.2 Technical potential

3.2.1 Production

In future, hydrogen produced by electrolysis will only be considered sustainable if the electricity used was generated entirely from renewable sources. On the production side, therefore, the availability of sufficient and predictable quantities of renewable electricity is a decisive condition in choosing a location for electrolysers. Existing wind and solar power capacity is not relevant in this regard, however, because the European Commission has made it clear that, in the medium term, it will only support the use of RES-E for electrolysis where it is based on additionally created RES capacities. This is to prevent the cannibalisation of exploitation options and the diversion of climate-neutral electricity needed for the electrification of consumer sectors into comparatively inefficient hydrogen production. Against this background, the Commission will formulate clear criteria for the recognition of green hydrogen as a renewable fuel in a long-awaited delegated act to the Renewable Energy Directive. According to the latest leak, the criterion of additionality is to be met for recognition after a transitional phase running until 2028: The electricity used must come from plants that were connected to the grid no earlier than 36 months before the electrolyser came on line.[10]

Although upcoming pilot projects will be protected by the transition period, the long-term sustainability requirements for a European hydrogen economy are thus clearly defined. When setting up significant electrolysis capacities, geographical proximity to future large-scale wind power and PV projects will represent a locational advantage. This requires correspondingly unexploited RE potential. Kakoulaki et al. (2021) have analysed the potential of regional sites for RES-E generation at the NUTS-2 regional level.[11] Specifically, the maximum annual potential for generating electricity from solar, hydro and wind power (onshore + offshore[12]) was estimated for the individual regions on the basis of topographical-climatic site information. Figure 3 illustrates this potential based on the total area of the region so that the geographical concentration of generation potential can be compared.[13] As expected, the potential is particularly high in the regions around the North Sea (wind power), in sunny Member States also in inland regions. On the input side, there is thus no need for hydrogen production in Europe to be heavily concentrated in a particular geographical area. However, a closer consideration must include a geographical comparison alongside the regional demand potential.

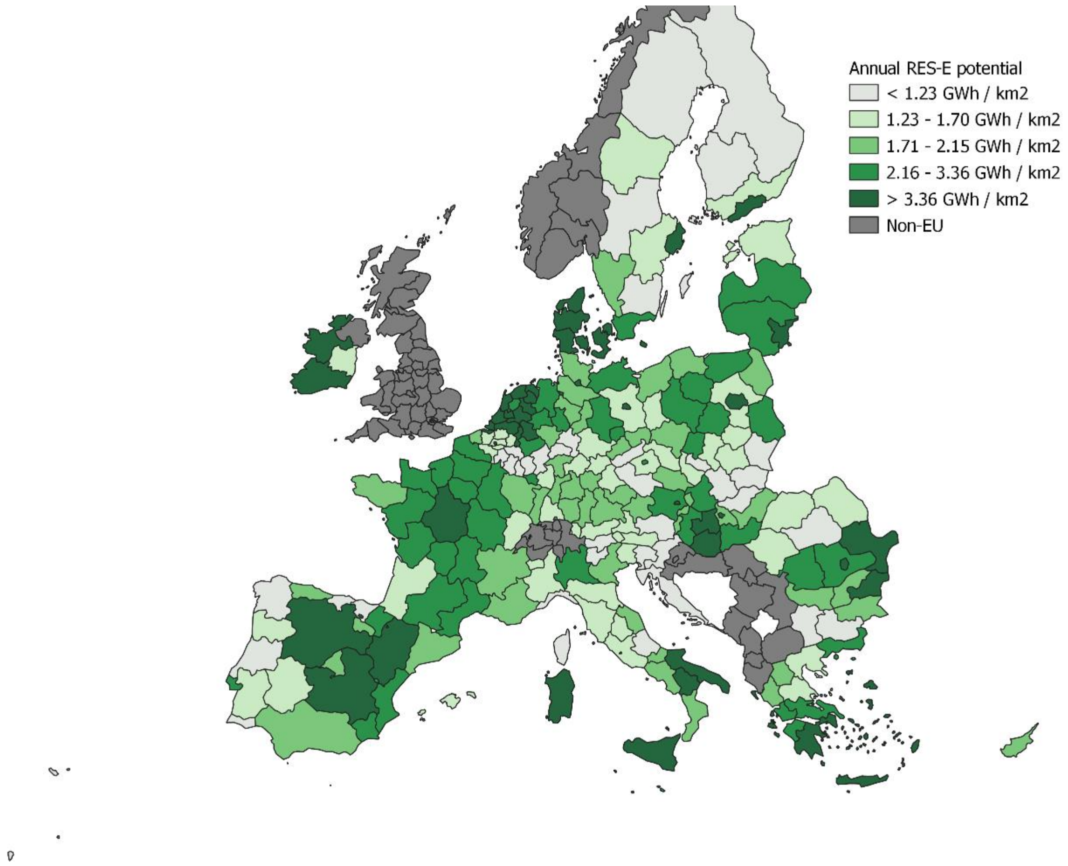
[10] SP Global (2022). New European Commission draft hydrogen rules draw industry, NGO ire.

[11] Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., & Jäger-Waldau, A. (2021). Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. Energy Conversion and Management, 228, 113649.

[12] In distributing offshore wind power potential, the authors used a simplified procedure due to the lack of a primary regional location: National estimates were assigned to individual regions based on the regional electricity demand distribution. This must be considered in the interpretation.

[13] Here and in subsequent maps, the EU regions have been divided into five equal groups (quintiles) based on their indicator values.

Figure 3: Regional RES-E potential in the EU



Sources: Kakoulaki et al. (2021); Eurostat (2022); own calculations

3.2.2 Usage - Industry

Hydrogen - still primarily obtained from fossil sources (steam reforming of natural gas, coal gasification) - is already used as a raw material in many production chains in the chemical and petrochemical industries. In the chemical industry, pure hydrogen is used together with nitrogen in the production of ammonia, an essential base material in the manufacture of many different nitrogen-based fertilisers. Hydrogen is used in conjunction with CO_2 to produce methanol. Methanol is the base material for a large number of chemical products (including formaldehyde and acetic acid). It is also of interest to the transport sector as a potential synthetic fuel. In the petroleum industry, hydrogen is used both as a raw material and as an energy source in the processing of crude oil. In various hydrogenation processes, hydrogen is used to remove impurities, particularly from sulphur.[14] In the medium term, converting fossil-fuel-based hydrogen production to electrolysis thus offers huge potential for the decarbonisation of important chemical process chains.

Existing feasibility studies assign the **chemical industry** a key role in the future industrial utilisation of green hydrogen.[15] Regions with pronounced economic activity in this area are therefore to be considered as potential centres of exploitation. In the absence of detailed information on the relevant production volumes at regional level, the regional employment density in the chemical industry can be used as an indicator of the potential. Individual regions in France (Île de France), Germany

[14] IEA (2019). The future of hydrogen – Technology report. June 2019. International Energy Agency.
[15] Hydrogen Council (2020). Path to hydrogen competitiveness – a cost perspective. 20 January 2020.

(Düsseldorf region, Rheinhessen-Pfalz) and Belgium (Antwerp region) clearly stand out in a Europe-wide comparison. Overall, the geographical distribution shows a positive correlation with the regional RES-E potential presented in Section 3.2.1 (correlation coefficient: +0.23). Regions with a potentially high demand for hydrogen due to the chemical industry therefore also have a comparatively high natural supply potential of renewable electricity for electrolysis.

In addition to utilisation as a raw material, the use of green hydrogen as a reduction agent in **steel production** is also the focus of feasibility studies. The customary, high-carbon method of steelmaking, where coke is used to smelt iron ore in blast furnaces, could be replaced by so-called direct reduction processes. In that case, the iron ore is not smelted but reduced to solid sponge iron, for which both natural gas and hydrogen can be used as the reducing agent. The use of green hydrogen can significantly improve the CO_2 balance of the process.[16] The presence of steel producers is thus also a significant indicator of regional potential for using green hydrogen. No regional comparative figures on the employment situation in Europe are available specifically for the steel industry. Instead, we have used geo-information from the industry association *Eurofer* on the distribution of steel production capacity in Europe, as the basis for the regional comparison.[17] A regional allocation of these figures at NUTS 2 level provides a geographical pattern that also correlates positively with the distribution of RES-E potential, albeit to a somewhat lesser extent than in the case of the chemical industry (correlation coefficient: +0.16). The geographical relationship between hydrogen demand and production-side potential is therefore less clear for this form of usage.

In addition to its use in material processing, green hydrogen can also be used as fuel for the provision of **heat for industrial processes**. Industrial heat use will have to play an important role in any future decarbonisation strategy, as it is responsible for a significant part of total energy end-use (according to IEA estimates, about 25% globally[18]). The vast majority of plants for heat generation are currently still operated using fossil fuels. Their share of final industrial energy consumption in the EU as a whole was 83% in 2020.[19] As a heat source for gas turbines and industrial furnaces, green hydrogen could help to significantly reduce this share. However, the strong competition from technology alternatives such as power-to-heat (heat pumps, electrode boilers) and biomass must be considered. For efficiency reasons, direct electricity use in particular will be the preferred path to decarbonisation for many applications in the medium term.[20] However, hydrogen is predicted to have a future in some high-temperature processes where electrification would be particularly technically difficult and costly. Here, hydrogen as an admixture or sole energy carrier could make established gas-based technologies carbon neutral and thus reduce the investment costs of decarbonisation.[21] In any case, the decision on this will be highly process-specific and will also vary within sectors. No sector can be generally excluded. In the regional comparison of heat-related utilisation potential in industry, heat consumption for industrial processes is therefore taken as a whole. Figure 4 shows the geographical distribution of estimated regional annual consumption per km_2. Industrial centres such as the Benelux countries, south-west Germany and northern Italy can clearly be identified as major consumers. Away

[16] Dena (2022). Einsatzgebiete für Power Fuels.

[17] Eurostat (2022). Map of EU steel production sites.

[18] IEA (2020). Renewables 2020 - Renewable heat. International Energy Agency. https://www.iea.org/reports/renewables-2020/renewable-heat

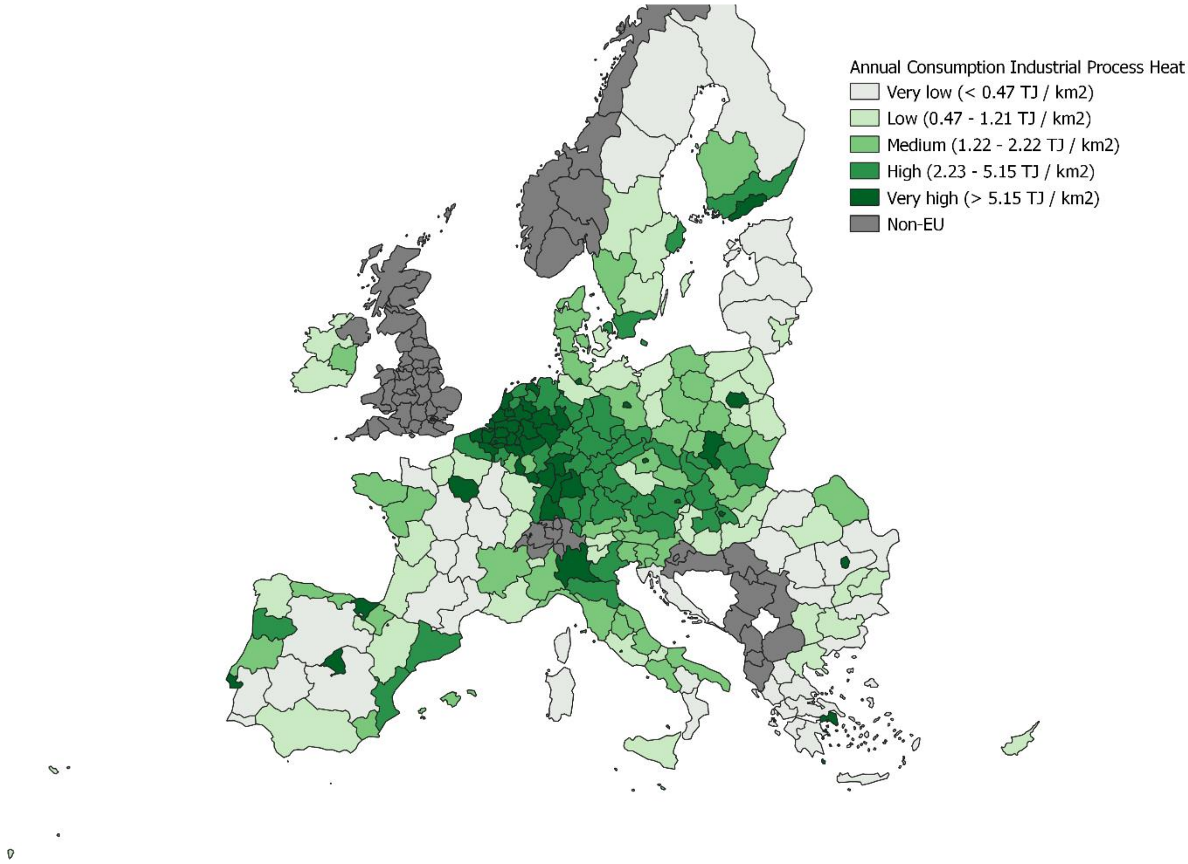
[19] Eurostat (2022). Energy balance sheets April 2022- EU27 energy balance 2020.

