3 Identifying regional access to hydrogen, carbon capture and storage, and climate-neutral freight

Making the key manufacturing sectors described in Chapter 1 climate neutral requires infrastructure. This chapter shows how access conditions and costs may differ across regions. Both hydrogen, needed for chemicals and steel production, and captured CO_2 emissions, most generally needed for cement production, are best transported via pipelines. Pipelines are subject to scale economies: clustered production sites will face lower costs. The first hydrogen transport network will therefore likely be laid out in Northwest Europe. In some regions, local renewable electricity production potential will not be sufficient or too costly to produce the needed hydrogen and will require imports. Good connection to ports also matters: hydrogen or hydrogen-derived products may also be shipped. Moreover, transport to and from ports plays an important role to provide the basic materials key industries produce to downstream industries. Any costs from decarbonising road transport could impact transport costs in inland production locations the most.

Hydrogen, CO_2 capture and storage (CCS) and zero-carbon road freight transport are important to reach climate neutrality in key manufacturing sectors. This chapter investigates access conditions to needed infrastructure and related costs. As shown below, access conditions and infrastructure costs can differ substantially across regions. The chapter analyses these issues for European regions, mostly in European Union (EU) countries.

The first section starts with scenario projections for electricity, hydrogen and CCS needs for emissions and energy-intensive manufacturing sectors in a climate-neutral economy in 2050. It provides the quantitative basis for the analysis in the following sections and explains underlying assumptions. The following sections investigate the regional determinants of supply and demand of hydrogen and CCS respectively. The final section provides an analysis of regional aspects of decarbonising road freight for the key manufacturing sectors, drawing on modelling results to describe the potential regional impact of carbon taxes on road freight.

Scenarios for electricity, hydrogen and CCS use in a climate-neutral economy

The analysis of this section presents projections of electricity, hydrogen and CCS use in the chemicals, steel and cement industries in regions of the European Union and the United Kingdom according to scenarios in which these industries contribute to reaching climate neutrality in 2050. These scenarios are based on the study *Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry "Industrial Transformation 2050"* (Material Economics, 2019[1]). This report distinguishes three pathway scenarios to decarbonise energy-intensive industries, in particular comprising steel, chemicals (including ammonia production) and cement by 2050. The resulting hydrogen, energy and CCS demands differ (Figure 3.1).

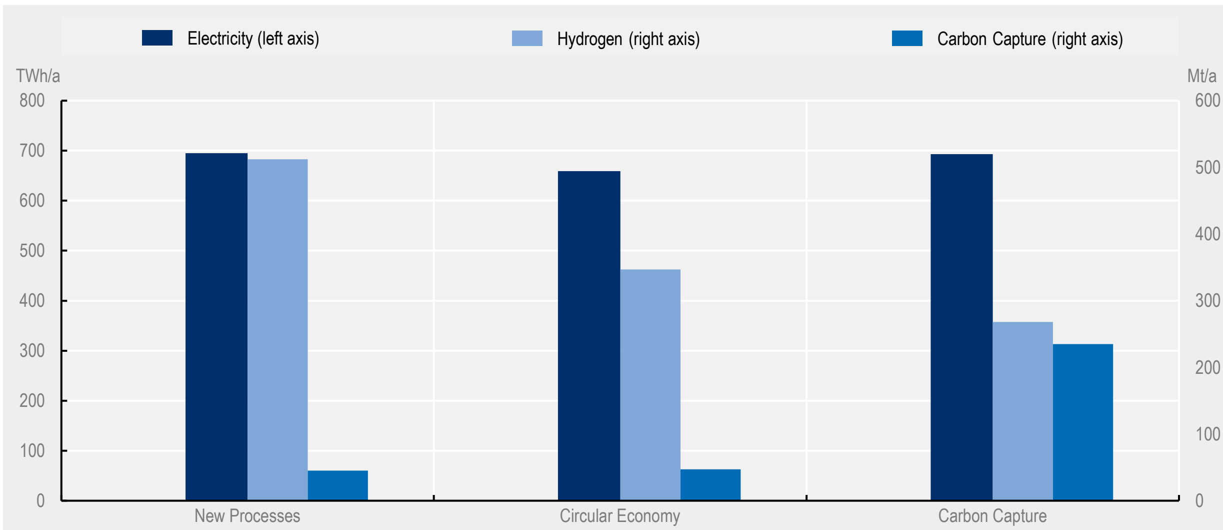
- One pathway with a strong shift to innovative production processes (called New Processes, NP).
- The Circular Economy (CE) pathway, relying mainly on circular economy practices to reduce emissions.
- The Carbon Capture and Storage (CS) pathway, using carbon capture and storage to a greater extent than the other pathways.

The three pathway scenarios – New Processes (NP), Circular Economy (CE) and Carbon Capture and Storage (CS) – all use CCS but to a different extent. The CS pathway focuses mainly on CCS to reach climate neutrality in the 3 manufacturing sectors. Efficiency improvements and other new technologies are used less than in NP (Material Economics, 2019[1]). In the NP and CE pathway scenarios, production processes are electrified directly or indirectly, including with the use of green hydrogen, sharply reducing the need for CCS.

The analysis of regional CCS demand in the following section is based on the CS scenario pathway which implies the largest CCS demand, allowing to point out the largest potential infrastructure needs. The precautionary principle may however argue in favour of limiting reliance on CCS to those activities where it may be unavoidable. CCS has not yet been deployed at scale. Relying on it may imply the risk that emission reductions will not be made if deployment at scale is not forthcoming. The precautionary principle has become embedded in EU environmental protection (Science for Environment Policy, 2017[2]). CCS is most likely to be unavoidable for emissions in cement production, consistent with the analysis in the first chapter. The emission locations from cement production and the challenges in CCS deployment can also be identified in the analysis below and are described in more detail in a forthcoming working paper (Fuentes Hutfilter et al., 2023[3]).

Figure 3.1. The circular economy can damp energy and hydrogen demand from new production processes while limiting reliance on carbon capture

Demand for hydrogen, electricity and carbon capture in emissions and energy-intensive industries: steel, chemicals (including ammonia production) and cement according to three scenarios



Note: The horizontal axis shows three different pathway scenarios to reach climate neutrality by 2050 in steel, chemicals (including ammonia) and cement production. The vertical axes show the amount of electricity (left-hand axis), hydrogen and carbon capture (both right-hand axis) required by each scenario. Carbon capture can include carbon capture and use (CCU) as well as storage.
Source: Material Economics (2019[1]), *Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry*, https://materialeconomics.com/publications/industrial-transformation-2050.

StatLink https://stat.link/zavl9t

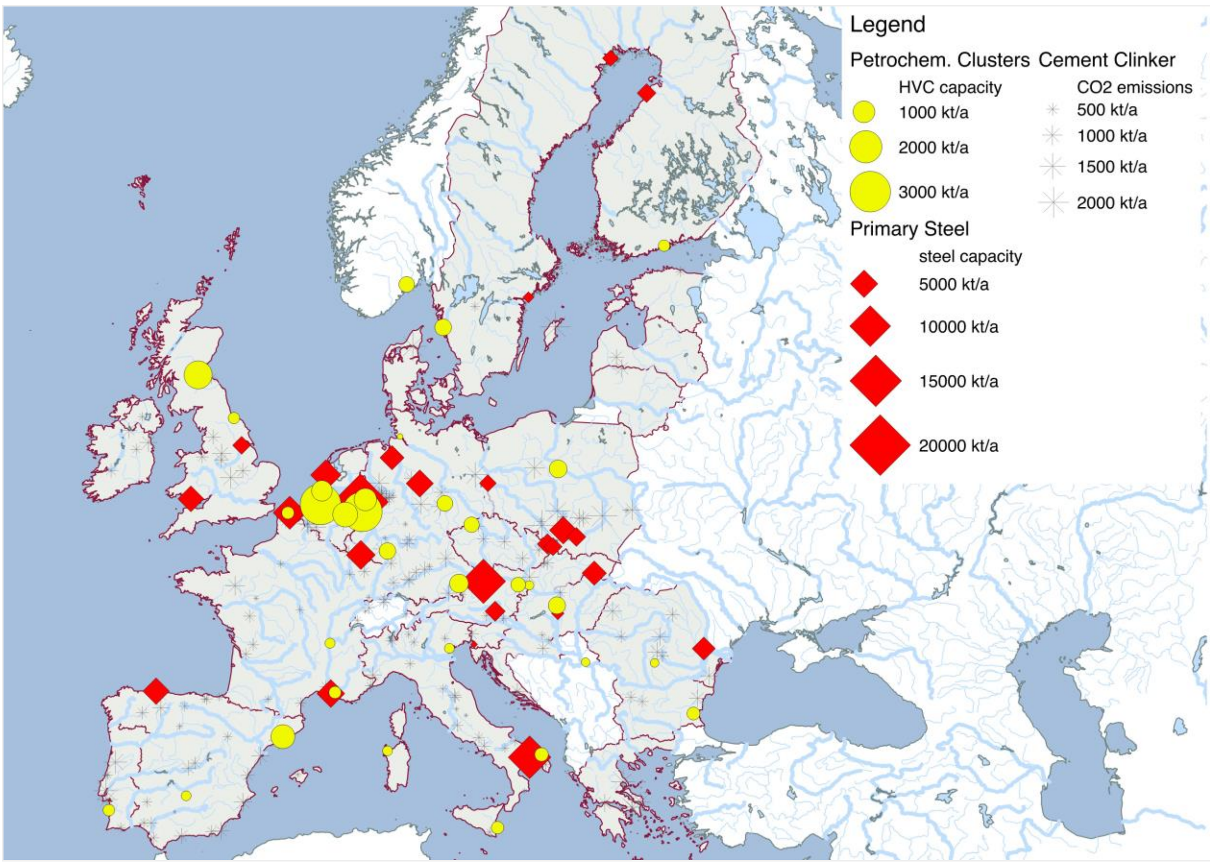
CCS is sometimes classified as an unsustainable technology, such as by the German Federal Environment Agency (UBA). Due to the lack of experience regarding possible negative effects on the environment and health, as well as the violation of intergenerational justice in the case of intensive use of limited CO_2 storage capacity, the UBA recommends the use of CCS only as a transitional technology (Viebahn et al., 2018[4]). A major topic is a legal framework for the export and offshore storage of CO_2 (Benrath, 2021[5]).