[20] Piebalgs, A., Jones, C., Dos Reis, P. C., Soroush, G., & Glachant, J. M. (2021). Cost-effective decarbonisation study. European Energy & Climate Journal, 10(1), 46-74.

[21] Deloitte (2022). Hydrogen opportunities for industrial products companies - Heat and power generation.

from the geographical centre, above-average values are largely confined to individual metropolitan regions. Here, too, there is an overall positive correlation with regional RES-E potential, which is somewhat more pronounced than in the case of the other industrial forms of utilisation (correlation coefficient: +0.38).

Figure 4: Estimate of regional consumption of heat for industrial processes in 2019



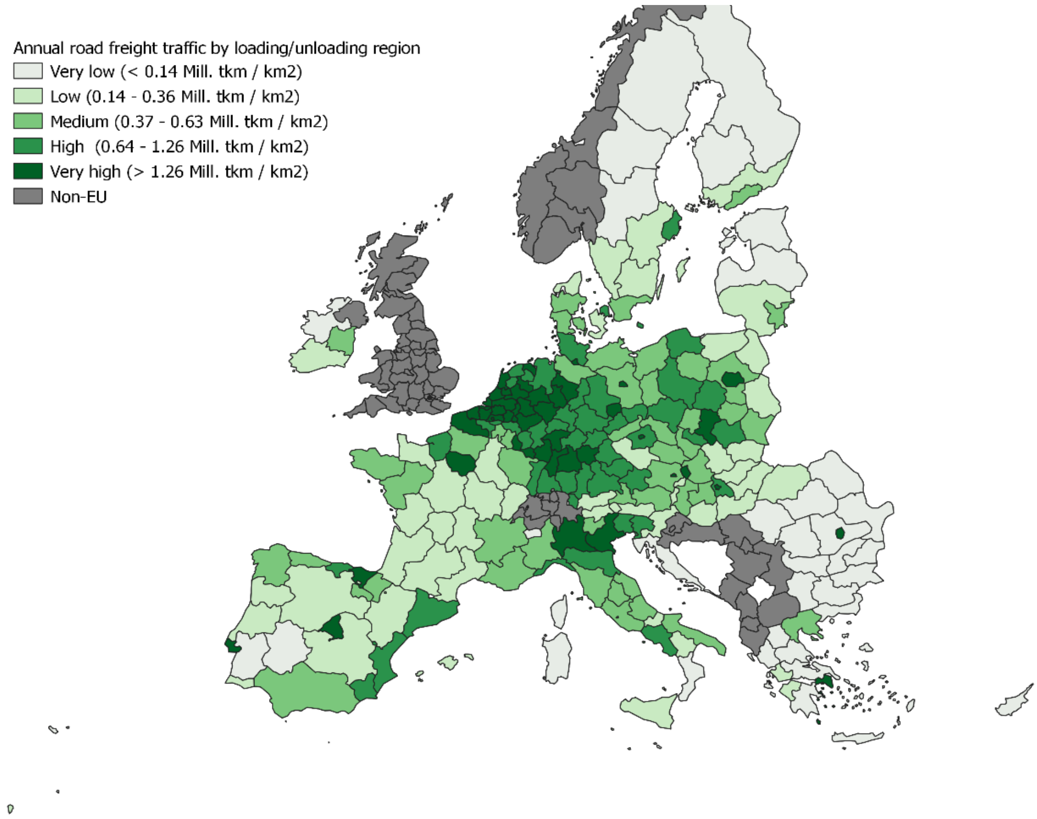
Source: Eurostat (2022); own illustration.

3.2.3 Usage- Mobility sector

In Europe, the mobility sector was the historical starting point for considerations on the development of cross-regional hydrogen supply chains. Right from the beginning, the focus has been on fuel cell technology. In the hydrogen fuel cell, energy from the chemical reaction between hydrogen and oxygen is converted into electricity. Fuel cell vehicles use hydrogen as fuel and are propelled by the electricity that is generated. However, this is by no means the only way of using hydrogen for vehicle propulsion. Hydrogen combustion engines can use hydrogen directly as a fuel. For this purpose, hydrogen is first compressed or liquefied. Alternatively, green hydrogen can also contribute indirectly to the transport transition as the starting point for the production of climate-neutral synthetic fuels. Synthetic fuels can be blended with petrol for petrol engines or the latter can be converted with little effort to use only synthetic fuels. The possible applications of the technologies, and the competitive situation with battery electric vehicles, differ depending on the mode of transport. Due to the high energy content of hydrogen (in a compressed state), hydrogen-based propulsion systems generally have the advantage of greater range than battery-powered vehicles. The refuelling process is also significantly less time-consuming.[22] These advantages are offset, however, by a significantly lower efficiency level than that of battery vehicles. A study by Horváth & Partners estimates average figures of 25% to 35% for this, as compared with 70% to 80% in the case of battery electric vehicles.[23]

In road transport, cost analyses nevertheless see competitive potential for the fuel cell, but mainly in heavy vehicles with long range requirements. In this segment, it can make the most of its advantages over battery-electric vehicles, of higher energy density and shorter charging times.[24] **Heavy goods transport** is thus an obvious area of application. Here, too, regional variations in utilisation potential are likely: The main transport routes for intra-European freight traffic are used to varying degrees by the regions. In this respect, it is not possible to measure a direct regional consumption potential - in the sense of a regional distribution of fuel consumption by trucks. There are no statistics for the location of refuelling operations. However, a comparatively high level of future demand can also be inferred based on the amount of cargo loaded and unloaded in a region. As an indicator for the intensity of regional road freight transport, we therefore use the average amount of freight loaded and unloaded per year in the region (in tonne-kilometres) according to Eurostat, in relation to the total area of the region. Figure 5 shows the regional distribution of this indicator in Europe. As to be expected, it is very similar to the distribution of industrial exploitation potential (see Section 3.2.2). Accordingly, its correlation with regional RES-E potential is also of a comparable (positive) order of magnitude (correlation coefficient: +0.32).

Figure 5: Intensity of regional road freight transport in 2019



Source: Eurostat (2022); own illustration.

22 VDI/VDE (2019). Brennstoffzellen- und Batteriefahrzeuge - Bedeutung für die Elektromobilität. VDI/VDE-Studie May 2019.
23 Horváth & Partners (2019). Automobilindustrie 2035 – Prognosen zur Zukunft.
24 Hydrogen Council (2020). Path to hydrogen competitiveness – a cost perspective. 20 January 2020.

There is broader scope for application in the **shipping sector.** Here, battery electric drives are largely impractical for longer distances. Green hydrogen will play a key role in the decarbonisation of these modes of transport. In the shipping sector, various hydrogen technologies are in direct competition with one another. In addition to fuel cells and the development of synthetic marine fuels, direct use via hydrogen combustion engines is also the subject of research. Current studies conclude that the future of maritime transport will lie in a combination of different climate-neutral fuels, depending on the local production potential in the port regions, and on the distances to be covered. Hydrogen-based fuels, especially ammonia, will play an important role in this.[25] Ammonia not used as fuel can be used for further processing in the fertiliser industry (see Section 3.2.1). Thus, in the future, port regions could become attractive as locations for regional H_2 production chains, in several respects: for the production of marine fuels, as well as for the further processing of imported hydrogen derivatives. The prerequisite is the establishment of suitable port infrastructure (e.g. ammonia crackers). As an indicator of regional exploitation potential in maritime transport, we use figures for the annual volume of cargo loaded and unloaded in regional seaports, in relation to the total area of the region. This indicates that significant potential only exists in a few coastal regions, particularly on the North Sea and the Mediterranean. The correlation with the regional distribution of RES-E potential is nevertheless clearly positive (correlation coefficient: +0.32), mainly due to high wind power potential in the coastal regions.

Finally, in the **aviation** sector, green hydrogen will play a key role in the future as a basis for the production of synthetic kerosene.[26] In the absence of viable alternatives, the goal of reducing greenhouse gas emissions in aviation, at least on longer routes, can only be achieved via the large-scale substitution of fossil fuels by synthetic paraffin, complemented by the use of biofuels. The intensity of airport use in the region, measured in terms of annual passenger volume (incoming + outgoing) per km^2, is a suitable indicator of regional potential. Here, too, there is a certain amount of correlation with the RE potential on the generation side (correlation coefficient: + 0.25).

3.2.4 Usage - Building sector

Green hydrogen can also be used as a heat source for room heating and hot water in homes, company offices and other buildings. Within certain technical limits, the existing gas grid infrastructure can be used to transport green hydrogen to heat consumers (see Section 3.3.3). However, the use of green hydrogen for room heating faces strong competition from other climate-neutral heating technologies. These include, most notably, the direct use of electricity from renewable energy (power-to-heat) in the form of heat pumps and electrode boilers. In principle, efficiencies of almost 100% or even, in the case of heat pumps, far more than 100%, are possible here, which means that power-to-gas technology will remain very much overshadowed in this area of application, even with future increases in efficiency.[27] In this sector, therefore, green hydrogen is particularly interesting for a transition phase in which the aim is to reduce the CO_2 footprint of the European heating sector as quickly as possible by using the existing heating technologies.

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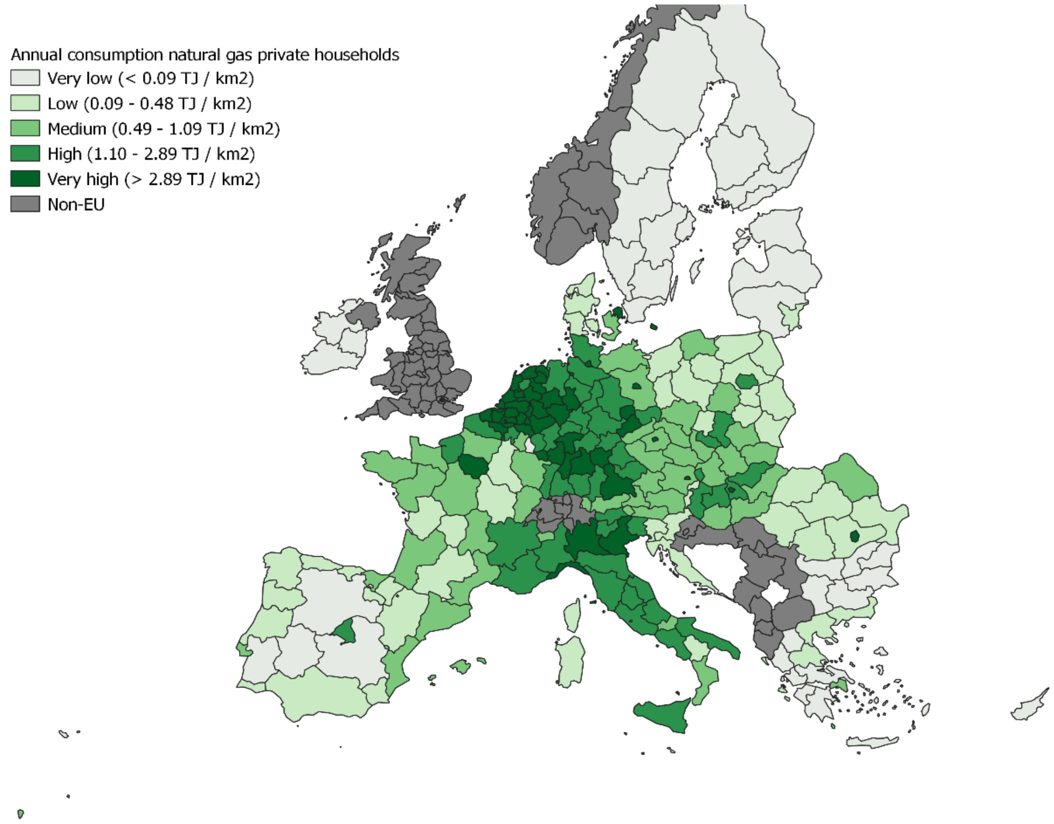
[25] Ics-shipping (2022). Fuelling the fourth propulsion revolution – an opportunity for all. May 2022. International Chamber of Shipping – In collaboration with Prof. Dr. Stefan Ulreich.