The analysis of hydrogen demand below is based on the NP scenario pathway, which implies the largest hydrogen requirements of the three scenario pathways. Again, this allows to identify the largest related infrastructure needs. To ensure consistency with reaching climate neutrality, only “green” hydrogen, produced with renewable energy, is considered. Only hydrogen production from zero-carbon electricity production is consistent with climate neutrality. Most expansion of zero-carbon electricity production will be from renewables, as illustrated, for example, in the International Energy Agency (IEA) sustainable development scenario.

Today’s industrial production sites and their relative production volumes are assumed to remain constant in the assessment of the spatial distribution of hydrogen and CCS demand. Shifts in locations in the transition to climate neutrality are hence not taken into account. Such shifts may however arise as a regional comparative advantage may change, possibly as a result of differences in access to needed infrastructure. While the largest production sites of basic chemicals are geographically concentrated, steel and especially cement production are more dispersed (Figure 3.2). More dispersed production sites may result in stronger regional development challenges for matching supply and demand for CCS and hydrogen, as discussed below. This is because, for both CCS and hydrogen, new infrastructures are subject to economies of scale. The unit cost for industrial use of new infrastructures will be lower if demand in a given location is high.

Figure 3.2. Petrochemicals, steel and cement production is spread across Europe

Production capacities in petrochemical and primary steel production in kilotonnes per annum (kt/a) and CO_2 emissions in kt/a



Note: Petrochemical production capacity refers to high-value chemicals (HVC).
Source: Wuppertal Institute (2019[6]), *Project INFRA-NEEDS - Infrastructure Needs of an EU Industrial Transformation towards Deep Decarbonisation*, https://wupperinst.org/en/p/wi/p/s/pd/818.

Regional determinants for supply and demand of CCS

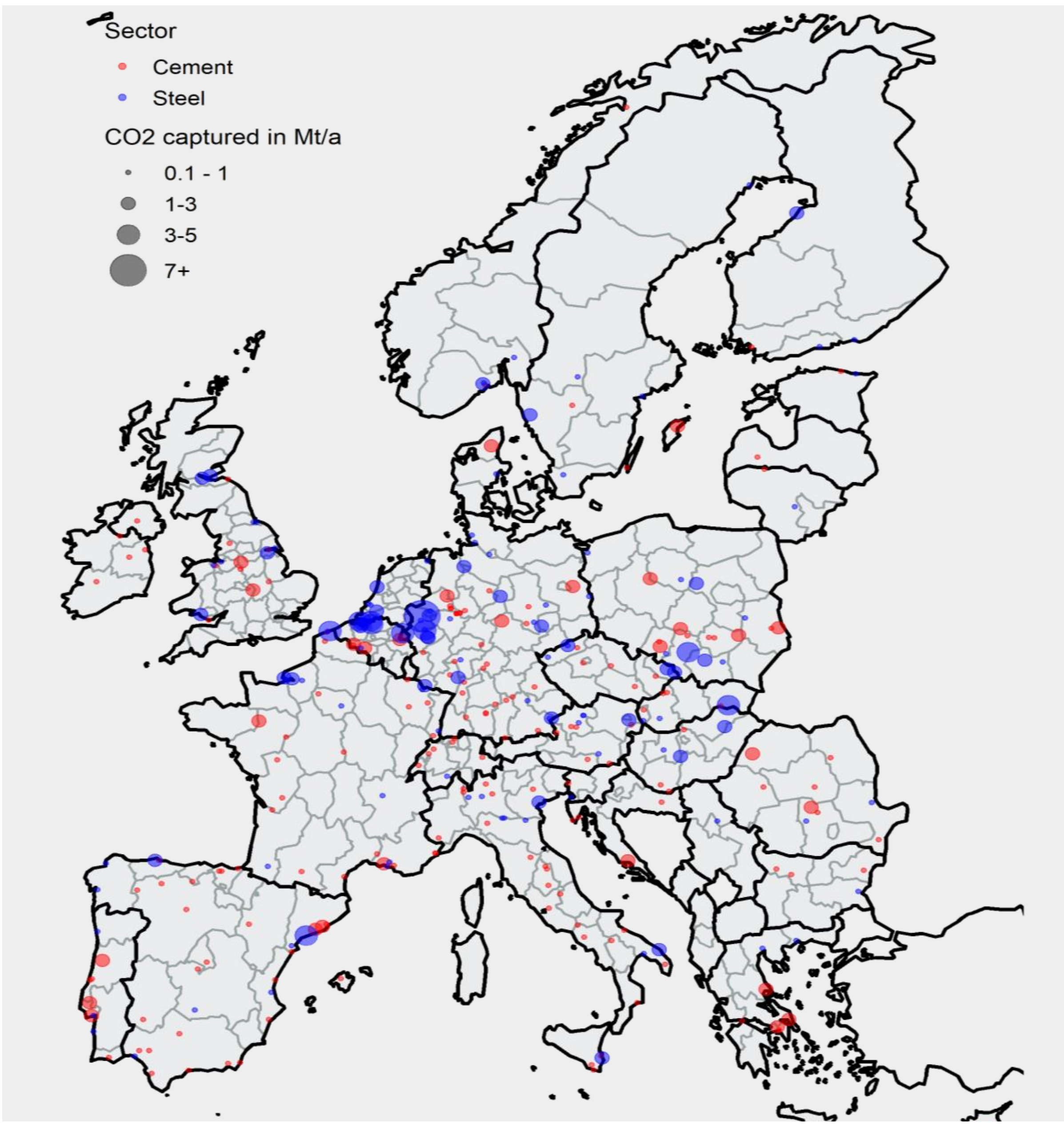
European storage potentials seem to be sufficient on aggregate to meet potential CCS demand. But taking into account constraints from economic and geologic reasons as well as public acceptance, realistic storage sites may often be distant from the location of emissions needing storage. An immense transport effort is needed even if both on- and offshore storage is used. As this section will argue, in most European countries, offshore CCS may have the biggest chance of realisation, due to restrictions, risks and public acceptance issues with potential onshore sites.

Determining industrial CCS demand and its locations

Figure 3.3 shows the distribution of CO_2 emission sources to be captured and stored in 2050 following the CS scenario pathway illustrated in Figure 3.1 and established industrial sites. A major challenge is to develop a sensible infrastructure for small amounts of CO_2 emissions from each of the many dispersed production facilities. The cement sites are spread across Europe in small-scale production units, posing particular challenges for connecting them to CO_2 transport pipelines, as argued below. Since CCS is likely to require new transport infrastructure and infrastructure is subject to economies of scale, quantity reduction results in a higher cost per unit of CO_2.

Figure 3.3. Industrial CO_2 emissions that may be addressed with CCS

2050, million tonnes per year



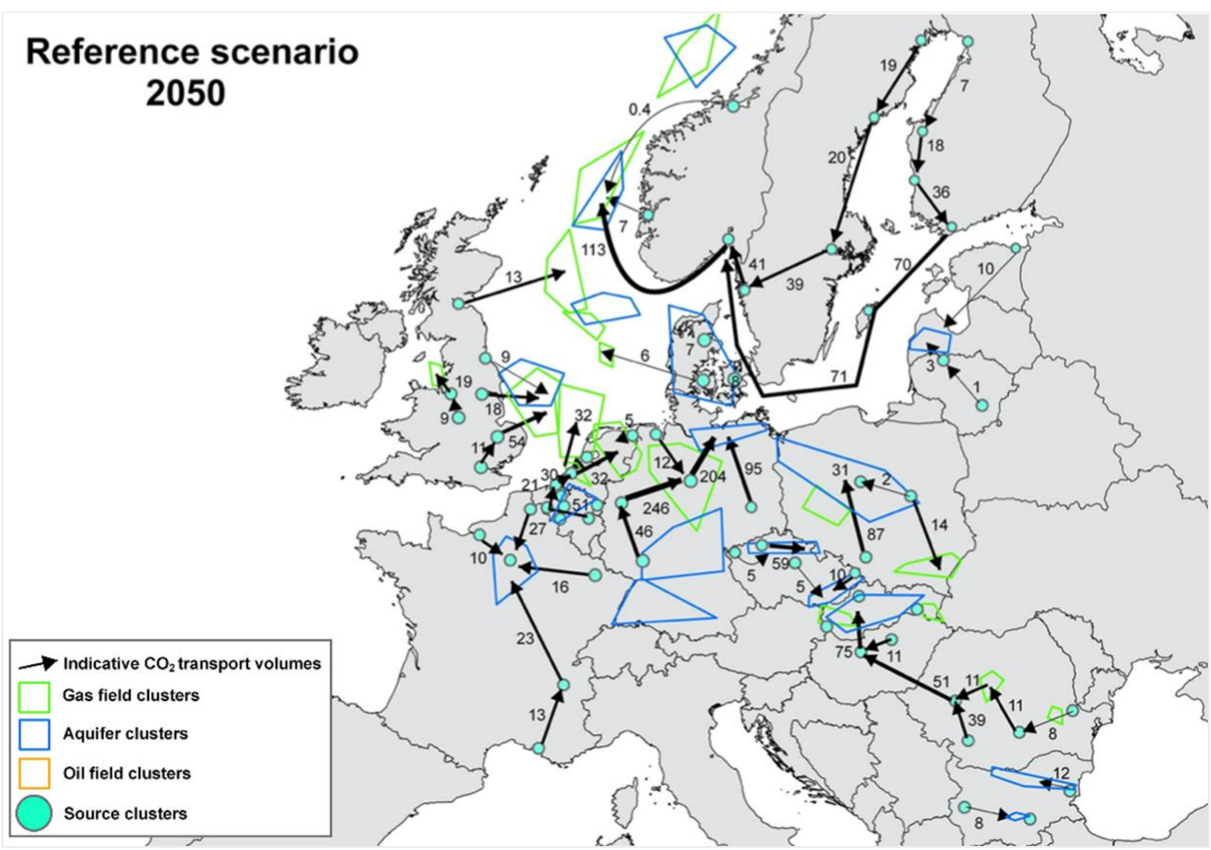
Source: Material Economics (2019[1]), *Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry*, https://materialeconomics.com/publications/industrial-transformation-2050.