[26] IPP (2019). Potenzialstudie Wasserstoffwirtschaft. IPP ESN Power Engineering.

[27] Gerhardt, N., Bard, J., Schmitz, R., Beil, M., Pfennig, M., & Kneiske, T. (2020). Wasserstoff im zukünftigen Energiesystem: Fokus Gebäudewärme. Studie zum Einsatz von 2 im zukünftigen Energiesystem unter besonderer Berücksichtigung der Gebäudewärmeversorgung.

Modern gas condensing boilers can tolerate relatively high admixture rates of hydrogen (up to 30% according to the manufacturer Vaillant[28]). Relatively large sectoral exploitation potential thus arises for regions in which natural gas heating systems are particularly widespread as a heating technology. The **regional natural gas consumption of private households** is a good indicator of this. Figure 6 shows the distribution of estimated annual consumption per km^2. This indicates that the centres of consumption are largely concentrated in Central Europe. In some Member States, gas is generally of secondary importance for room heating. Here, too, there is a weak positive correlation with regional RES-E potential (correlation coefficient: +0.37). Similar estimates can be obtained for the regional use of **natural gas in the heating of commercial buildings**. In this case, urban economic centres show up even more clearly as large consumers in a regional comparison; apart from this, here too, the relationship to regional RE potential is basically positive (correlation coeff.: +0.32).

Figure 6: Estimate of regional natural gas consumption by households in 2019



Source: Eurostat (2022); own depiction of regions according to Sandoval's method (2021)[29]

Another possible use of green hydrogen in the building sector is in centralised heating supply systems. In combined heat and power plants, electrolytically produced hydrogen can be used as a heating source to generate district heating, either alone or in combination with other non-fossil (or fossil) fuels, depending on the technology. Here, too, the efficiency of electrolysis is of great importance for the question of viability.[30] **District heating consumption** is very unevenly distributed in Europe. District

[28] BBB (2022). Neue Heizgeräte versprechen Durchbruch beim Wasserstoff. BundesBauBlatt 1-2/2022.

[29] Sandoval, J.E. (2021). Estimation and simulation of gas demand time series for European NUTS-3 regions. Master's Thesis. University of Oldenburg.

[30] Böhm, H., Moser, S., Puschnigg, S., & Zauner, A. (2021). Power-to-hydrogen & district heating: Technology-based and infrastructure-oriented analysis of (future) sector coupling potential. International Journal of Hydrogen Energy, 46(63), 31938-31951.

heating is a particularly popular heating technology in northern and central Europe, but is hardly used in the south. This results in a certain geographical congruence with the wind power potential on the North Sea and Baltic Sea coasts; the correlation of regional district heating consumption with local RES-E potential is also positive (correlation coeff.: +0.31).

3.3 Local framework conditions

3.3.1 Know-how and knowledge sharing

The realisation of technical potential depends not only on infrastructure investment, but also on the availability of human capital. The transformation processes and application technologies of a future hydrogen economy give rise to a variety of new knowledge requirements for the labour force working in the sectors concerned at regional level. Due to the cross-sectoral applications of hydrogen, this could potentially affect a variety of professional groups, both at managerial (organisation) and operational (technical implementation) level. As a result, labour market experts also expect the emergence of new fields of activity and cross-divisional positions for which no standardised training programmes currently exist. In his analysis for the US labour market, Bezdek (2019) has produced a list of a total of 42 new hydrogen-related job titles. They are mainly in the highly paid segment and include primarily, but not exclusively, occupations in the engineering environment and project management/supervision activities.[31]

For the European regions that are being considered as future hydrogen locations, this is an important reminder. Regions that already have a particularly large number of highly qualified people in the technical and scientific fields, due to the presence of companies and research centres, will have a head start. Knowledge acquisition is likely to be easier here, and there will also be sufficient multipliers for knowledge sharing within these regions.

In order to gain a picture of this at NUTS-2 level, it helps to look firstly at the density of scientists and engineers working in a region (see Figure 7). Again, there are clear differences both between and within Member States. The Benelux/Hauts-de-France region and parts of south-western Germany stand out, as do some metropolitan regions in the Member States. Europe's industrial centres are largely well represented here, so there is a certain geographical correlation with industry's hydrogen requirements. Regional qualification initiatives are a second essential factor with regard to hydrogen technologies. The content taught on traditional engineering/technical degree courses and training programmes will remain relevant in the future but will be limited in their coverage of the special qualifications needed for a hydrogen economy. Therefore, complementary programmes tailored to hydrogen technologies will be needed for people in this field of activity. This will involve new degree courses and training programmes, but also opportunities for continuing education for those in employment.

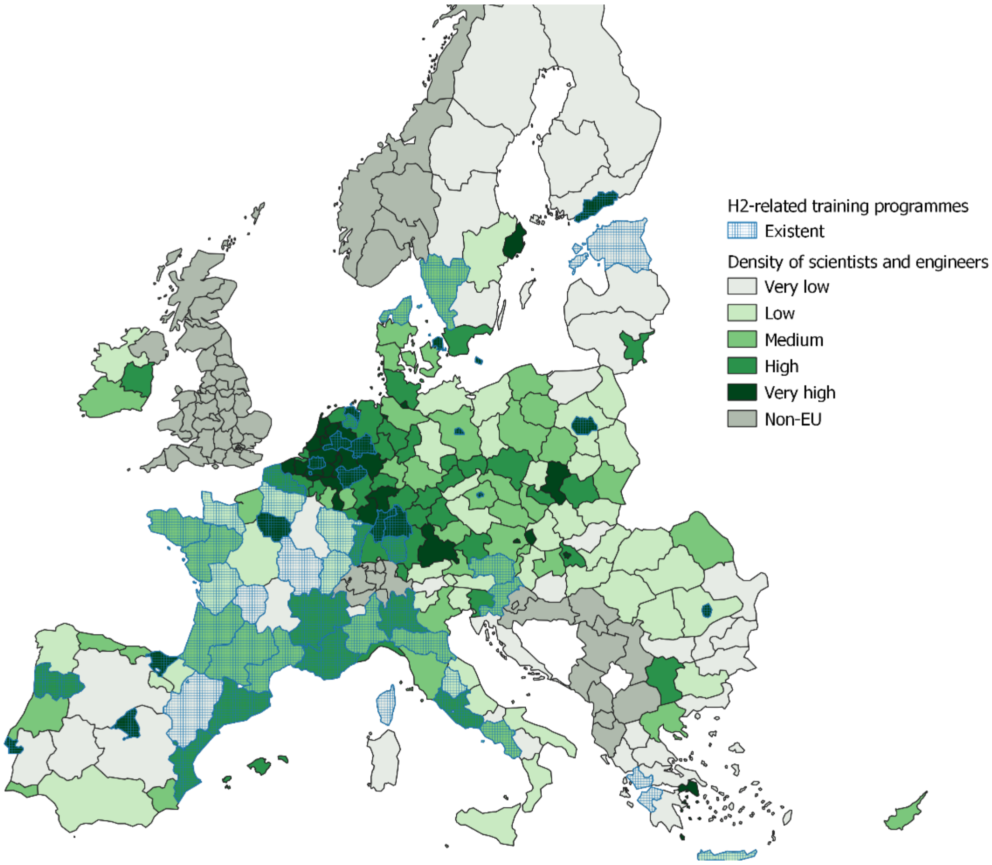
The *Fuel Cells & Hydrogen Observatory* (FCH Observatory) collects information on the current supply of education/training programmes focusing on hydrogen technologies in Europe.[32] These include

[31] Bezdek, R. H. (2019). The hydrogen economy and jobs of the future. Renewable Energy and Environmental Sustainability, 4, 1.

[32] FCH Observatory (2022a). Training programmes. Fuel Cells & Hydrogen Observatory. https://www.fchobservatory.eu/observatory/education-and-training/training-programmes?combine=&field_education_category_target_id=All&field_education_language_target_id=All&field_education_focus_target_id=All

bachelor's and master's degree programmes, workshops and summer schools. In total, the FCH Observatory currently lists (as of: 16 November 2022) 486 such programmes distributed across Europe. Figure 7 shows regions with at least one of these programmes shaded in blue. Here, too, a geographical concentration is apparent, but this only corresponds to a limited extent with the pattern of qualified employees. A geographical focus can be seen in France and northern Italy, while Germany has so far only set up isolated regional programmes. In the eastern EU regions, services are largely concentrated in a few metropolitan areas. This picture, of course, reveals nothing about the quality of the individual programmes. However, it clearly shows that, in terms of qualifications, there are substantial differences in the extent to which the Member States and regions are taking hydrogen seriously. Initial advantages, such as those resulting from the current distribution of skilled labour in the individual regions, are no reason for complacency.

Figure 7: Indicators of H_2 know-how in Europe



Sources: Eurostat (2022); FCH Observatory (2022a); own calculations

3.3.2 Local upstream producers

Another supporting factor is the regional presence of providers of upstream products. It not only increases the chances of regional multiplier effects with respect to value added and employment, it also improves the possibilities for knowledge sharing and cooperation between production levels in the area of research and development. This, in turn, benefits the attractiveness of the location. An essential link in the field of production is the presence of manufacturers of electrolysers or their components. From a pan-European perspective, external dependencies arise primarily in the raw materials sector: The production of polymer membrane (PEM) electrolysers, which are particularly valued for their fast reaction times, depends on access to rare metals such as platinum and iridium, which are mined and processed outside Europe.[33] In contrast, European companies are strongly represented in the emerging markets for electrolysers themselves. Going forward, the EU issued a joint declaration with 20 industry CEOs in May 2022, setting the target of a tenfold increase in electrolyser production capacity by 2025. To this end, manufacturers along the entire production chain are to be brought together via, among other things, "electrolyser partnerships".[34]

Official regional industry statistics provide hardly any indication of their regional location; the technology is too new and too specific for that. However, the FCH Observatory provides a list of European manufacturers that, based on the location of their (main) sites, can be attributed to NUTS-2 regions.[35] In terms of the number of regional sites represented, Germany stands out in Europe. According to information from the FCH Observatory, relevant companies have sites in at least 11 NUTS 2 regions. This corresponds to a share of 29% of all NUTS-2 regions in Germany; a high figure also in comparison to other Member States (see Table 1). These sites have long since focused not only on the large industrial centres but are also spread across the country. In France and Italy, on the other hand, the presence is more limited to individual industrial locations (e.g. Île de France, Lombardy). For the eastern European region, the list only contains individual locations in Hungary and Estonia. A similar picture emerges for manufacturers of application technologies. For example, half of all German NUTS-2 regions are home to fuel cell producers or component manufacturers. Producers in this segment in France and Italy are also much more limited to regional centres.

Table 1: Country comparison of regional sites of upstream suppliers

Country	Number of NUTS-2 regions	Number of regions with corporate sites		
		Production of electrolysers/electrolysis stacks	Production of fuel cells	Production of stack components
Germany	38	11	19	11
France	27	3	8	3
Italy	21	1	3	1
Spain	19	1	2	1

Source: FCH Observatory (2022b); own regional allocation

3.3.3 Physical infrastructure

The development of a physical hydrogen infrastructure is a basic prerequisite for regions to participate in future European markets. The first crucial factor is the choice of the main form of transport. Transport by ship (either as liquefied elemental hydrogen or as a chemical compound such as ammonia) will be largely limited to imports into the EU, as the fixed energy costs of conversion for transport are only profitable over long distances.[36] in some cases, for the purely local distribution of

[33] Ansari, D.; Grinschgl, J.; Pepe, J.M. (2022). Electrolysers for the hydrogen revolution- Challenges, dependencies and solutions. SWP Comment 2022/C 57, Stiftung Wissenschaft und Politik.

[34] ECH Alliance (2022). European electrolyzer summit – joint declaration. European Clean Hydrogen Alliance. Brussels, 5 May 2022.