Carbon capture, storage and transport supply

Social acceptance of CO_2 storage might be rather low, especially for onshore storage. This is reflected, for example, in the German legal situation. The Act on the Demonstration of the Permanent Storage of Carbon Dioxide (*Kohlendioxid-Speicherungsgesetz*) limits storage in Germany and leaves it up to each regional government to prohibit the storage of CO_2 completely, which already occurs in some regions. Depleted oil and natural gas fields, mostly offshore, have an additional advantage, as old infrastructure can often be used (e.g. pipelines or oil rigs). As discussed in more detail in a forthcoming working paper (Fuentes Hutfilter et al., 2023[3]), saline aquifer storage sites, which are the main storage sites onshore, may be subject to more uncertainty with respect to storage capacity and therefore economic viability, as well as with respect to other local risks, such as the re-emergence of stored emissions.

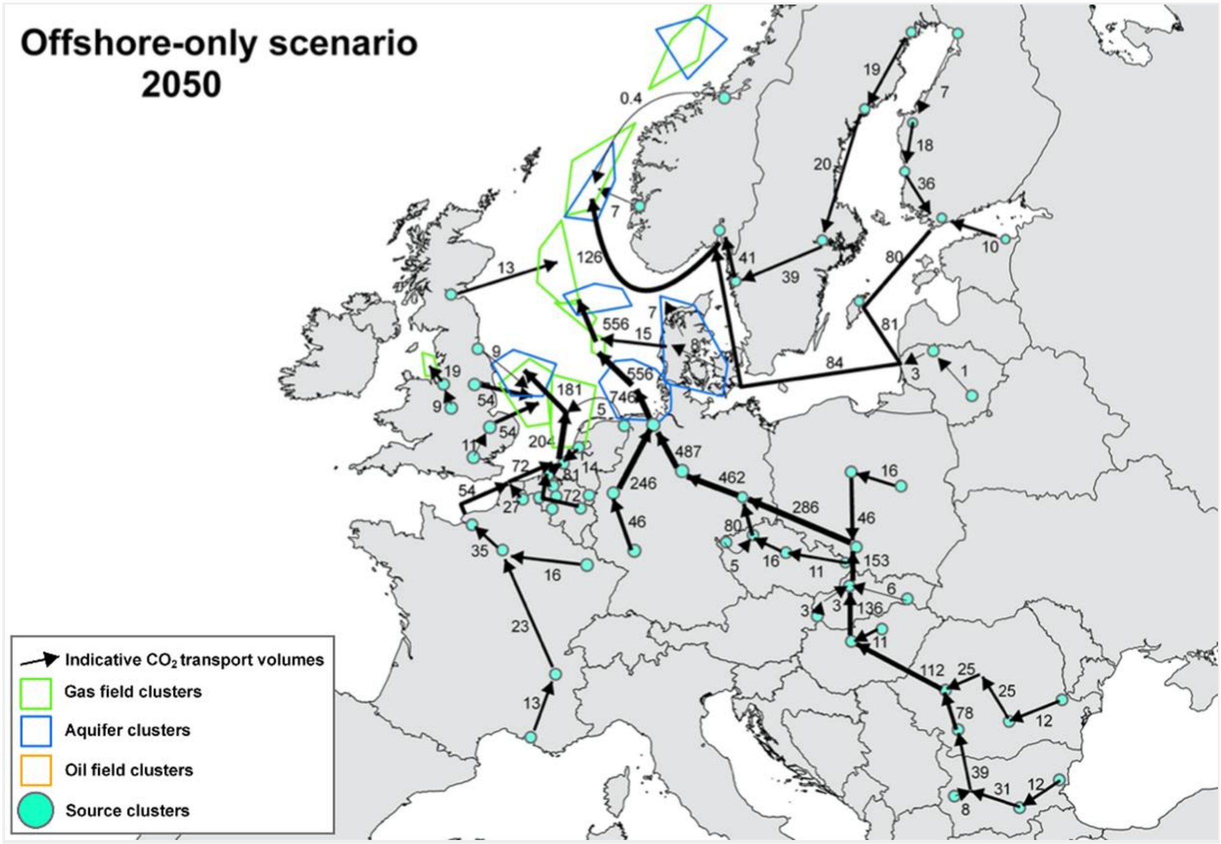
The matching of captured CO_2 to storage sites is primarily a transport problem. Planning and building this infrastructure are time-consuming and costly. No matter which geological storage options are actually used in the future, the captured CO_2 will have to be transported over long distances. Figures 3.4 and 3.5 illustrate what a European CO_2-pipeline-infrastructure solution could roughly look like for the year 2050 in a "reference scenario" with onshore and offshore storage (Figure 3.4) as well as an "offshore-only scenario" (Figure 3.5). No study appears to exist to date to show how the industrial emission sources illustrated above could be linked to potential CCS sites. Therefore, instead, the two scenarios shown in Figures 3.4 and 3.5 were designed for CO_2 emissions from power generation (Neele et al., 2011[7]).

Figure 3.4. CO_2 to be transported and geological storage options in the reference scenario in 2050



Source: Neele, F. et al. (2011[7]), *Towards a Transport Infrastructure for Large-scale CCS in Europe*, http://www.co2europipe.eu/.

Figure 3.5. CO_2 to be transported and geological storage options in the offshore-only scenario in 2050



Source: Neele, F. et al. (2011[7]) , *Towards a Transport Infrastructure for Large-scale CCS in Europe*, TNO, http://www.co2europipe.eu/.

From today's perspective, power generation should not be decarbonised with CCS, given the available low-cost zero-emission electricity generation. Even so, the scenarios shown in Figures 3.4 and 3.5 are illustrative, as the challenges industrial production locations face to be connected to a CO_2 pipeline transport infrastructure system may be broadly similar. The scenarios are ten years old but the broad locations of storage sites identified at the time remain broadly valid today. The pipeline infrastructure in the reference scenario with 21 800 km as well as in the offshore-only scenario with 32 000 km suggests that an immense transport effort is necessary in either case. Moreover, existing natural gas pipelines are more difficult to repurpose for CO_2 transport than for hydrogen transport as discussed in the aforementioned forthcoming draft working paper. CO_2 transportation is therefore likely to require new infrastructure.

As argued above, it may be prudent to limit CCS for industrial emissions to process emissions in cement, which is likely to be the most dependent on CCS. As discussed in Chapter 1, doing away with CCS in the steel and chemicals sectors raises the demand for hydrogen and the depth of the transformation of production processes, requiring more focus on avoiding stranded assets. If CCS is limited to process emissions in cement, only between 31 and 35 $MtCO_2/a$ process-related emissions would have to be taken into account (Material Economics, 2019[1]). Even so, transportation needs would still be largely owing to the geographical spread of cement production, as process-related emissions will occur at every site unless production sites are closed. Owing to scale economies, limiting CCS to cement production is therefore likely to reduce transportation costs much less than proportionally to the reduction in demand for CCS.

As Figures 3.4 and 3.5 illustrate, transport costs may vary considerably across regions, especially in an offshore-only scenario. In regions where transport costs for CCS may be particularly high, the economic pressure to do without CCS may be strongest, which may in turn reinforce the need to integrate new industrial processes and related investment and technology needs. However, these regions may not be the most advanced technologically and their businesses may not have the strongest capacity to invest in these new technologies.

Determinants of pipeline transport costs

Table 3.1 illustrates the economies of scale from pipeline deployment. For example, the investment costs for an 18-inch-wide pipeline and a distance of 500 km are higher in absolute terms (EUR 1 002 per metre) compared to a 12-inch pipeline (EUR 884 per metre). In unit terms, however, investment costs of a larger pipeline are significantly lower, as the transport capacity may be more than twice as high. Regions with a high density of industrial point sources (e.g. Northwestern Europe), which may also be economically more developed, benefit from more potential to reduce unit costs. Higher unit costs in less economically developed regions could be a source of territorial divergence.

Table 3.1. Investment costs for CO_2 pipelines, in EUR/metre

Inner diameter in inches	100 km distance	250 km distance	500 km distance	1 000 km distance
48	4 559	3 195	2 749	2 516
40	3 666	2 504	2 130	1 888
36	3 299	2 221	1 787	1 652
30	2 455	1 698	1 451	1 327
28	2 316	1 586	1 363	1 227
24	2 100	1 405	1 174	1 062
18	1 879	1 222	1 002	888
12	1 699	1 085	884	775

Source: Kjärstad, J. et al. (2016[8]), "Ship transport - A low cost and low risk CO_2 transport option in the Nordic countries", *International Journal of Greenhouse Gas Control*, Vol. 54/5, pp. 168-184.

In regions with high industrial density in key future CCS transport network locations and with good access to offshore sites, industrial sites and their owners may pursue collective strategies to develop pipeline infrastructure to access such sites. There may be pressure to include more emissions in CCS in such regions to benefit from scale economies, though small and more distant emitting plants may still be left out. In regions with poor access to offshore sites and low industrial density, it is particularly important to explore distributed onshore sites (Fuentes Hutfilter et al., 2023[3]).