[35] FCH Observatory (2022a). Company directory. Fuel Cells & Hydrogen Observatory. https://www.fchobservatory.eu/observatory/technology-and-market/company-directory

[36] Cf. Ics-shipping (2022).

hydrogen (or hydrogen derivatives) within industrial conurbations, existing local pipelines can be used. For interregional transport within the EU, on the other hand, infrastructure has yet to be created. In this case, analyses show that for the intra-European transport of significant quantities of hydrogen, pipelines are the more efficient form of transport compared to the alternative of transport by truck.[37]

One still controversial question is to what extent this requires the construction of dedicated hydrogen pipelines, and to what extent blending hydrogen into the existing gas network is technically feasible and justifiable. One thing is clear: Transporting large quantities of hydrogen in the natural gas grid will require the replacement of some pipeline components such as compressors and valves. This is due to its chemical properties, especially its reactivity; there is otherwise a risk of damage to the pipes and a reduction in the degree of purity leading to losses in efficiency.[38] In addition, the construction of new pipelines will be necessary in regions where there are likely to be particularly large hydrogen flows. The *European Hydrogen Backbone Initiative* has developed a vision for a European hydrogen pipeline network. It will initially connect major ports, industrial clusters and generation regions by 2030, then grow into a true pan-European network by 2040.[39] Regions with existing hydrogen pipelines have a natural local advantage when it comes to swift implementation of such visions. While the European gas network covers almost the entire EU area, only a few regions currently have a local hydrogen network that is in use. These are pipelines used internally by the local chemical industry. The most extensive intra-industrial networks are found in the Benelux countries, the Ruhr area, Saxony-Anhalt and the Auvergne-Rhône-Alpes region.[40]

When it comes to user infrastructure, the availability hydrogen refuelling stations constitutes a critical bottleneck in the development of supply chains. Investment in the construction of hydrogen refuelling stations is now subsidised by a number of Member States (see following section). The geographical distribution of these investments is crucial for the use of fuel-cell propulsion systems for long-distance transport in Europe. It is not enough to equip a few conurbations with hydrogen stations. The equipment must be as evenly distributed as possible across the board. Here too, Europe is still far from achieving region-wide infrastructure, as an evaluation of the current location information provided by *glpautogas* shows.[41] By far the largest number of hydrogen stations in a country comparison are located in Germany and France but, even there, availability has so far been concentrated in individual conurbations (see Figure 8). In southern Europe, the density of hydrogen stations is generally much lower. In the eastern Member States, it is so far limited to a few metropolitan areas.

[37] Hydrogen Council (2020). Path to hydrogen competitiveness – a cost perspective. Report, 20 January 2020.

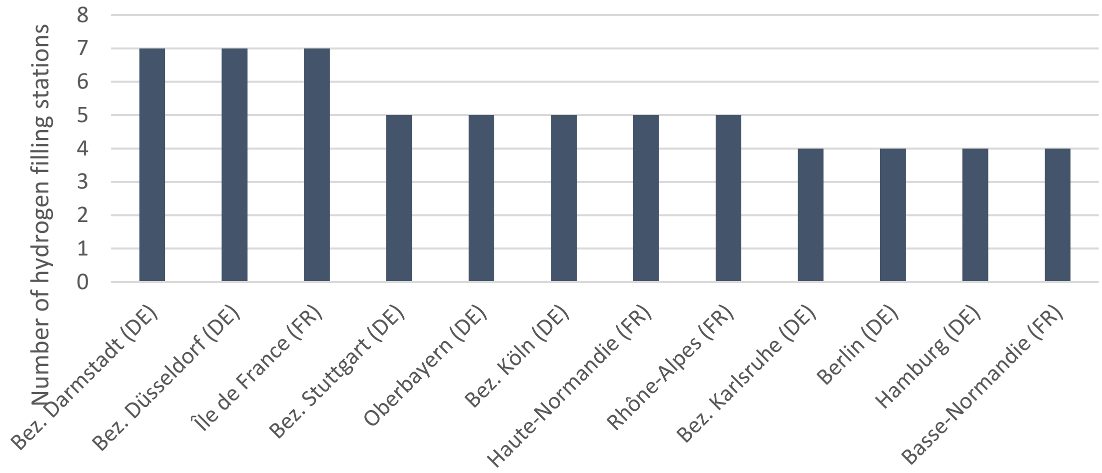
[38] EHB Initiative (2021). Analysing future demand, supply, and transport of hydrogen. Report – June 2021. European Hydrogen Backbone Initiative.

[39] EHB Initiative (2022). European Hydrogen Backbone Maps. European Hydrogen Backbone Initiative. https://ehb.eu/page/european-hydrogen-backbone-maps

[40] FCH Observatory (2022c). Hydrogen Pipelines. https://www.fchobservatory.eu/observatory/technology-and-market/hydrogen-pipelines

[41] glpautogas (2022). Hydrogen stations in November 2022. https://www.glpautogas.info/en/hydrogen-stations.html

Figure 8: EU NUTS 2 regions with the largest number of hydrogen refuelling stations



Source: glpautogas (2022) - As of: November 2022; own regional allocation

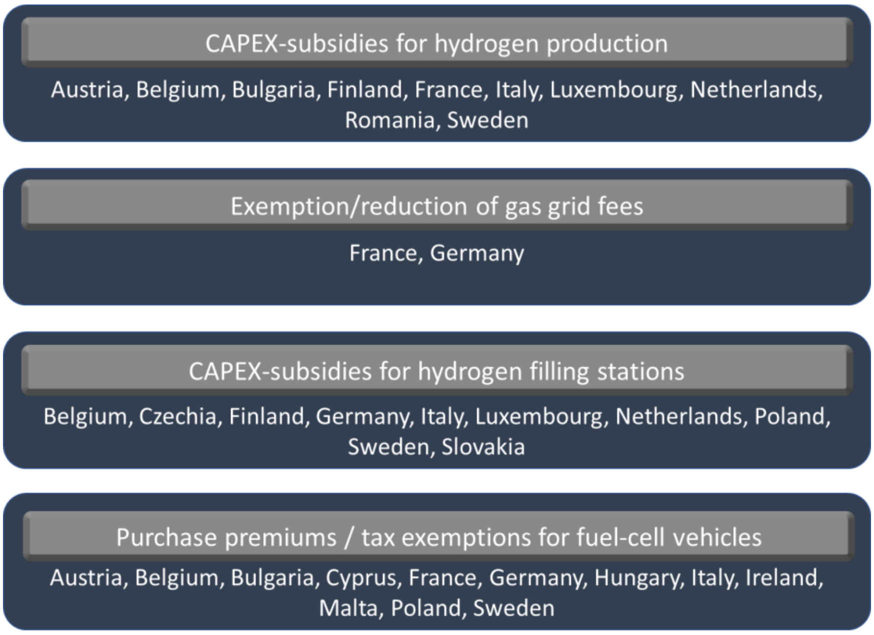
3.3.4 Policy incentives

In addition to the targeted promotion of hydrogen projects (see Section 4), the market ramp-up in Europe is now being supported by the government through a variety of fiscal instruments. Here, too, different stages of the value chain are being addressed, from production (exemption from state electricity price components, CAPEX subsidies for electrolysers in industry) and distribution (exemption/reduction of gas grid fees, investment subsidies for hydrogen filling stations) through to application technologies (purchase premiums for fuel-cell vehicles). The EU is far from being harmonised in this regard: the type and level of the incentives differ significantly from one Member State to another. Figure 9 gives an overview of the use of different measures in the Member States, according to information from the FCH Observatory's policy monitoring.[42] It should be noted that the scope of the respective incentive measures can vary greatly from country to country. This concerns, on the one hand, the question of whether measures apply to electrolysis hydrogen in general or only to hydrogen produced through the use of electricity from renewable sources, and how it is distinguished from other production technologies. On the other hand, some of the measures are time limited or linked to certain forms of hydrogen utilisation.

These differences also make fiscal incentive policy a potentially significant location factor for the development of regional H_2 value chains in intra-European comparison. Direct measures to reduce costs or increase demand will increase expected operating surpluses and shorten the payback period of H_2 investment projects, thus also improving their financing possibilities. Only a detailed analysis of the national legal frameworks can clarify the extent to which the different national policies in the EU area work in this respect.

[42] FCH Observatory (2022d). Policy and RCS. Fuel Cells & Hydrogen Observatory. https://www.fchobservatory.eu/observatory/policy-and-rcs

Figure 9: Policy incentives in the Member States



Source: FCH Observatory (2022d) – As of: November 2022; own graphic

3.3.5 Overall assessment by region

Overall, the aforementioned framework conditions aim to be complementary rather than to substitute each other. In addition to existing technical potential, the development of a regional hydrogen economy with high value added, ideally requires a combination of targeted infrastructure investments, the presence of upstream suppliers, a supportive incentive policy and a qualified pool of employees. A lack of capacity in transport infrastructure, for example, can hardly be compensated for by regional excellence in skilled labour. Incentive measures are only effective at regional level to the extent that there is an industrial base to carry out production and exploitation Measures to improve the framework conditions should also therefore be tackled in parallel as far as possible. The question of which European regions will take on the role of flagships in the future will only become clear in a few years' time as a result of the upcoming transformation process. Currently, though, it is at least possible to examine which NUTS 2 regions have the best starting conditions for this based on their initial situation. For this we can use the regional indicators discussed in Sections 3.3.1.-4. As regards complementarity, we consider the conditions to be particularly favourable in those regions that bring together a high density of scientists and engineers, upstream suppliers, hydrogen filling stations and the existence of state market incentives (in line with the national parameters). Table 2 sets out the resulting list of regions. At the same time, most of these regions also have high utilisation potential for hydrogen across sectors (see Section 3.2).

Table 2: Regions with particularly favourable framework conditions

NUTS-ID	Name Region	Density scientists/ engineers	Presence Upstream producers	Physical infrastructure	Policy incentives (national)
BE10	**Région de Bruxelles**	Very high	Fuel cells, Stack-Comp.	Hydrogen stations: 1	Purchase FCEVs, Investment H2-stations
BE21	**Prov. Antwerpen**	Very high	Electrolysers, Fuel cells, Stack-Comp.	Hydrogen stations: 2; local hydrogen pipelines	Purchase FCEVs, Investment H2-stations
DE11	**Bezirk Stuttgart**	Very high	Electrolysers, Fuel cells, Stack-Comp.	Hydrogen stations: 5	Purchase FCEVs, Electricity for electrolysis, Investment H2-stations
DE12	**Bezirk Karlsruhe**	Very high	Electrolysers, Fuel cells Stack-Comp.	Hydrogen stations: 4	Purchase FCEVs, Electricity for electrolysis, Investment H2-stations
DE14	**Bezirk Tübingen**	High	Fuel cells, Stack-Comp.	Hydrogen stations: 2	Purchase FCEVs, Electricity for electrolysis, Investment H2-stations
DE30	**Berlin**	Very high	Electrolysers, Stack-Comp.	Hydrogen stations: 4	Purchase FCEVs, Electricity for electrolysis, Investment H2-stations
DEA2	**Bezirk Köln**	Very high	Electrolysers, Fuel cells, Stack-Comp.	Hydrogen stations: 5	Purchase FCEVs, Electricity for electrolysis, Investment H2-stations
DEA3	**Bezirk Münster**	High	Electrolysers, Stack-Comp.	Hydrogen stations: 2	Purchase FCEVs, Electricity for electrolysis, Investment H2-stations
ES51	**Cataluña**	High	Electrolysers, Stack-Comp.	Hydrogen stations: 1	Purchase FCEVs
FR10	**Île de France**	Very high	Electrolysers, Fuel cells, Stack-Comp.	Hydrogen stations: 7	Purchase FCEVs, Electricity for electrolysis
FRK2	**Rhône-Alpes**	High	Electrolysers, Fuel cells, Stack-Comp.	Hydrogen stations: 5; local hydrogen pipelines	Purchase FCEVs, Electricity for electrolysis
FRL0	**Provence-Alpes-Côte d'Az.**	High	Fuel cells, Stack-Comp.	Hydrogen stations: 2; local hydrogen pipelines	Purchase FCEVs, Electricity for electrolysis
ITC4	**Lombardia**	High	Electrolysers, Fuel cells, Stack-Comp.	Hydrogen stations: 2	Purchase FCEVs, Investment H2-stations
NL13	**Drenthe**	High	Stack-Comp.	Hydrogen stations: 1	Investment H2-stations
NL22	**Gelderland**	Very high	Fuel cells, Stack-Comp.	Hydrogen stations: 1	Investment H2-stations

Sources: Eurostat (2022), FCH Observatory (2022a;b;c;d); glpautogas.info (2022); FCEVs: Fuel-cell vehicles.

4 Green hydrogen as the subject of regional policy

4.1 The concept of Hydrogen Valleys

The use of green hydrogen in Europe has now gone beyond the purely technical testing phase. Current implementation projects are focussing on the creation of so-called **"Hydrogen Valleys"**. This essentially means the development of regional markets for hydrogen production and use, whereby use is not limited to individual customers but is designed to be cross-sectoral. The latest Hydrogen Valley Progress Report by Weichenhain et al. (2022) defines four constituent characteristics of Hydrogen Valleys: large scale investments (at least tens of millions), supply to several sectors, cover large parts of the value chain and a clear geographical scope.[43] Most notably, Hydrogen Valleys are distinct from pure pilot and demonstration projects: It is not about demonstrating the technical feasibility of hydrogen technologies, but about the next step in their implementation: scaling up under real market conditions and building economically viable supply chains. Geographical proximity is interpreted flexibly: Both small regions and large-scale transnational project areas can operate as Hydrogen Valleys. In this context, Weichenhain et al. (2022) distinguish between three archetypal hydrogen valleys: local valleys with small-scale generation capacities and mobility focus, local valleys with medium-scale generation capacities and industry focus, international valleys with large-scale generation capacities and export focus.

According to the *Hydrogen Valleys Platform* , however, the majority of global projects are located in Europe. The importance that this concept has acquired in the debate on funding policy in Europe is also reflected by the fact that it has become part of the European Commission's language. In her *State of the Union Address* 2020, Commission President Von der Leyen highlighted the development of Hydrogen Valleys as an important use of the *Next Generation EU* Fund.[44] In addition, a *European Hydrogen Valleys S3 Partnership of* European regions was formed as early as 2019 to represent the interests of leading H2 clusters in Europe in building a hydrogen economy.[45] The majority of the projects are currently still in the design or early implementation phase. The projects listed by the *Hydrogen Valleys Platform* also vary greatly in their scaling. A key common feature of the projects listed is their mixed funding. All projects from the EU area for which information on funding is available provide for co-financing from public sources (EU/national/regional).[46] This also raises the issue of the geographical allocation of taxpayers' money.

The concept of Hydrogen Valleys is unsuitable for practical regional economic analysis because it lacks geographical clarity. It is nevertheless helpful on a theoretical level because it draws attention to the geo-economic dimension of hydrogen value chains. This is especially important for the question of regional scaling: If projects become too large for regional needs, the market ramp-up will give rise to additional infrastructure needs. Investment will then be diverted away from production towards transport, and the development of production capacity will be delayed. Covering the cost of

[43] Weichenhain, U.; Kaufmann, M.; Benz, A.; Matute Gomez, G. (2022). Hydrogen Valleys – Insights into the emerging hydrogen economies around the world. FCH 2 JU / European Commission / Inycom / Roland Berger.

[44] Von der Leyen, U. (2020). State of the Union Address 2020 by President von der Leyen at the European Parliament Plenary. 16 September 2020. https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_20_1655

[45] EHV-S3P (2020). European Hydrogen Valleys Partnership. Presentation, 24 June 2020. https://clustercollaboration.eu/sites/default/files/WYSIWYG_uploads/hydrogen_-_presentation_ehv-s3p_eaac_2020-0624.pdf

[46] CHP/MI (2022). Mission Innovation Hydrogen Valley Platform. Clean Hydrogen Partnership/Mission Innovation. https://h2v.eu/hydrogen-valleys

infrastructure expansion can also impair price competitiveness and thereby reduce the effect of cost advantages in production which result from upscaling. The inappropriate geographical distribution of subsidies could thus delay the market ramp-up of hydrogen in Europe.

4.2 EU support policy

In addition to national level market incentives (see Section 3.3.4) and measures to encourage investment, direct action also comes from EU level. Research into hydrogen technologies has been funded by the EU since the late 1980s. In 2008, the EU, together with representatives from industry and research, founded the *Fuel Cells and Hydrogen Joint Undertaking* (FCH JU), a public-private partnership to provide financial support not only for research but also for projects to implement hydrogen production and infrastructure. One focus was on demonstration projects to prove the practicality of hydrogen applications.[47] These centred on the fuel cell as a technology for using hydrogen in the mobility sector and for reconversion into electricity. From 2014, the initiative was taken into a second phase under the umbrella of the EU's *Horizon Europe* research funding programme (FCH JU2) and continued to focus on projects relating to mobility applications and internal utilisation in the energy sector.[48]

The **European Hydrogen Strategy 2020** focused on the cross-sectoral use of green hydrogen and defined concrete targets (40 GW of electrolysis capacity in 2030).[49] In this context, the *European Clean Hydrogen Alliance* was created as an instrument for better coordination of stakeholders and investment projects. Then, in February 2021, the *Clean Hydrogen Partnership* was presented as the successor programme to FCH 2 JU.[50] An initial call for proposals in May 2022 produced a tender volume of € 300 million. These funds will be used to launch at least five Hydrogen Valleys.[51] In December 2020, 22 EU Member States and Norway also committed themselves in a manifesto to building European value chains in the field of "Hydrogen Systems and Technologies" and announced the deployment of *Important Projects of Common European Interest* as an instrument for this purpose.[52] An initial technology wave called *Hy2Tech* saw 41 such cross-border projects approved by the European Commission in July 2022. The approval of a second wave of *Hy2Use* projects with a total volume of more than 5 billion euros, focusing on application technologies and infrastructure, took place only a short time later in September 2022.[53]

The energy crisis sparked by the Ukraine war has fuelled further activity. Green hydrogen is expected to make a significant contribution to the decarbonisation of European process chains in the medium term. In May 2022, the European Commission formulated, for the first time, concrete volume targets for the production of green hydrogen, as part of its **RePowerEU** plan: By 2030, 10 million tonnes of

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47 De Colvenaer, B., & Castel, C. (2012). The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) in Europe. International Journal of Low-Carbon Technologies, 7(1), 5-9.

48 EU Funding Overview (2022). Fuel Cells and Hydrogen 2 Joint Undertaking. https://eufundingoverview.be/funding/fuel-cells-and-hydrogen-2-joint-undertaking-other-organisations

49 European Commission (2020). A hydrogen strategy for a climate neutral Europe. 8 July 2020. https://ec.europa.eu/commission/presscorner/detail/en/fs_20_1296

50 CHP (2022). European Partnership for Hydrogen Technology. https://www.clean-hydrogen.europa.eu/index_en

51 EURACTIV (2022). EU unveils €300 million plan to fund hydrogen research. 15 March, 2022. https://www.euractiv.com/section/energy/news/eu-unveils-e300-million-hydrogen-research-priorities/

52 EU-Countries/Norway (2020). Manifesto for the development of a European “Hydrogen Technologies and Systems” value chain. https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/ipceis-hydrogen_en

53 European Commission (2022b). State Aid: Commission approves up to €5.2 billion of public support by thirteen Member States for the second Important Project of Common European Interest in the hydrogen value chain. Press release, 21 September 2022. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_5676

renewable hydrogen will be produced in the EU, supplemented by imports also amounting to 10 million tonnes. For this purpose, the Commission is aiming, among other things, to double the number of Hydrogen Valleys in Europe by way of increased funding activities under the *Horizon Europe* umbrella.[54] In her *State of the Union Address* 2022, von der Leyen also announced the establishment of a European Hydrogen Bank, which will provide a further 3 billion euros to support the development of a European hydrogen market.[55] Details of this new instrument are to be presented in 2023. In addition, there are a variety of initiatives at Member State and regional level. Overall, this has given rise to a plethora of very different channels wanting to launch implementation projects using public funds, more or less independently of one another. An overview of the planning situation for the next few years is therefore important for steering purposes.

4.3 Current project landscape

The rapid expansion of funding channels for practical projects has promoted the formation of project consortia in (almost) every corner 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 design of pan-European supply chains, including the associated transport infrastructure. In view of the path dependencies discussed, it is precisely the large-scale projects currently in the starting blocks that will very likely shape the geographical structure of a future European hydrogen economy in the coming decades. This has considerable influence on whether and when the market launch of green hydrogen will succeed. The regional usage potential discussed in Section 3 will play a key role in this regard: It will determine the economic viability of projects in the initial phase of building interregional transport networks. It will also determine whether flagship regions for the hydrogen economy can be established in Europe at an early stage, which could then incentivise trans-regional market integration through the expansion of infrastructure.

When it comes to evaluating state support policy, this means that the evaluation should not only focus on the level of support volume but also on its geographical distribution. Due to the large number of funding institutions and funding programmes, this is no easy task. There is currently no official central register of publicly funded hydrogen projects in Europe, although some platforms do maintain more or less extensive project databases. By far the most comprehensive database is the *Hydrogen Projects Database* of the International Energy Agency (iea).[56] According to its own information, it includes almost all projects announced to date since the year 2000 that serve to produce hydrogen as an energy source and/or a means of combating climate change. In addition to numerous completed micro-projects from the past, it also contains the large-scale projects that have recently been announced, including information on the time frame and scope of the planned production capacities as well as the envisaged utilisation purposes. We cross-checked this project list with two other current databases: the overview of projects on the *Mission Innovation Hydrogen Valley Platform*[57] and on the *Hydrogen Project Visualisation Platform*[58] of the European Network of Transmission System Operators for Gas.

[54] Cf. European Commission (2022a).

[55] Von der Leyen, U. (2020). State of the Union Address 2022 by President von der Leyen at the European Parliament Plenary. 14 September 2022. https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_5493

[56] IEA (2022). Hydrogen Projects Database. International Energy Agency. As of: November 2022 https://www.iea.org/data-and-statistics/data-product/hydrogen-projects-database

[57] Cf. CHP/MI (2022).

[58] ENTSOG (2022). Hydrogen Project Visualisation Platform. European Network of Transmission System Operators for Gas. https://h2-project-visualisation-platform.entsog.eu/

After cleaning up[59] the overview thus obtained, a list of a total of 262 project entries was created, which we subsequently assigned to individual NUTS-2 regions based on their electrolysis location (according to publicly available project information).

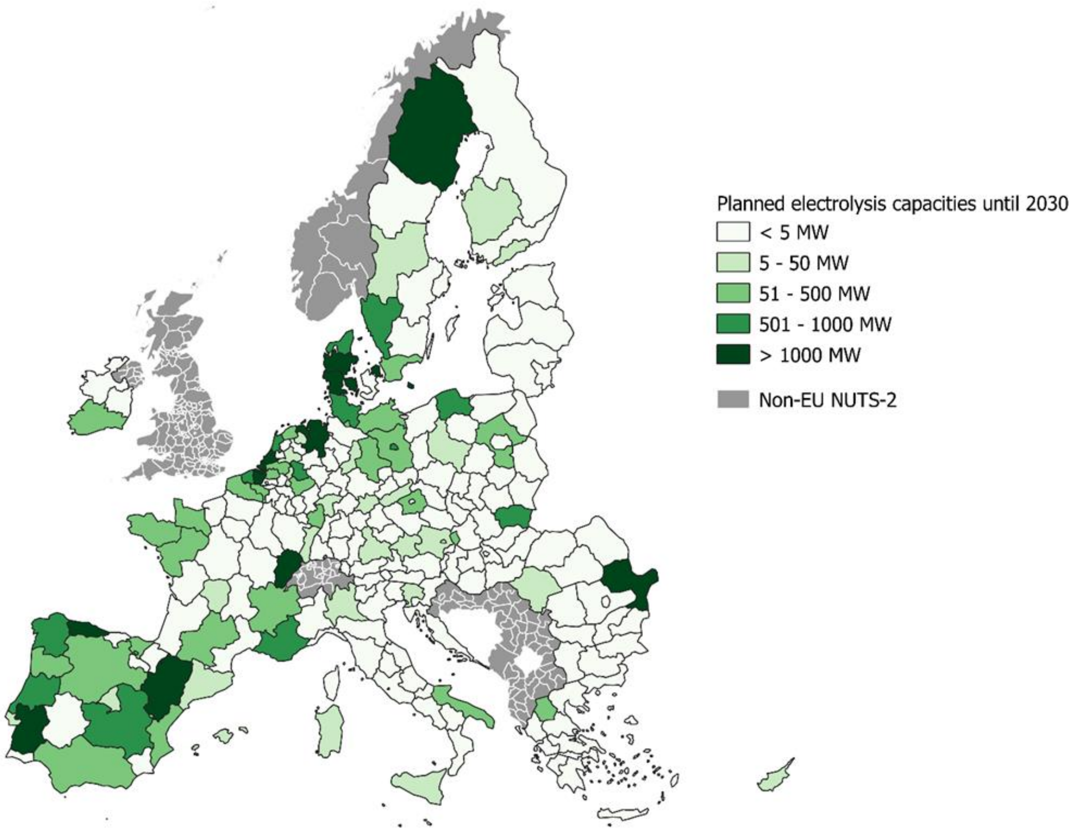
Figure 10 shows the distribution of total capacities obtained for the regions for the planning period to 2030. As a result of the upscaling planned for the coming years, it is largely informed by major projects currently in the planning phase. It cannot, of course, provide any information on the technical feasibility of individual projects. In this respect, it should be seen principally as a map of aspirations. It shows a Europe moving at very different speeds. There are prominent regional production centres which, at the same time, are widely distributed across the EU area. The Iberian Peninsula and the North Sea region stand out as the main centres. Overall, coastal regions will have an important role in the planning process. In a country comparison, the low representation on the project map of Italy, central parts of France and southern Germany is striking. This includes many regions in which above-average usage potential and good local framework conditions have been identified (see Section 3), including core industrial regions such as *Ile-de-France* (FR) and *Lombardia* (IT). With the exception of a few major projects, project planning in the eastern Member States is also comparatively modest overall.