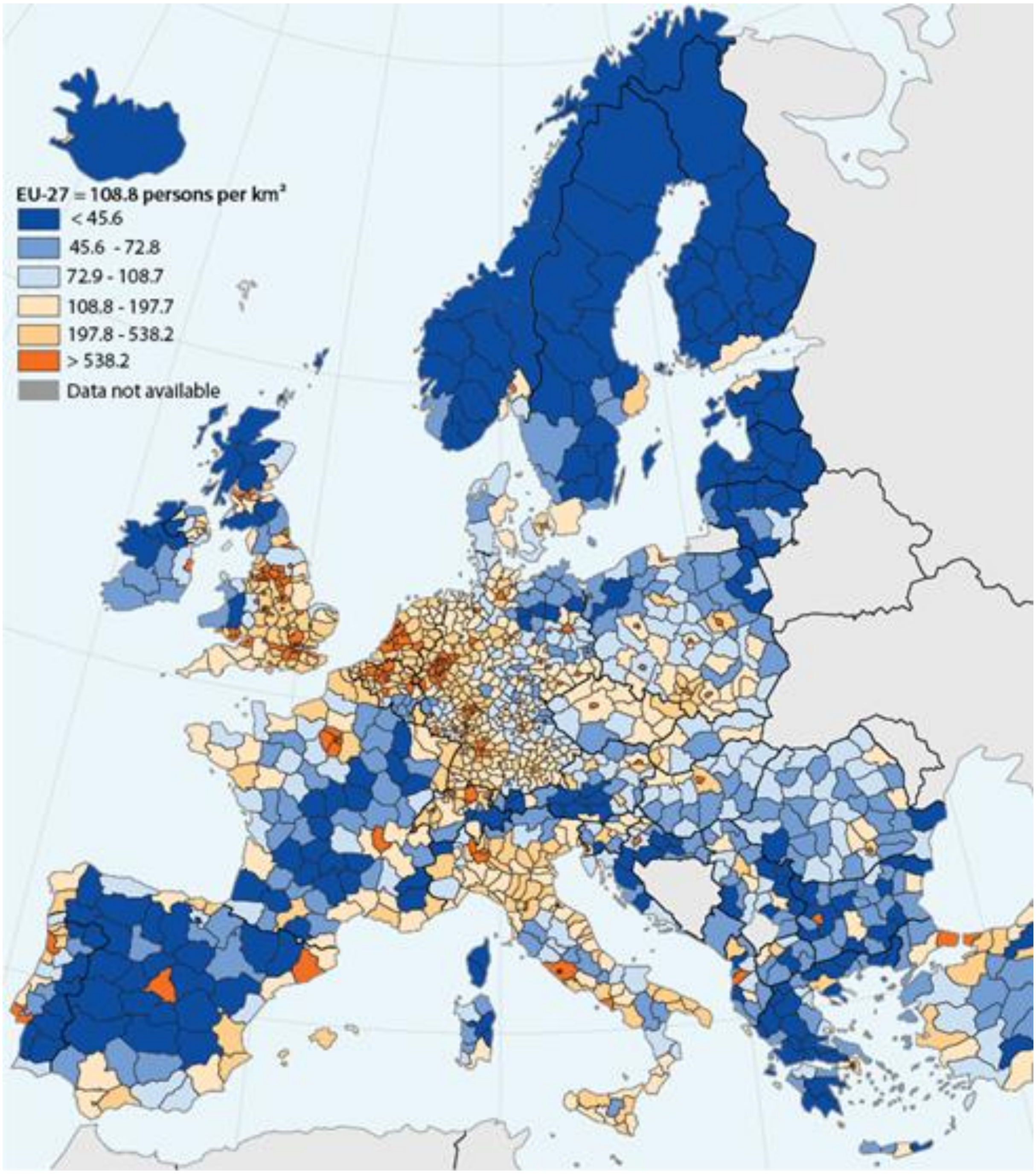
The terrain to be crossed and the distance have a major influence on the cost. Land that is difficult to cross, including densely populated or mountainous areas, may need to be bypassed and, if crossed, mountainous areas may require more energy for pumping (Kjärstad et al., 2016[8]; IEAGHG, 2013[9]). The following terrain factors for cost have been estimated, for a given distance:

- 1.2 for flat terrain.
- 1.5 for hilly terrain.
- 2 for densely populated areas, wetlands and nature reserves.

These three terrain factors that raise transport costs are unequally distributed across regions (Figures 3.6 and 3.7).

Figure 3.6. Population density raises pipeline costs

Population density across European regions



Source: EC (n.d.[10]), "Using CO_2 instead of storing it: carbon capture and use (CCU)", European Commission.

Figure 3.7. Wetlands raise pipeline costs

Wetlands locations across European countries

Source: (European Environment Agency, 2000[11]) Wetland concentration in Europe https://www.eea.europa.eu/data-and-maps/figures/wetland-concentration-in-europe-2000.

CCU may be an alternative to CCS. CCU is particularly useful when CO_2 capture and CO_2 use occur at the same site. This is usually only the case for integrated applications in the chemical industry, although this can be very specific to the site. Therefore, an individual assessment for each site is required. Cement and lime plants, in contrast, are often spatially distributed and usually do not have a direct potential user on site. They would have to look for a buyer in the surrounding region. Climate neutrality would also require that local supply and demand of CO_2 match very closely quantitatively.

Only CO_2-absorbing products that have very long product life cycles of at least several decades and do not ultimately release the CO_2 themselves contribute to decarbonisation. It has not yet become clear which products can satisfy these conditions. One example is to blow the captured CO_2 into greenhouses in order to achieve better plant growth. The decisive factor would in this example be how the biomass is subsequently used. CO_2 capture can entail a considerable additional expenditure on electricity and process heat (about 30%) and CO_2 capture only achieves capture rates of 80-90%, depending on the technology (Samadi et al., 2018[12]).

Regional determinants for supply and demand of hydrogen

As this section will argue, even though European renewable generation potentials might be sufficient to meet electricity and green hydrogen demand, including from industry, if fully exploited, hydrogen imports play an important role because of their potentially low cost. Hence, the proximity to well-suited renewable generation potentials and hydrogen transport infrastructures such as ports and repurposed natural gas grid pipelines is important.

Determinants for industrial hydrogen demand

Hydrogen can be used for the climate-neutral production of steel as well as chemicals. Among the three pathways considered above (Material Economics, 2019[1]), the lowest hydrogen demand is in the Carbon Capture and Storage (CS) pathway, which includes the least transformations in production technologies. The Circular Economy (CE) pathway results in slightly higher hydrogen demand. The New Processes (NP) pathway implies by far the highest demand for hydrogen (Figure 3.1). In the following, this pathway is chosen – as previously explained – to illustrate hydrogen demand implications.

Figure 3.8 shows the resulting spatially resolved hydrogen demand in the year 2050, assuming a development according to the NP pathway (ENTSO-E, 2014[13]) assuming the current production sites are maintained until 2050.

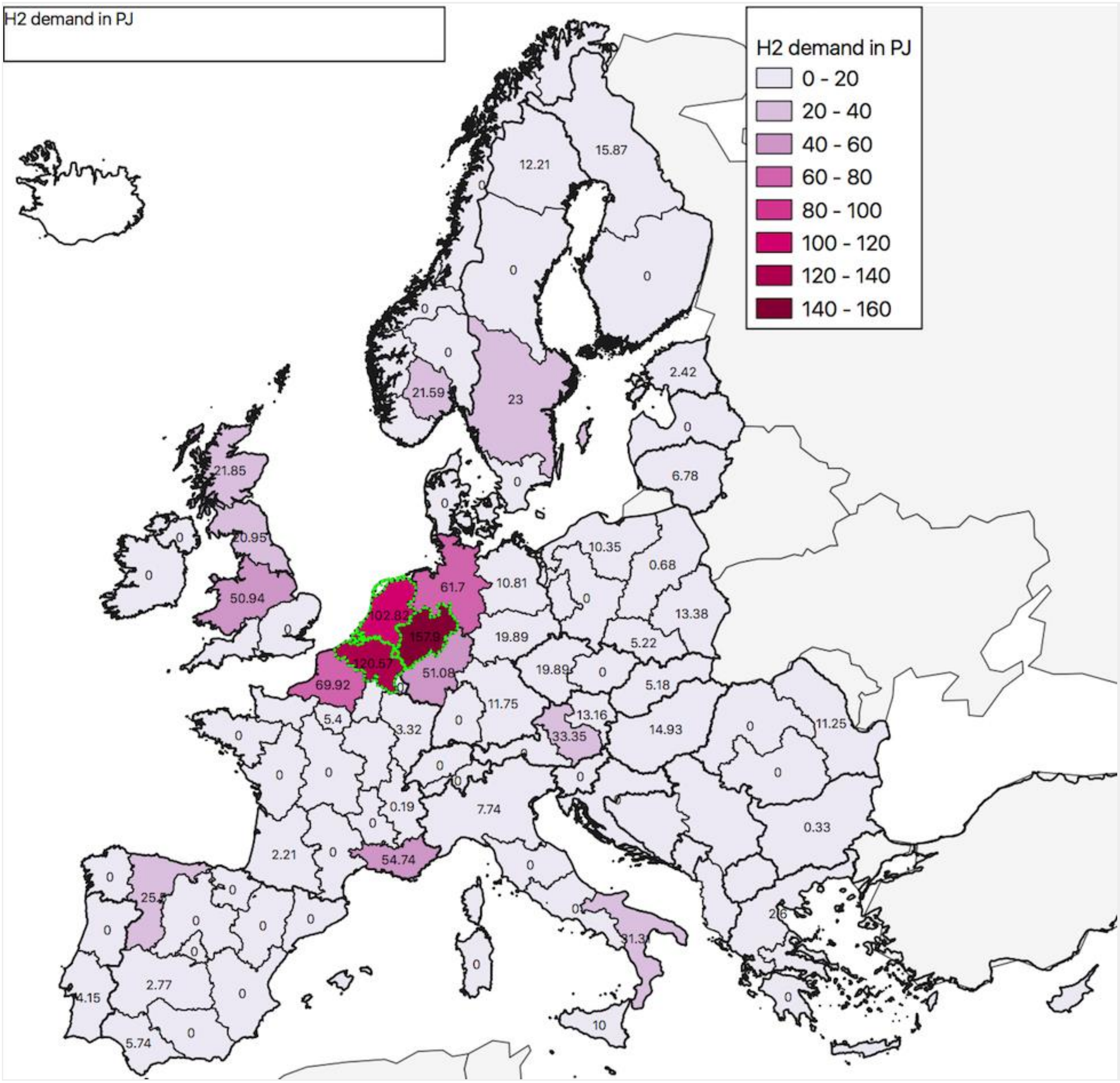
There will be some regions with highly concentrated industrial hydrogen demand. Hydrogen demand from non-industrial sectors such as transportation must, in addition, also be considered for future infrastructure.

Determinants of hydrogen supply

Green hydrogen is produced using renewable electricity in electrolysis. Renewable energy (RE) sources are essentially solar (photovoltaic, PV, or concentrated solar power, CSP), wind power (on- and offshore) and electricity generation from hydropower. Well-suited hydrogen production sites are locations with steady, strong wind speed and solar irradiation. In addition, the technical electricity generation potential is determined by the properties of the land: residential areas may be suitable for rooftop PV but not for wind power generation; agricultural activity, forests or mountains also influence which and how many renewable power plants can be built. The combination of weather conditions and the installable capacity (available places) is referred to as the technical generation potential. In addition, nuclear electricity could also be attractive. But scenarios for reaching climate neutrality by 2050 generally posit that most of the large-scale increase in zero-carbon electricity generation must come from renewables and electricity is typically generated at the lowest cost from renewable sources.