The special role that individual flagship regions will play in the formation of a European hydrogen economy requires a separate analysis. In this regard, we will consider as a subgroup those NUTS 2 regions for which, on the basis of current knowledge, electrolysis capacities of more than 1 GW are planned by 2030. This applies to 14 of the 241 EU regions. These 14 regions make up a total planned capacity of 55.3 GW. This alone would represent more than half of the EU-wide capacity that the *European Clean Hydrogen Alliance* estimates will be needed to reach the 10 million tonne target by 2030.[60] Three of these areas, referred to below as "**focus regions**", are located in Denmark, three in the Netherlands, two in Spain, and one each in Belgium, Germany, France, Portugal, Romania and Sweden. A comparison of their specific potential with the rest of the EU provides information on how local conditions could contribute to the market launch in Europe.

[59] We only included projects that envisage the creation of capacities for the electrolytic production of hydrogen, and that have issued clear quantity targets and time frames for this. Of these we excluded micro-projects (< 1 MW electrolysis capacity) as well as projects providing exclusively for reconversion as a recovery option. Future offshore electrolysis capacity was excluded due to the lack of allocation possibilities.

[60] ECH (2022). European Electrolyser Summit – Joint Declaration. Brussels, 5 May 2022. file:///C:/Users/user/Downloads/signature%20Joint%20Declaration%20European%20Electrolyser%20Summit%20V9%20public.pdf

Figure 10: Planned electrolysis capacities in EU NUTS-2 regions by 2030

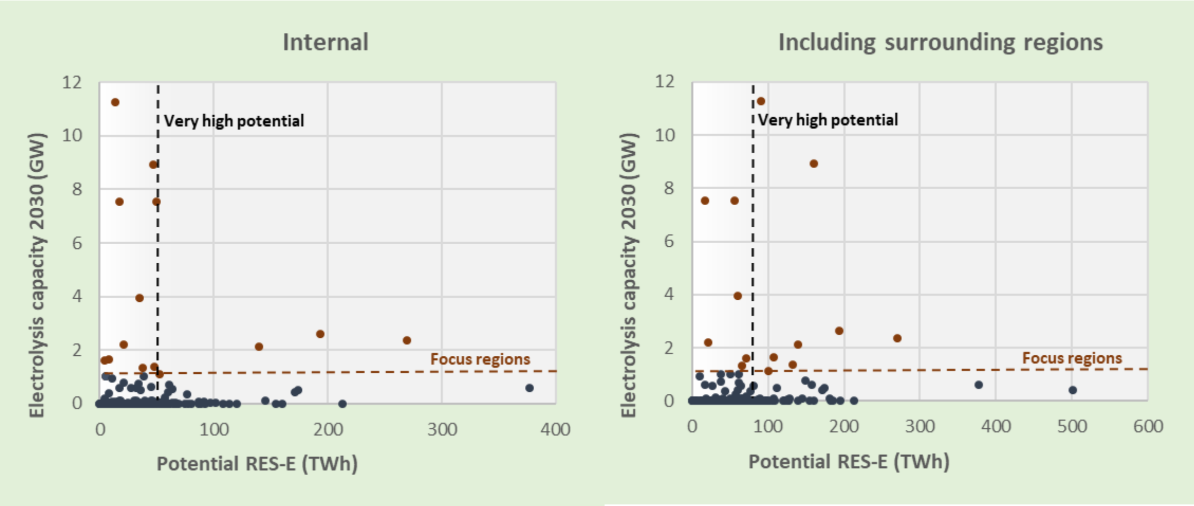


Sources: iea (2022); CHP/MI (2022); ENTSOG (2022); As of: November 2022; own calculations.

According to the estimates of Kakoulaki et al. (2021), some of the focus regions have very large area potential for RES-E generation in comparison with the rest of the EU (see Figure 11). This is particularly true, considering the size of the region, for North Sea coastal regions, in conjunction with their high wind-power potential. However, it is by no means true for all focus regions. On the demand side, the picture is also very diverse. A clear correlation with the planned amount of capacity is not apparent in any case (see Figures A1-A3 in the Appendix). For only five of the 14 focus regions does a comparison of the forms of exploitation reveal mainly high to very high potential within the region. These cover all three application sectors (industry, mobility, heat/buildings). In the other focus regions, the estimated demand potential is only above average, if at all, in individual areas and is mainly low in some regions. Table A2 in the Appendix summarises the potential within the regions. The picture obtained remains basically the same even if the potential in the respective surrounding regions is included.[61]

[61] For this purpose, we add the potential of the regions located within a distance of 100 km from the region under consideration. We have taken the interregional distances from the dataset of Kurbucz & Katona (2022) .

Figure 11: Planned electrolysis capacities v. generation potential of RES-E



Sources: Kakoulaki et al. (2021); IEA (2022); CHP/MI (2022); ENTSOG (2022); own calculations. Very high potential: 20%-highest values among EU regions.

As regards local framework conditions (see Section 3.3), the focus regions as a whole hardly seem exceptional. Special features tend to be found the regional relations between sectors and physical infrastructure. At least half of the focus regions are home to fuel cell manufacturers, and at least a quarter are home to manufacturers of electrolysis stacks/systems - figures that are well above average in an EU comparison (36 % EU-wide and 12 % of all regions). The focus regions also have on average a higher density of hydrogen filling stations than the rest of the EU, and some are considered suitable locations for the long-term storage of large quantities of hydrogen for geological reasons (existence of salt caverns).[62] On the other hand, in terms of the availability of skilled labour and rules on incentives, the focus regions as a group do not display systemically better regional conditions.

From a pan-European perspective, therefore, the regions currently chosen as important locations for hydrogen production are only partially predestined for their role. In particular, in some cases, there is a mismatch between the prominent position as a production location and the likely importance as a consumer region, even when the potential available in surrounding areas is taken into account. Apart from general regional cost differences, soft factors may be the main explanation for this pattern: differences in entrepreneurial emphasis, regional stakeholder networks, and not least the political backing at regional and national level. The price of this situation is that the cross-regional transport of hydrogen will have to form part of the business model for many large-scale projects, even in the initial phase, including the creation of the necessary capacities for this.

[62] Małachowska, A., Łukasik, N., Mioduska, J., & Gębicki, J. (2022). Hydrogen Storage in Geological Formations—The Potential of Salt Caverns. Energies, 15(14), 5038.

5 Implications for European policy

5.1 Need for steering

If the project plans analysed in the previous section were to be implemented, the development of a European hydrogen economy would initially be made up of just a few focus regions providing green hydrogen on a large scale. In principle, in view of the existing economies of scale in production, this also seems to make sense. However, the selection of these regions can only be partly justified on the basis of above-average regional potential in both supply and demand. In some cases, cross-regional distribution of the hydrogen produced will therefore have to form part of the business plan, even in the early stages. Conversely, many European regions that are characterised by a particularly favourable combination of potentials (see Chapter 3) have seen little significant project planning. Without a pan-European transport infrastructure, there is a danger that existing scaling potential will not be swiftly exploited and thus the chicken-and-egg problem in infrastructure development discussed at the beginning will remain unresolved. This threatens to delay the development of hydrogen supply chains in Europe that can compete on price with other energy sources. The EU cannot, however, afford to lose time on this. Not only with regard to the goals it has set itself but also regarding the development of import channels from third countries, which is being pursued in parallel. Although green hydrogen imported from regions such as North Africa or South America is expensive due to the cost of transport, this is offset on the production side by the particularly favourable natural conditions for the generation of renewable electricity. In addition, the long-distance transport of hydrogen by ship is likely to see significant cost reductions in the future due to a combination of innovative conversion technologies.[63]

This will be an important component of the integrated cross-sectoral energy system of the future and, when it comes to hydrogen production, the EU cannot afford to miss the boat in the early stages. This would have negative consequences, not only for industrial policy due to loss of value creation and employment. There is also the threat of new external dependencies emerging which is exactly what Europe wants to avoid by means of decarbonisation. Decision-makers in the EU and Member States are therefore well advised to be even more consistent in gearing their support policy on green hydrogen towards the goal of competitiveness. Firstly, this involves encouraging integrated projects in geographical proximity to future European usage centres: "Hydrogen Valleys" will only live up to their name if the geo-economic advantages of short distances can really be exploited. Secondly, the current project landscape is forcing decision-makers to be even more resolute in addressing the development of infrastructure and the harmonisation of regulatory frameworks for the formation of transnational markets. Several instruments are available for this purpose, some of which have already been introduced into the EU legislative process as proposals by the European Commission.

[63] Cf. Hydrogen Council (2020).

5.2 Instruments

Supply side: Standards and certification as market signals

Green hydrogen from Europe will only become economically viable in the near future if the sustainability advantages of domestic hydrogen production from renewable sources become visible on the market. With regard to carbon emissions, corresponding price signals have already been secured but future price development is uncertain. The signals are also limited to intra-European carbon emissions along the process chain. In order to create sufficient investment incentives, legitimacy and regulatory commitment need to be complemented by EU-wide binding standards on sustainably produced hydrogen and certification, covering the entire supply chain if possible. In the context of its draft *Directive on common rules for the internal markets in renewable and natural gases and in hydrogen*, the European Commission refers to a definition of so-called "*renewable hydrogen”* contained in the proposed revision of the Renewable Energy Directive. This defines renewable hydrogen as hydrogen that draws its energy content from non-biogenic renewable sources and achieves a reduction in GHG emissions of at least 70% compared to fossil fuels.[64] However, the methodology for calculating these savings has not yet been defined. In particular, the essential question of which parts of the production and supply chain should be covered, and what the basis of information should be in each case, remains unresolved. The subsequent certification process also still needs to be developed. The European Commission needs to submit proposals promptly in this regard and coordinate them with the relevant stakeholders from industry. In particular, in view of the significant deterioration in the gas supply situation since publication of the draft law, a critical discussion is needed as to whether so-called "low-carbon" hydrogen can still play a role as a complementary option for Europe. This refers to hydrogen from non-renewable energy sources, which also achieves a GHG reduction of at least 70% compared to conventional technologies through measures such as carbon capture. To take account of the potential contribution of green hydrogen, not only in combating climate change but also with regard to Europe's independence from producers of fossil-based raw materials, it seems appropriate to restrict sustainability standards to the origin from renewable sources.

Demand side: Risk hedging instruments as investment incentives

The realisation of regional usage potential depends crucially on the willingness of demand-side actors to invest in the switch to hydrogen technologies. Uncertainties about the future regulatory treatment of green hydrogen, but also regarding carbon pricing in Europe, are an obstacle to such long-term investment decisions. Reducing such barriers by way of risk hedging instruments may also contribute to a geo-economically more favourable distribution of flagship projects in Europe. This is because, with basically open access to such standardised instruments, political backing and regional stakeholder networks become less important as alternative hedging mechanisms. A state guaranteed fixed CO_2 price, in particular, will enable investors to better calculate future cost savings from CO_2 avoidance as an essential component of the return on investment. Over an agreed period of time, the state will compensate the difference between the contractually fixed price and the prevailing market price in

[64] European Commission (2021). Proposal for a Directive of the European Parliament and the Council on common rules for the internal markets in renewable and natural gases and in hydrogen. COM/2021/803 final.

emissions allowance trading. To take account of expected long-term price increases in allowance trading, the contract duration can be limited in time, thus minimising government budget risks.

Market integration: Uniform competitive conditions and consistent infrastructure development

In order to advance the development of a European hydrogen economy despite below-average local sales potential in some flagship project regions, increased efforts are needed to promote cross-regional market integration. Firstly, this requires the existence of sufficient investment incentives for infrastructure operators. In hydrogen transport, this relates to both the modification of parts of the gas network and the additional construction of new hydrogen pipelines. To shorten planning and approval procedures and save construction costs, existing gas networks should be converted wherever this is technically possible. In the interests of affordable transport costs in the start-up phase, barriers to financing arising from unbundling requirements should be kept to a minimum without ignoring the risk of market concentration. At the same time, regulatory barriers in cross-border transport should be removed and there should be non-discriminatory access for all suppliers of hydrogen that is certified as sustainable. In addition, the competition conditions for hydrogen supply chains should be harmonised as far as possible throughout Europe. This concerns the burden of charges on electricity purchases by electrolysers, but also the question of discounts on charges for grid use in hydrogen transport by electrolysers and storage operators. The aim should be to create a European division of labour that is shaped less by the activities of individual flagship projects and their path dependencies, and as much as possible by the genuine comparative advantages of the regions.

6 Conclusion

The rapid development of markets for green hydrogen is essential for launching a European hydrogen economy. For this to succeed, economies of scale in hydrogen production must be exploited and obstacles to incentives in infrastructure development must be overcome. Regional production and exploitation potential plays a key role here: In the absence of a trans-regional infrastructure, it is the economic driver for capacity building in all parts of the supply chain, and thus also for the future emergence of trans-regional markets. The success of the transformation will therefore depend not only on technology and business optimisation, but also crucially on Europe’s regional economic geography. Production, infrastructure and application technologies must not only be expanded in parallel, the expansion must also be synchronised geographically.

This cepInput aims to facilitate a better understanding of this problem by providing the first comprehensive analysis of the production and exploitation potential of green hydrogen on a regional level in Europe. Two crucial findings emerge from the mass of detailed results. Firstly, despite the diversity of factors specific to each region, there is a certain correlation between the geographical distribution of RE potential and the utilisation potential for green hydrogen in Europe, and this applies across all potential fields of application. Regions that are predestined to be future hydrogen consumers due to their economic structure tend to have a relatively large average area potential for the production of renewable energies. This pattern does not apply to all regions but certainly does apply to the economically strong North Sea coastal areas and some Mediterranean regions. As regards the local framework conditions, some of these regions were also found to have a particularly favourable starting position. This is good news for the development of regional supply chains, as transport over longer distances will pose major challenges for the input (electricity) and the output (hydrogen) sides, both economically and in terms of the energy system.

Secondly, looking at the geographical distribution of Hydrogen Valleys currently being planned, individual regions clearly stand out as regards the planned electrolysis capacity. However, this fact is by no means always accompanied by above-average regional production or utilisation potential, even when surrounding regions are included. In the crucial forthcoming phase of capacity expansion, there is thus a risk that the path towards economic viability will be partially obstructed by trans-regional infrastructure restrictions. Since a considerable amount of public money is invested in these projects, European policy needs to exercise a steering role in this regard. Better geographical coordination and a more consistent alignment of the projects currently funded through a wide variety of channels is needed.

Trans-regional integration of the emerging markets is the next step in building a European hydrogen economy. It is a prerequisite for establishing an efficient geographical division of labour in the production and use of green hydrogen. This is the only way for European hydrogen supply chains to be competitive with the parallel import channels that are established. The right political impetus is needed in order to accelerate this process. Here, too, a value-chain oriented approach is necessary: Regulation should focus equally on production, exploitation and infrastructure and treat them consistently in terms of incentives. European harmonisation is important here to avoid any distortion in the allocation. This concerns the burden of charges on electrolysers and storage operators as well as the regulation of future hydrogen transport networks. The European Commission has already presented proposals in this vein in its latest draft legislations, but in many cases there is still a need for more precision and coordination.

Going forward, better geographical management also requires an expansion of the information base. This involves the estimation of regional production costs and volume projections as well as the cost of interregional hydrogen transport. Firstly, this will require detailed bottom-up analyses of the small-scale potential as a supplement to the official regional data. Secondly, the planning of an intra-European hydrogen transport infrastructure should be defined more specifically in terms of geography and capacity, so that the costs resulting from geographical distance can be identified more precisely.

7 Annex

7.1 Data basis

Table A 1: Overview of data sources

Category	Indicator	Explanation	Time	Unit	Source	URL
	Capacities Electrolysis 2030	Sum of planned electrolysis capacities until 2030	Plans until 2030 (As of: November 2022)	MW	Own regional allocation, based on IEA (2022); CHP/MI (2022); ENTSOG (2022)	..
Framework Conditions						
Know-how	**Density scientists & engineers**	Density scientists & engineers	Year 2019	No. empl. / km2	Eurostat (2022)	Link
	H2 training programmes	Existence of H2-related training programmes	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
Local Upstream Producers	**Production of electrolysers/electrolysis stacks**	Regional presence of manufacturers	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
	Production of fuel cells	Regional presence of manufacturers	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
	Production of stack components	Regional presence of manufacturers	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
Infrastructure	**Hydrogen filling stations**	Number of hydrogen filling stations	As of: November 2022	No. of stations	glpautogas (2022)	Link
	Hydrogen pipelines	Existence of dedicated hydrogen pipelines	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
Policy Incentives	**Purchase premiums / tax exemptions FCEVs**	Existence instrument (national)	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
	CAPEX-subsidies hydrogen filling stations	Existence instrument (national)	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
	CAPEX-subsidies hydrogen production	Existence instrument (national)	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
	Reduction / exemption gas grid fees	Existence instrument (national)	As of: November 2022	Yes/no	FCH Observatory (2022)	Link
Potentials						
Production	**RES-E potential**	Annual potential RES-E	..	TWh	Kakoulaki et al. (2021)	..
Usage: Building sector	**District heat consumption private households**	Annual consumption	Year 2019	TJ	Own regional allocation based on Eurostat (2022) according to the method of Sandoval (2021)	..
	Natural gas consumption private households	Annual consumption	Year 2019	TJ	Own regional allocation based on Eurostat (2022) according to the method of Sandoval (2021)	..
	Natural gas consumption service sector	Annual consumption	Year 2019	TJ	Own regional allocation based on Eurostat (2022) according to the method of Sandoval (2021)	..
Usage: Industry	**Consumption industrial process heat**	Annual consumption	Year 2019	TJ	Own regional allocation based on national energy consumption and regional employment by industry sector (Eurostat (2022))	..
	Capacities steel production	Annual production capacities steel	As of: November 2022	t	Own regional allocation based on EUFOR (2022)	Link
	Employees chemical industry	No. employees	Year 2019	No.	Eurostat (2022)	Link
Usage: Transport	**Road freight traffic**	Average loaded / unloaded annual freight	Year 2019	Mill. tkm	Eurostat (2022)	Link
	Passengers aviation	No. of passengers (Departures + arrivals)	Year 2019	Tsd. Pers.	Eurostat (2022)	Link
	Maritime freight traffic	Loaded + unloaded freight	Year 2019	kt	Eurostat (2022)	Link

Source: own representation

7.2 Detailed results for focus regions

Table A 2: Detailed results for focus regions

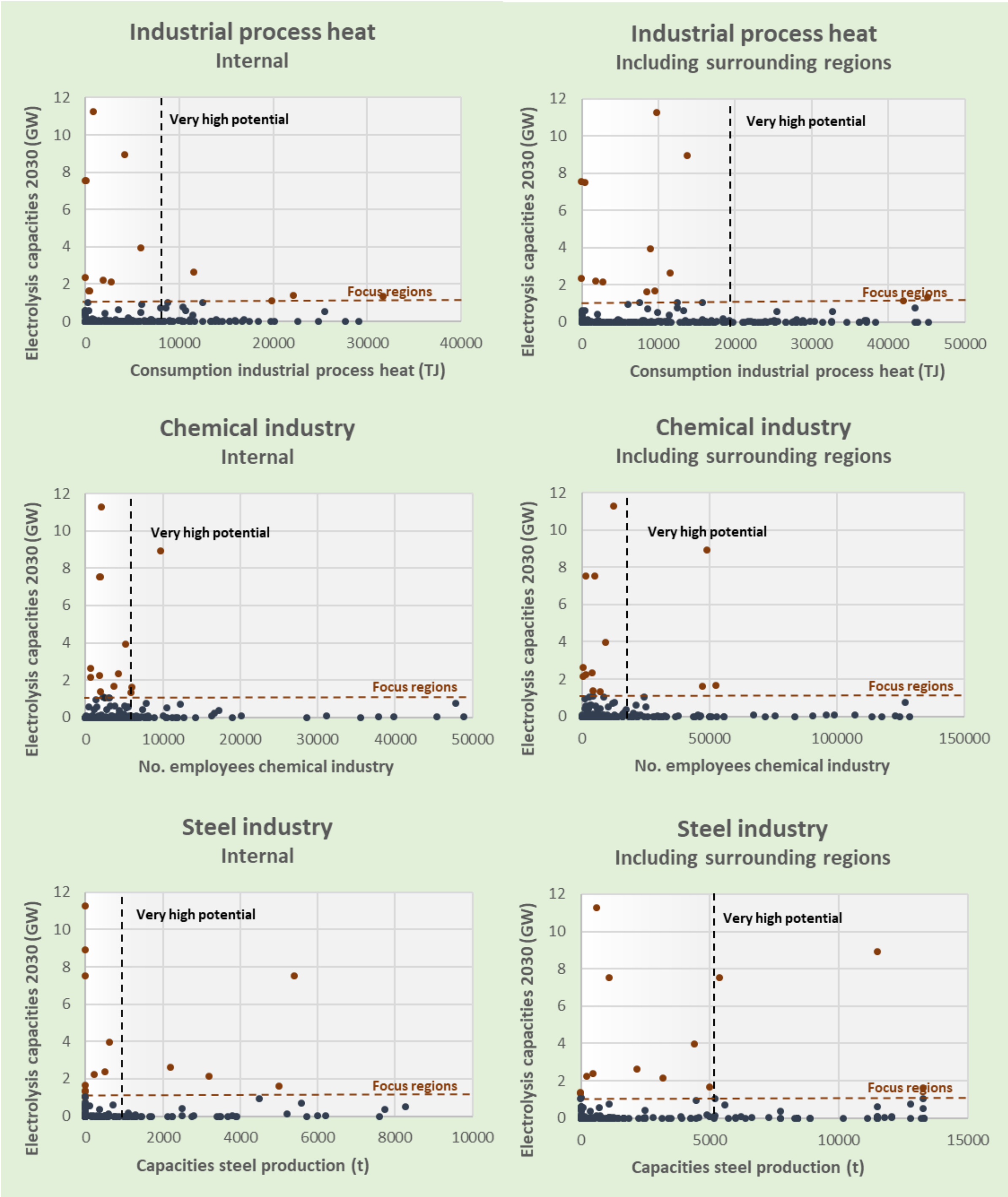
Category	*Indicator*	*Unit*	Focus regions													
	Region	NUTS_ID	**NL11**	**NL33**	**ES12**	**PT18**	**DE94**	**SE33**	**ES24**	**FRC2**	**RO22**	**NL34**	**BE23**	**DK04**	**DK01**	**DK03**
	Country	ID Country	**NL**	**NL**	**ES**	**PT**	**DE**	**SE**	**ES**	**FR**	**RO**	**NL**	**BE**	**DK**	**DK**	**DK**
	Name		**o**	**Zuid-Holland**	**Principado de Asturias**	**Alentejo**	**Weser-Ems**	**Övre Norrland**	**Aragón**	**France-Comté**	**Sud-Est**	**Zeeland**	**Prov. Oost-Vlaanderen**	**Midtjylland**	**Hovedstaden**	**Syddanmark**
	Area	km2	2405	3247	10601	31604	14987	164083	47722	16308	35774	1935	3009	13007	2559	12256
	Planned electrolysis capacities 2030	MW	11240	8913	7520	7504	3928	2600	2337	2200	2115	1625	1600	1350	1303	1100
Framework Conditions																
Know-how	**Density scientists & engineers**	No. empl. / km2	16.76	76.07	3.22	0.76	5.62	0.18	0.96	1.97	1.32	9.46	27.58	5.50	55.57	4.00
	H2 training programmes	Yes/no	Yes	No	No	No	No	No	Yes	Yes	No	No	No	No	Yes	No
Local Upstream Producers	**Production of electrolysers/electrolysis stacks**	Yes/no	No	No	No	No	No	No	No	Yes	No	No	No	No	Yes	Yes
	Production of fuel cells	Yes/no	No	Yes	No	No	No	No	No	Yes	No	No	No	No	Yes	Yes
	Production of stack components	Yes/no	No	Yes	No	No	Yes	No	Yes	Yes	No	No	No	Yes	Yes	Yes
Infrastructure	**Hydrogen filling stations**	No. of stations	1	3	0	0	1	1	3	0	0	0	1	1	2	2
	Hydrogen pipelines	Yes/no	No	Yes	No	No	No	No	No	No	No	No	Yes	No	No	No
Policy Incentives	**Purchase premiums / tax exemptions FCEVs**	Yes/no	No	No	Yes	No	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No
	CAPEX-subsidies hydrogen filling stations	Yes/no	Yes	Yes	No	No	Yes	Yes	No	No	No	Yes	Yes	No	No	No
	CAPEX-subsidies hydrogen production	Yes/no	Yes	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Reduction / exemption gas grid fees	Yes/no	No	No	No	No	Yes	No	No	Yes	No	No	No	No	No	No
Regional potential by km2: Internal																
Production	**RES-E potential**	TWh	5.93	14.55	1.70	1.58	2.35	1.18	5.67	1.32	3.92	4.39	1.53	3.74	14.78	4.29
Usage: Building sector	**District heat consumption private households**	TJ	0.35	1.30	0.00	0.00	0.40	0.07	0.00	0.12	0.08	0.23	0.12	1.70	12.40	1.62
	Natural gas consumption private households	TJ	5.04	15.72	0.36	0.04	1.70	0.00	0.09	0.67	0.24	3.26	5.83	0.45	3.07	0.44
	Natural gas consumption service sector	TJ	1.66	7.51	0.15	0.03	0.71	0.00	0.05	0.32	0.06	1.08	3.82	0.15	1.19	0.13
Usage: Industry	**Consumption industrial process heat**	TJ	7.23	23.49	1.81	0.19	3.19	0.14	0.52	0.58	0.32	12.12	15.65	1.33	4.24	1.40
	Capacities steel production	t	0.00	0.00	0.51	0.00	0.04	0.01	0.01	0.01	0.09	0.00	1.66	0.00	0.00	0.00
	Employees chemical industry	No.	0.85	2.99	0.18	0.06	0.35	0.00	0.09	0.11	0.02	1.90	1.99	0.15	2.30	0.19
Usage: Transport	**Road freight traffic**	Mill. tkm	1.28	5.26	0.38	0.09	1.21	0.03	0.26	0.33	0.08	1.48	3.65	0.45	0.98	0.59
	Passengers aviation	Tsd. Pers.	0.00	0.65	0.13	0.00	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.05	11.78	0.31
	Maritime freight traffic	kt	2.52	138.24	2.10	1.23	2.85	0.08	0.00	0.00	1.45	20.11	11.08	1.02	6.05	1.62
Regional potential by km2: Including surrounding regions (NUTS-2 Regionen within 100 km radius)																
Production	**RES-E potential**	TWh	3.31	7.92	1.70	1.64	2.99	1.18	5.67	1.32	3.92	4.98	2.34	4.02	6.82	4.00
Usage: Building sector	**District heat consumption private households**	TJ	very high	0.68	0.00	0.01	0.44	0.07	0.00	0.12	0.08	0.44	0.28	1.59	4.62	1.66
	Natural gas consumption private households	TJ	2.88	8.96	0.36	0.12	2.59	0.00	0.09	0.67	0.24	8.11	4.40	0.43	1.18	0.44
	Natural gas consumption service sector	TJ	1.08	4.42	0.15	0.12	1.02	0.00	0.05	0.32	0.06	4.46	2.83	0.13	0.42	0.14
Usage: Industry	**Consumption industrial process heat**	TJ	4.24	16.67	1.81	0.77	4.23	0.14	0.52	0.58	0.32	16.71	9.48	1.34	1.83	1.36
	Capacities steel production	t	0.02	0.56	0.51	0.03	0.22	0.01	0.01	0.01	0.09	0.23	0.43	0.00	0.00	0.00
	Employees chemical industry	No.	0.46	2.41	0.18	0.15	0.46	0.00	0.09	0.11	0.02	2.44	1.54	0.14	0.77	0.17
Usage: Transport	**Road freight traffic**	Mill. tkm	1.16	2.96	0.38	0.22	1.34	0.03	0.26	0.33	0.08	3.42	2.13	0.48	0.50	0.52
	Passengers aviation	Tsd. Pers.	0.01	3.96	0.13	0.90	0.12	0.02	0.01	0.00	0.00	1.66	1.22	0.18	3.08	0.18
	Maritime freight traffic	kt	1.80	39.81	2.10	1.62	5.29	0.08	0.00	0.00	1.45	35.75	12.32	1.30	4.07	1.31