The estimates of the technical potential differ widely across studies. For example, in the study used below the potential is estimated at 6.900 TWh (ENTSO-E, 2014[14]). Figure 3.9 shows renewable electricity generation and the technical potential of RE generation from wind on and off shore, solar PV and CSP based on ENTSO-E data (ENTSO-E, 2014[14]) for European countries. Offshore potentials are allocated to the neighbouring land clusters. LBST (LBST, 2017[15]) estimates about double the potential (14 000 TWh).

Figure 3.8. Spatial distribution of hydrogen demand for decarbonising chemicals and steel production

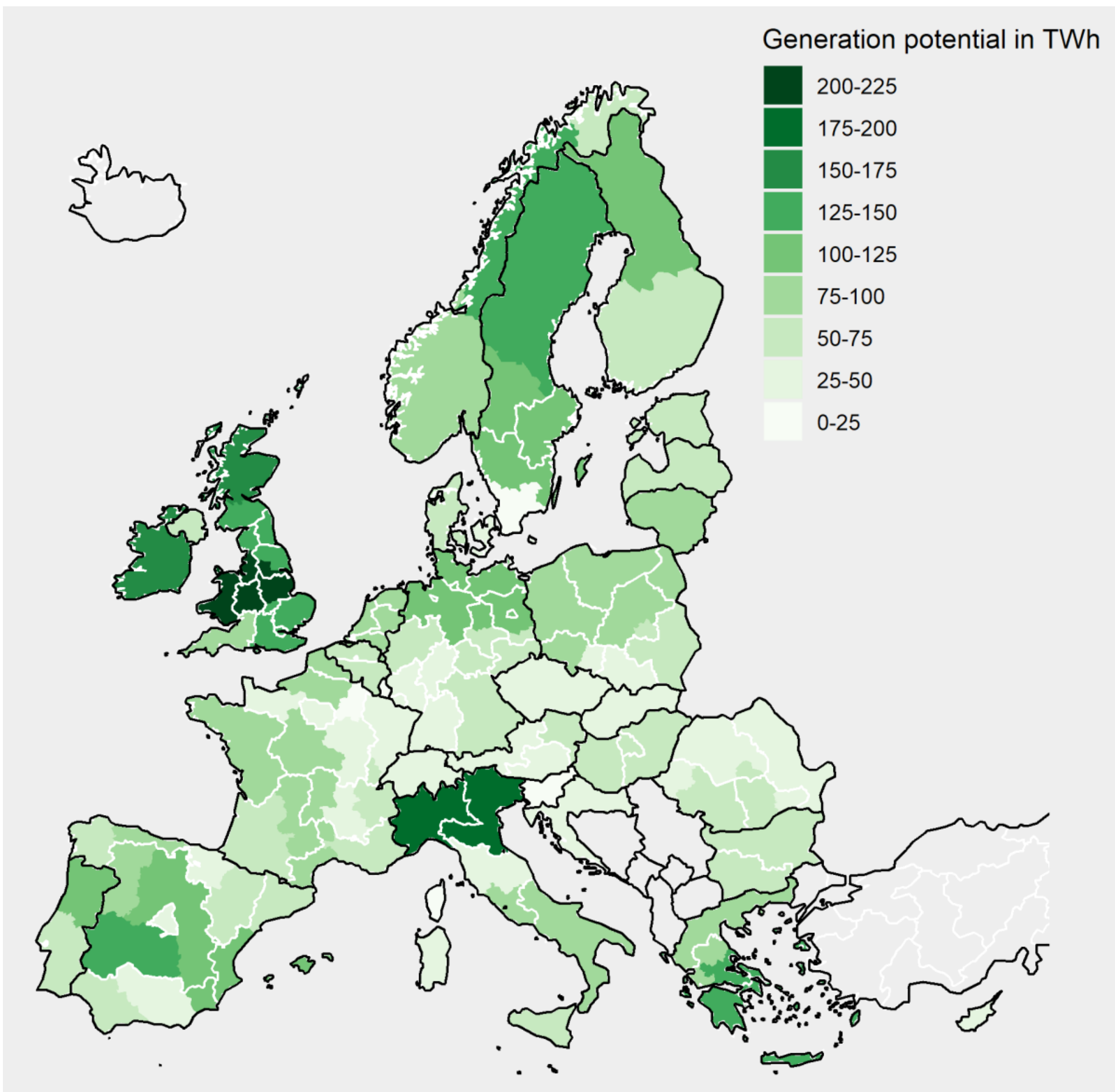


Source: (2014[13]); (ENTSO-E, 2014[14]) Wuppertal Institute calculations.

The potential of RE in Europe could be technically sufficient to meet demand including from climate-neutral industry. However, this would require exploiting the technical potentials to a large extent, including where it may be costly to do so, for example because wind or solar conditions are not optimal. Economic optimisation implies the import of hydrogen or hydrogen-based products, from the Middle East and North Africa (MENA) region for example (IEA, 2019[16]; Forschungszentrum Jülich, 2020[17]). Chile may also offer strong potential. Aiming for independence from foreign supply can lead to accepting the additional costs of local production. Some regions may be forced to be independent because their access to imported hydrogen is difficult.

For green hydrogen, the more uniform the electricity supply, the better the utilisation of electrolysis plants' capacity. CSP is attractive due to its thermal storage but its potentials are limited within the EU. This makes offshore wind generation suitable but often expensive, as shown below. Green hydrogen can also be produced with renewable electricity from distant locations and transported via a sufficiently developed electricity grid. Electrolysers with low-capacity utilisation owing to intermittent wind or solar power can also add value to climate-neutral energy systems as a flexibility instrument, running in times of surplus electricity generation and perhaps providing hydrogen for backup power plants. This option may become more viable as the capital cost of electrolysers falls. The determinants for the availability of green hydrogen can be summarised with spatial proximity to generation potentials, suitable electricity and gas grid nodes, hydrogen transport routes or hubs, and the density of hydrogen demand.

Figure 3.9. Renewable electricity technical potential from wind and solar vary across regions

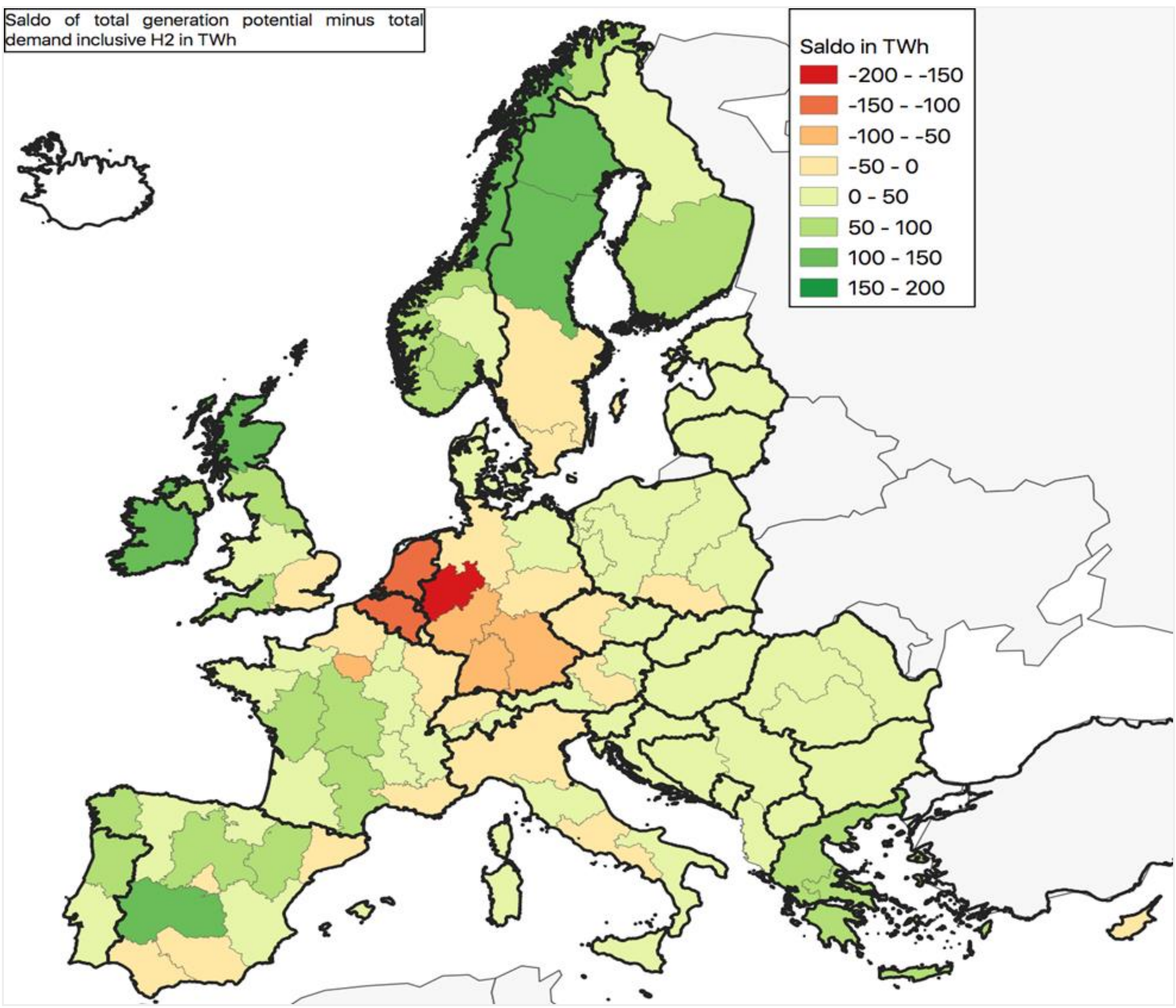


Note: Includes existing renewable electricity generation, including from other sources than wind or solar, and solar and wind technical potential.
Source: (2014[13]). (ENTSO-E, 2014[14])

Figure 3.10 shows the balance of renewable electricity generation potential and the demand for electricity in each region, including the demand for electricity to produce hydrogen for industrial needs. Red colours indicate that, in the respective region, electricity consumption is higher than the generation potential, and green colours show that excess generation could be achieved if the full generation potential were exploited.