very high **high** **medium** **low** **very low**

Sources: see Table A1; own representation

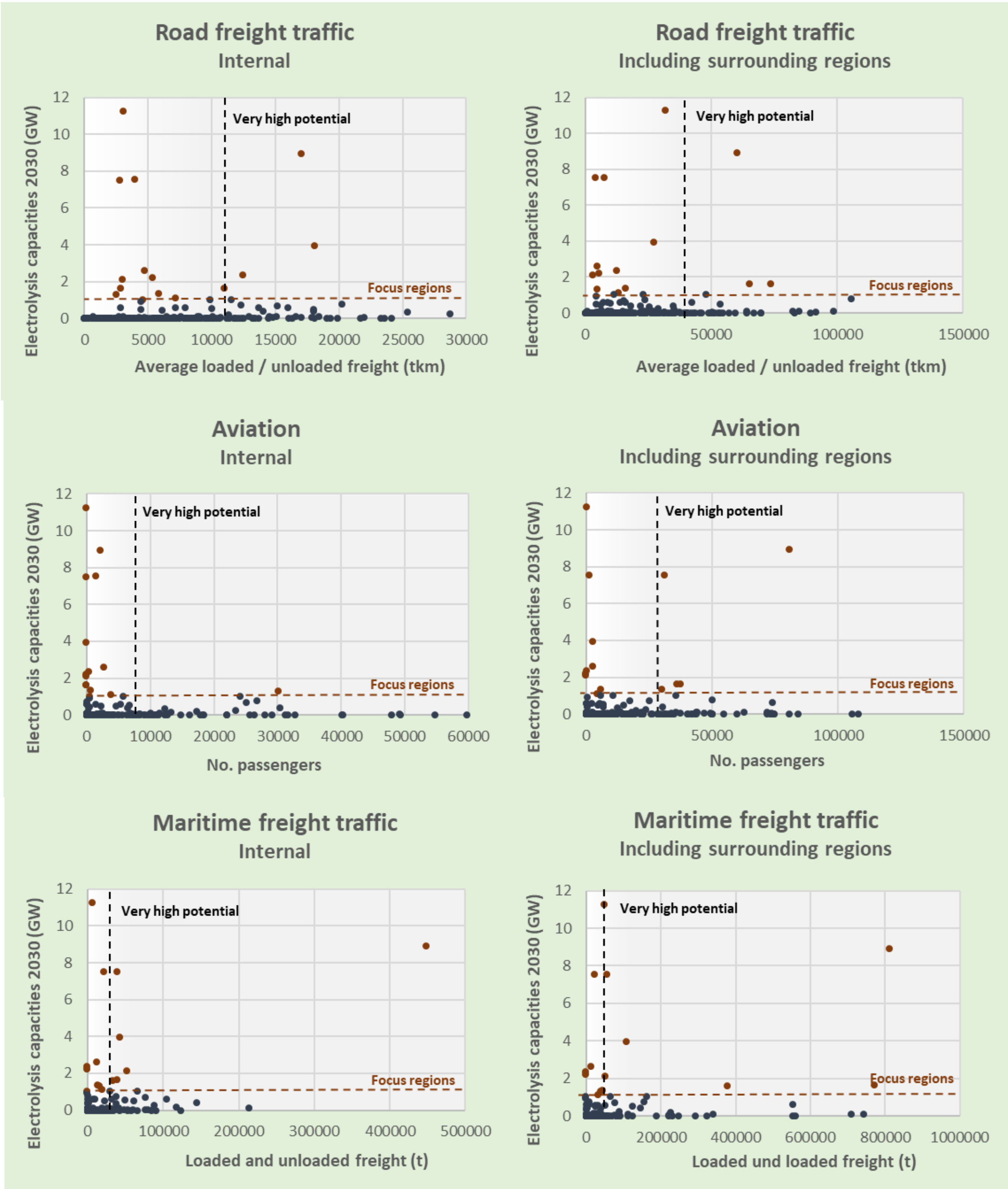
7.3 Comparison of regional usage potentials

Figure A 1: Usage potentials industries in EU NUTS-2 regions



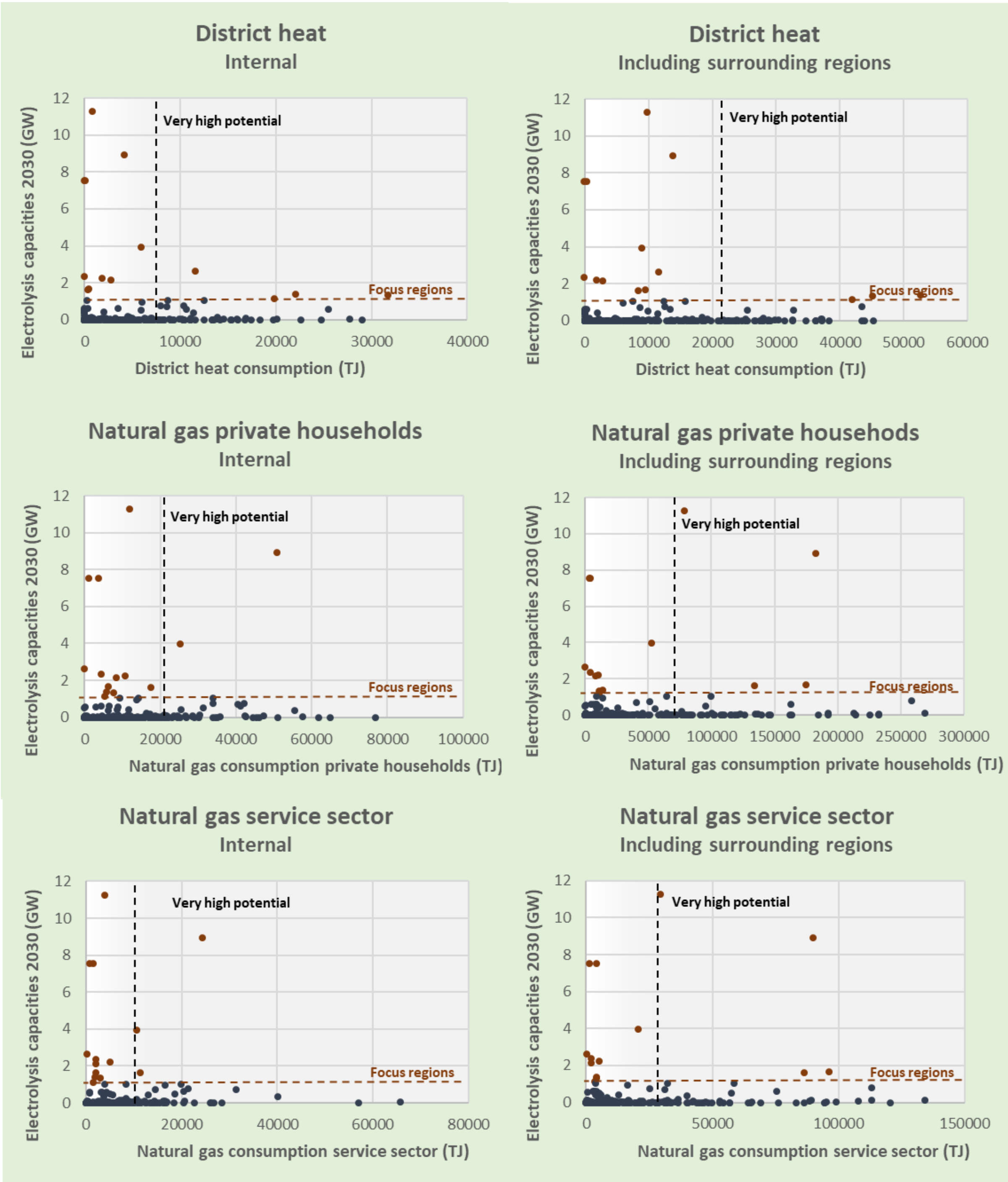
Sources: see Table A1; own representation; very high potential: 20%-highest figures for the EU regions; dark red: focus regions; demarcation of surrounding area: see Footnote 61

Figure A 2: Usage potential for mobility sector in EU NUTS-2 regions



Sources: see Table A1; own representation; very high potential: 20%-highest figures for the EU regions; dark red: focus regions; demarcation of surrounding area: see Footnote 61

Figure A 3: Exploitation potential for buildings sector in EU NUTS-2 regions



Sources: see Table A1; own representation; very high potential: 20%-highest figures for the EU regions; dark red: focus regions; demarcation of surrounding area: see Footnote 61

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