This overview shows that technical RE potentials in southern and northern Europe could be sufficient to meet the demands on a yearly basis without taking into account diurnal or seasonal fluctuations. But especially in Northwestern Europe, the demand is significantly higher than generation potentials. This will result in hydrogen imports. Imports may be more widespread than the map suggests owing to lower renewable electricity production costs outside Europe.

Figure 3.10. Balance of generation potential and projected total electricity demand in Europe



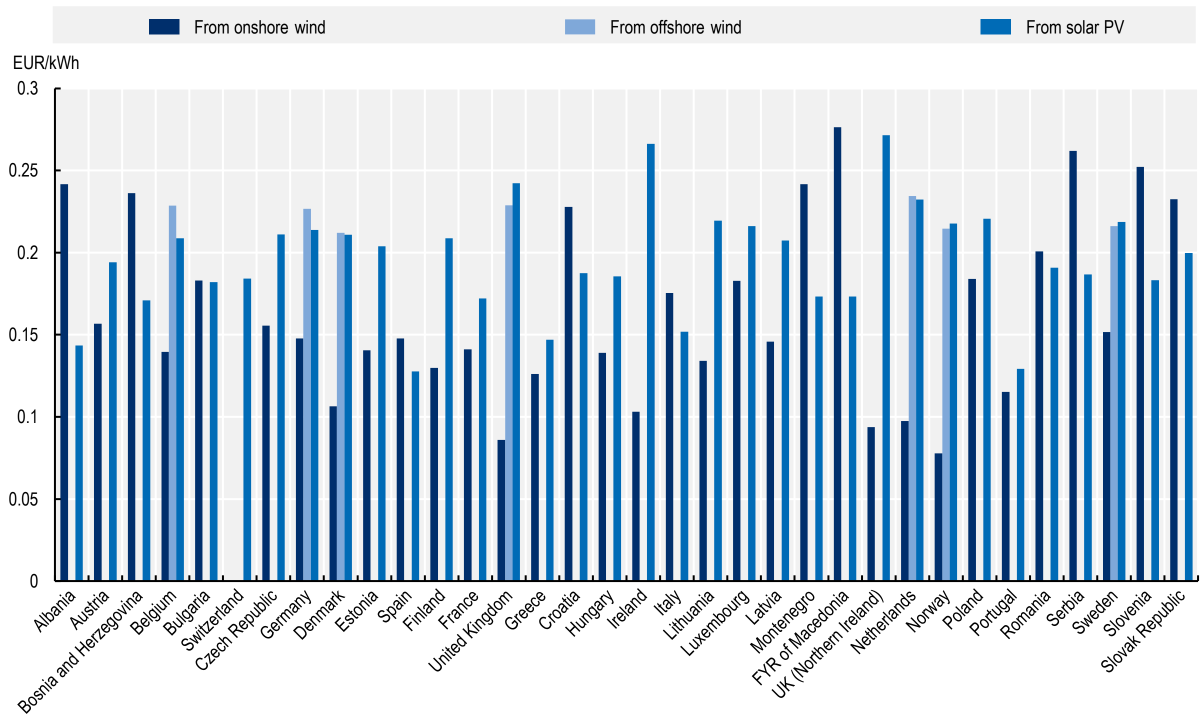
Source: (2014[13]); (ENTSO-E, 2014[14]) and Wuppertal Institute calculations.

Regional hydrogen production costs

While many regions may have sufficient technical potential for renewable electricity to cover their energy needs, including those needed to meet hydrogen production for industry, costs may be relatively high in some. Figure 3.11 shows hydrogen production costs across European countries. These are calculated assuming that electrolysers use electricity from either onshore or offshore wind or solar photovoltaics (PV) directly. Higher renewable yields lead to a better capacity utilisation of the electrolyser and thereby lower costs. Even higher full load hours can be achieved when combining wind and solar plants (Agora Verkehrswende/Agora Energiewende/Frontier Economics, 2018[18]).

Offshore wind is a rather expensive source of hydrogen: despite the high full load hours, the assumed high costs and low lifetimes of offshore wind plants lead to hydrogen costs between EUR 0.21 and 0.23/kWh.

Figure 3.11. Regional costs for producing hydrogen from onshore wind or PV in Europe in 2030



Source: Data supplied by Wuppertal Institute.

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There is a broad range of estimated import costs as a meta-analysis on hydrogen import costs to European countries reveals (Merten et al., 2020[19]), taking several studies with a focus on imports from northern Africa into account, and showing a range between 0.080 EUR/KWh (8 Ct/kWh) and 0.2 EUR/KWh (19.6 Ct/kWh). Some regions in Europe could produce hydrogen within the range of import prices. Other work (Merten et al., 2020[19]) has compared the cost of domestic production with the cost of imports.

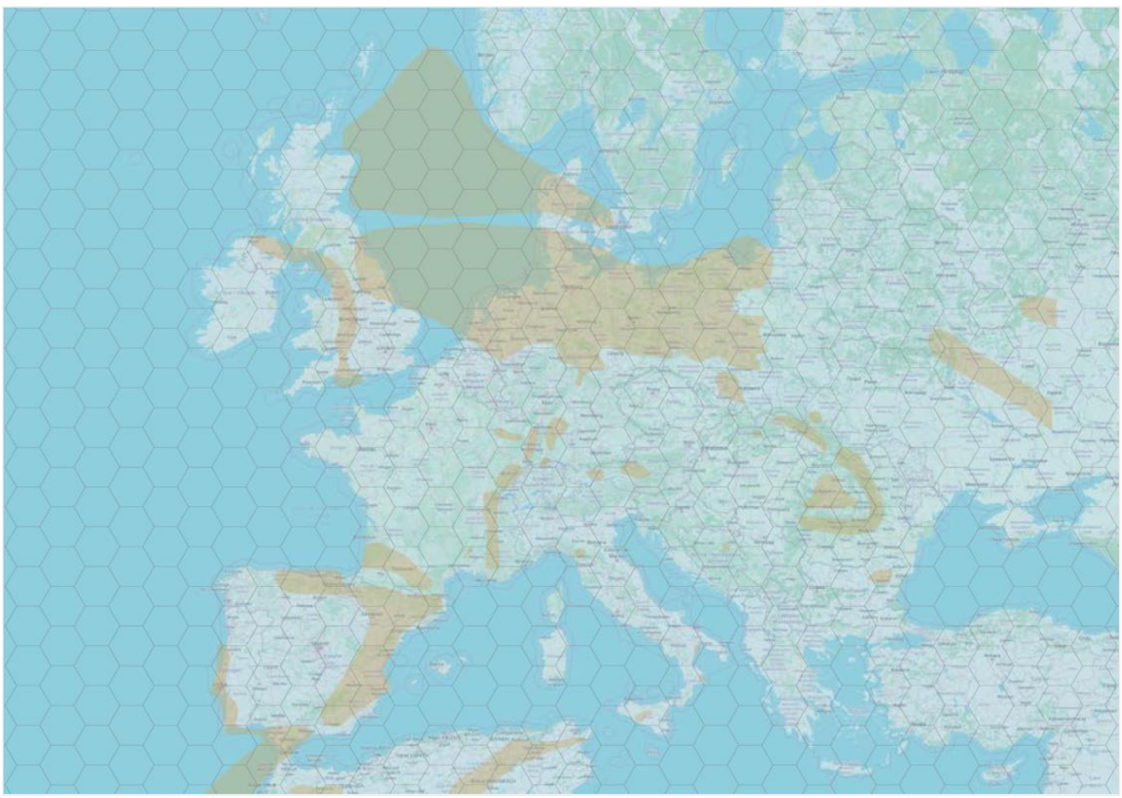
Hydrogen storage and electricity transmission capacity

The local availability of hydrogen storage and the transmission capacity of the electricity grid also have an impact on hydrogen availability and its cost. Seasonal storage in salt caverns is not possible everywhere (Figure 3.12) but is important for the overall energy system to manage fluctuations in hydrogen demand and intermittent renewable electricity supply. Sites with seasonal storage potential may be among the first sites to be connected to a future hydrogen grid. The spatial proximity to suitable salt caverns is therefore a regional advantage to provide an early connection to the hydrogen network.

For remote sites without good access to sufficient renewable generation and to a hydrogen infrastructure, it may be cheaper to use or reinforce the electricity grid for transporting the energy there, especially if they are located in difficult terrain and produce hydrogen from this electricity.

One effect of the decarbonisation of industry is that electricity demand concentration is intensified with implications for electricity transmission. Decarbonisation will lead to a shift in energy use from fossil fuels to electricity and hydrogen produced with renewable electricity. As a result, regions with much industrial production will experience a much stronger increase in electricity demand than regions with low industrial production.

Figure 3.12. Salt strata in Europe indicating possible seasonal hydrogen storage sites



Note: Orange shading indicates salt strata.
Source: Agora Energiewende/AFRY Management Consulting (2021[20]), *No Regret Hydrogen - Charting Early Steps for H_2 Infrastructure in Europe*, https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_02_EU_H2Grid/A-EW_203_No-regret-hydrogen_WEB.pdf.

Hydrogen transport

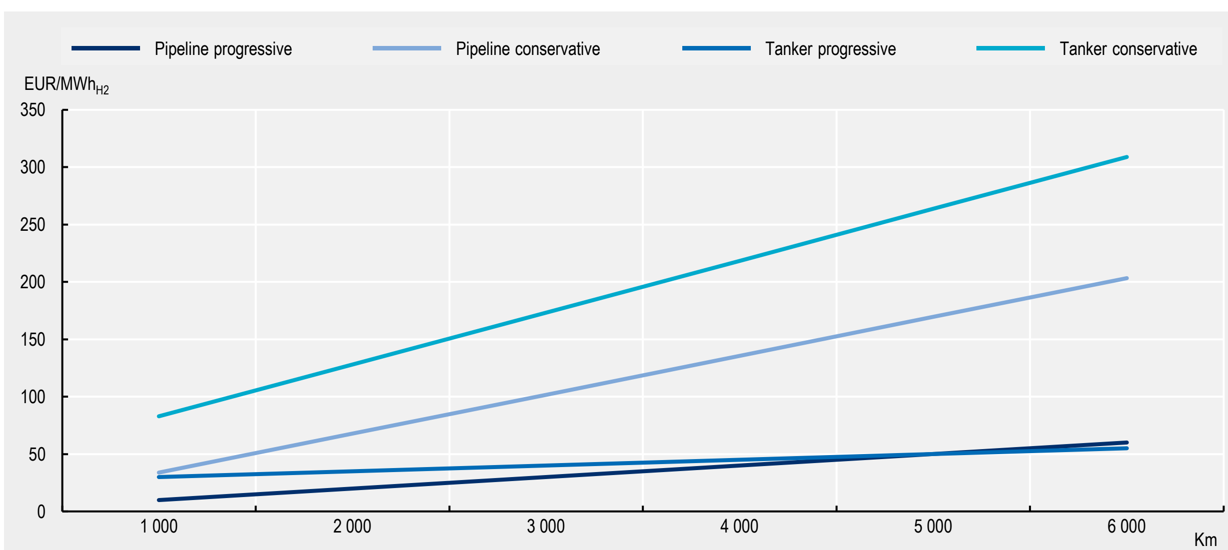
Hydrogen can be transported in various forms: as a gas in pipelines, as a compressed gas or cryogenic liquid in tankers or by train or truck. An important determinant for hydrogen availability is therefore access to the corresponding infrastructure. In principle, trucks can reach almost any site but, like trains, they are not economic for large quantities of hydrogen and their operation requires energy. Port locations offer the best access to the "world market" for hydrogen: since distances for transport by ship are of less relevance, hydrogen can also be landed here from distant world regions. Pipelines enable the transport of large quantities of hydrogen onshore over long distances but are cost-intensive to provide if newly built over long distances. Larger clusters of consumers can be connected via pipelines but the associated additional costs are high for small consumers. A very important alternative to the construction of new hydrogen pipelines is the repurposing of existing natural gas pipelines. These have to be retooled for that purpose since natural gas and hydrogen have different chemical features.[1] Natural gas pipelines offer the great advantage of an interconnected network that is well developed, especially in industrial locations with a high demand density.

There are different alternatives to transporting pure hydrogen gas: liquid organic hydrogen carriers (LOHCs) are chemical substances which are easily storable and can absorb and release hydrogen through chemical reactions. They are suitable for transport by tanker, train, truck or pipeline. LOHCs are liquid even at ambient pressure and temperature (IEA, 2019[16]). The advantage of this transport method is that the energy density is several hundred times higher; however, LOHCs require additional energy input. Transport of hydrogen-derived ammonia is also an option; ammonia is especially suitable for transport by ship. The energy density is about twice as high as LOHCs (4.25 kWh/l). After transport, hydrogen can be recovered or the ammonia can be used in downstream chemical production. Another indirect form of transporting hydrogen is to import iron produced with hydrogen without emissions (see Chapter 1): it could be produced in RE-strong regions, be transported to the steel plant and avoid hydrogen use there. The transport of direct-reduced iron might be a solution for steel sites without sufficient access to renewable hydrogen.

Costs for long-distance hydrogen transport

The different forms of transport have different implications for European regions. The costs for pipeline transport increase significantly with distance than the costs for transport by ship (Figure 3.13).

Figure 3.13. Relationship between transport distance on transport costs for hydrogen



Note: "Progressive" refers to low-end estimates of costs, "conservative" to high-end estimates of cost.
Source: Merten, F. et al. (2020[19]), "Policy brief – Infrastructure needs of an EU industrial transformation towards deep decarbonisation, based on research project funded by EIT Climate-KIC. Task ID: TC_2.11.1_190229_P259-1B".

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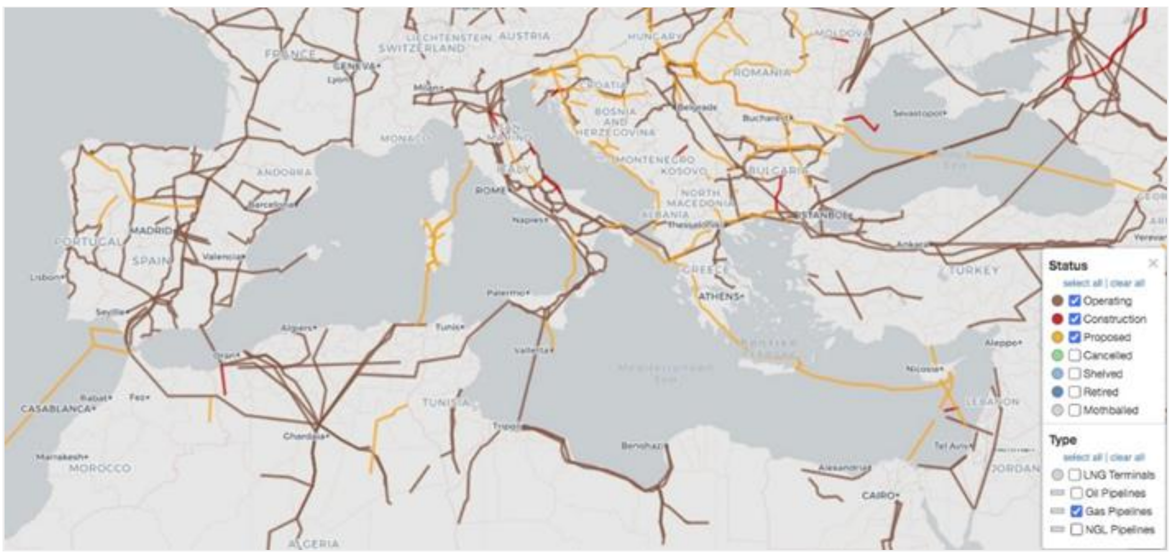
Regions that are close to potential hydrogen-producing regions, such as MENA, and benefit from mostly land-based connections can take advantage of lower-cost pipeline transport, such as Southwestern Europe via Algeria and Morocco. Natural gas pipelines could be repurposed for hydrogen (Figure 3.14).

The costs for hydrogen transport by ship are less distance-dependent but the proximity to a suitable port and the existence of the corresponding infrastructure is an advantage. Especially ports which today serve as natural gas hubs could also play an important role for hydrogen in the future. Even though existing liquefied natural gas (LNG) terminals may not easily be repurposed for hydrogen, they are entry points to the natural gas grid.

LOHCs and ammonia have lower transport costs than gaseous or liquid hydrogen due to higher energy density and easier handling but require additional infrastructure for coupling and decoupling them to hydrogen. Hydrogen transport per ship may be around two to three times cheaper when using ammonia than transporting liquid hydrogen (EC, 2021[21]). The IEA (2019[16]) sees both ammonia and LOHCs to be much cheaper than hydrogen transportation.

Figure 3.14. Existing and planned natural gas pipelines connecting Europe and MENA



Source: Global Gas & Oil Network (2020[22]), *Global Fossil Infrastructure Tracker*, http://ggon.org/fossil-tracker/.

Repurposing natural gas pipelines is typically the lowest-cost option. The capital cost of repurposing existing pipelines is about 10-25 % of the cost of building new hydrogen pipelines (Wang et al., 2020[23]) . The European gas grid infrastructure will offer good connection conditions for many industrial locations in the longer term but, in the medium term, its pipelines will still mostly be required for natural gas: 82 % of the German natural gas pipeline network, for example, may be technically suitable for conversion but, depending on different availability scenarios, only 13-46% of the necessary hydrogen pipelines may be available before 2030, though this varies with the ambition of climate action and geopolitical developments. Northwestern Europe may have an early-mover advantage. It has a double infrastructure, with gas pipelines becoming obsolete for gas by 2030. They can first be repurposed for hydrogen without compromising the gas supply.

New pipelines will also need to be built, for example, to serve industrial plants that have not used gas but may require hydrogen, such as in steel production. The terrain has a major influence on the costs of new pipelines. Even though the absolute numbers may differ, the principles for CO_2 pipeline construction outlined above also apply to hydrogen pipelines. Repurposing existing pipelines reduces the impact of terrain on cost.

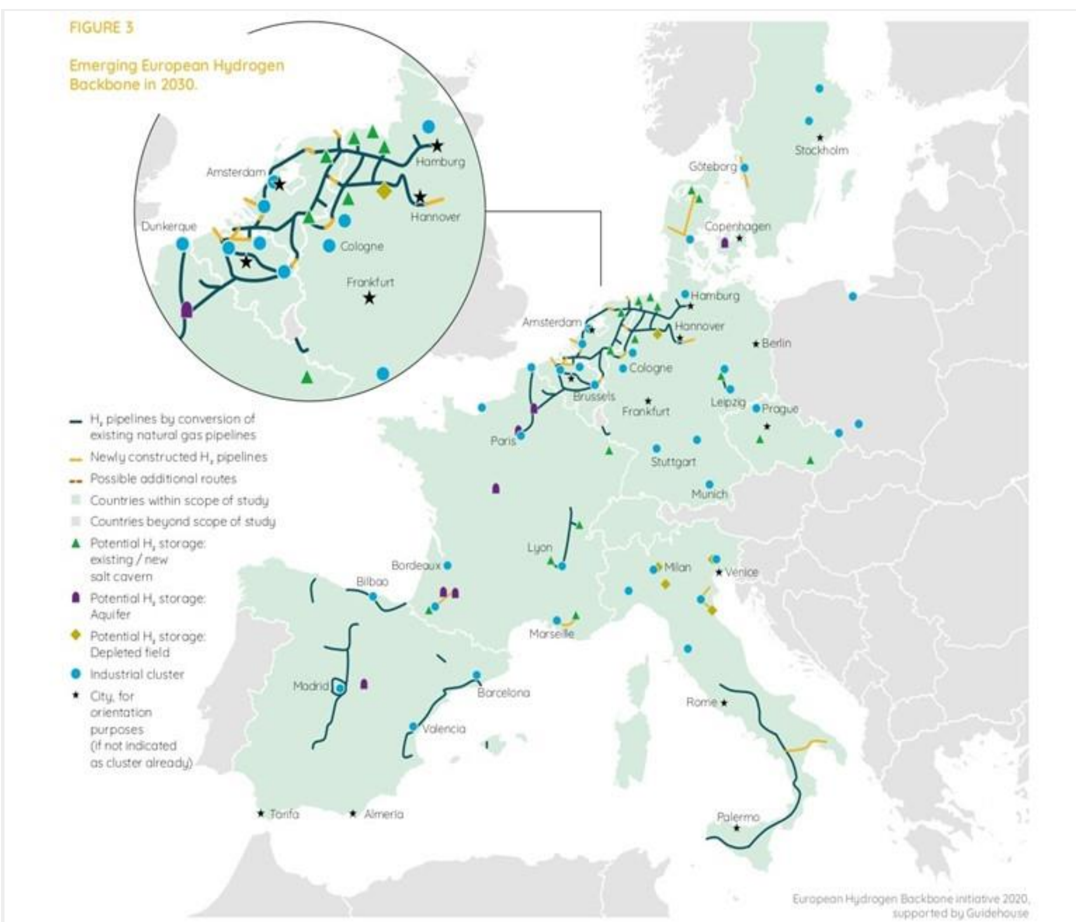
As in the case of CO_2 pipelines, scale economies apply. The amount of hydrogen demanded in a region has an influence on the transport cost: larger pipelines have lower costs per unit if used at full capacity. As a result, hydrogen consumers in an area of high overall hydrogen consumption have a cost advantage.

In summary, locations with a high density of industrial consumers and close to the coast have advantages over spatially distributed hydrogen demand in areas that are more difficult to access via existing pipelines. Coastal industrial clusters host important opportunities for establishing hydrogen infrastructure (IEA, 2019[16]).

Examples of building up a hydrogen transport infrastructure

The local availability of hydrogen, regional demand and the spatial characteristics and storage potentials need to be taken into account when hydrogen infrastructure is developed. A look at such existing plans can indicate which locations can benefit from the development of the infrastructure at an early stage and which are likely to be connected only in the long term. There are a few proposals for establishing a hydrogen infrastructure for some European countries in Western Europe (Figures 3.15 and 3.16) (Agora Energiewende/AFRY Management Consulting, 2021[20]). They all begin with connecting initial locations where hydrogen demand is particularly high, notably chemical production clusters in Northwestern Europe until 2030 and, from there, building a growing network that will eventually connect all European regions. They rely to a large extent on existing natural gas pipelines.

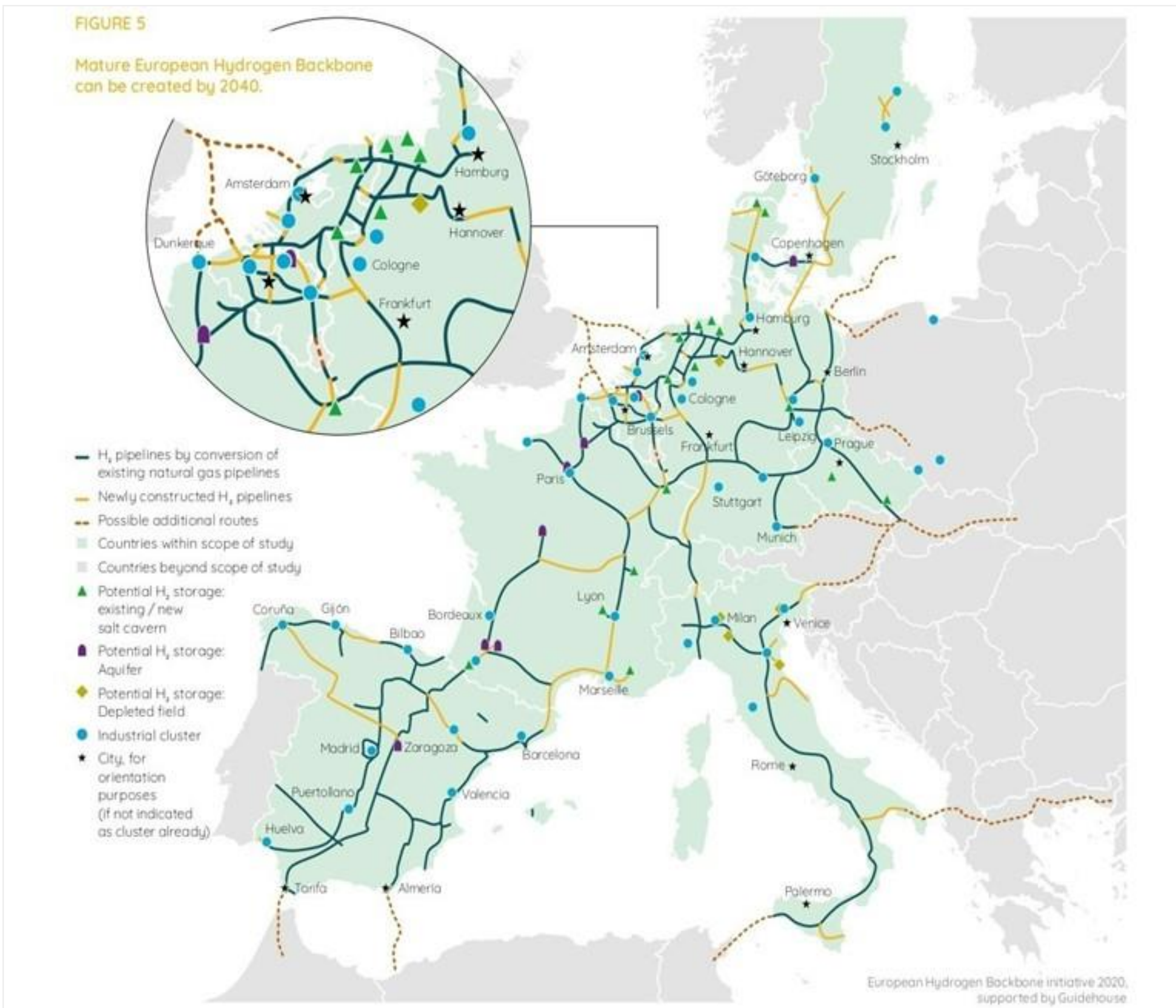
Figure 3.15. Possible development of a hydrogen network in 2030



Source: Wang, A. et al. (2020[23]), *European Hydrogen Backbone - How a Dedicated Hydrogen Infrastructure Can Be Created*, Guidehouse.

They illustrate regional development challenges that result from hydrogen use in climate-neutral industry. Regions with industrial clusters may be able to build needed infrastructure first and at a lower cost, reflecting economies of scale and pre-existing infrastructure. Policy makers will need to consider how to integrate these regional development challenges into spatially balanced policies to reach climate neutrality. One option may be to require more demanding, earlier steps towards climate neutrality in regions with industrial clusters which will be first served with hydrogen.

Figure 3.16. Possible development of a hydrogen network in 2050



Source: Wang, A. et al. (2020[23]), *European Hydrogen Backbone - How a Dedicated Hydrogen Infrastructure Can Be Created*, Guidehouse.

The total investment until 2040 may amount to between EUR 27 and 64 billion for the full capital cost of building and retrofitting, and operational expenditures may amount to between EUR 1.6 and 3.5 billion per year.

Regional challenges in road freight

Decarbonisation in road freight is less advanced than in passenger transport, as zero-carbon technologies to be deployed at scale have not yet been chosen for freight. CO_2 emissions from heavy-duty transport vehicles account for approximately one-quarter of total CO_2 emissions from transport and almost 5% of total 27 European Union member states and the UK greenhouse gas emissions. Deployment of such technologies is a near-term priority to move road freight towards net-zero emissions. One important impact of transport decarbonisation policies is on transport costs (Halim, Smith and Englert, 2019[24]). As the first chapter has shown, road transport plays a dominant role in the transport of output of key sectors, especially in intra-EU transport. Freight transport is particularly important for these sectors because the key sectors produce essential materials and goods.

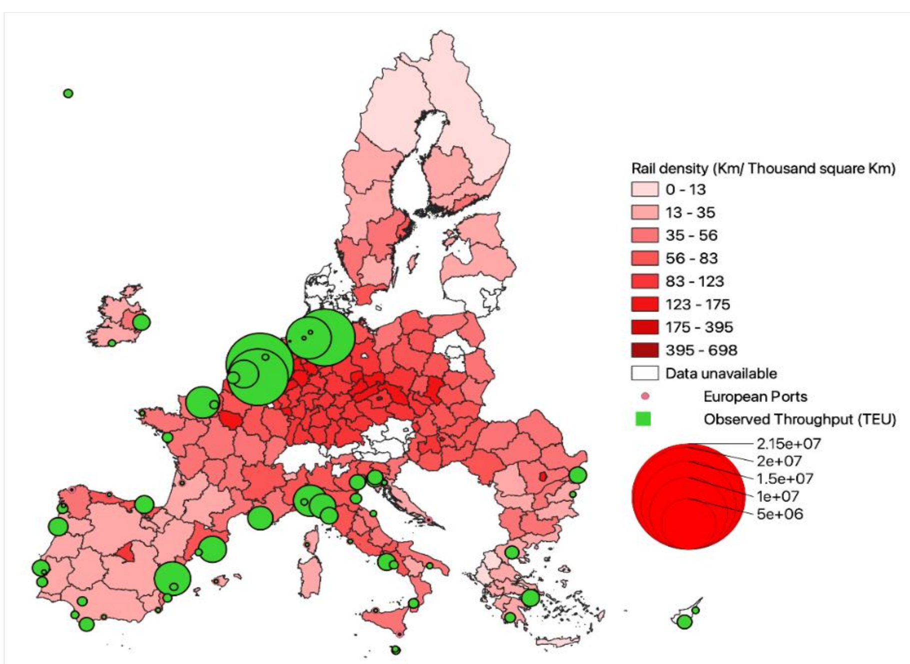
If decarbonisation of freight raises transport costs, higher transportation costs can fall back on the manufacturing industries that rely heavily on road transport and their value chains, notably for industries producing basic materials. This increase in road transport costs may trigger a shift to cheaper modes of transport, such as railways or waterways – if these modes are available in the region. Railways and inland waterways could increase their share of freight to ease the transition to climate-neutral road transport. For example, the EU aims to shift 50% of medium-distance freight journeys to rail by 2050.

The impact of decarbonising freight will vary between European regions, due to different dependencies on road freight across manufacturing sectors and regions. Regions that depend heavily on road freight may see higher increases in transport costs than those which do not (Wilmsmeier, Hoffmann and Sanchez, 2006[25]). Firms may relocate their manufacturing facilities to regions that offer lower transport costs.

Regions with a higher density of the rail network that connects the regions to their major trade partners, including via maritime ports, may see lower increases in transport and logistics costs. Port-hinterland infrastructure strongly determines international-trade related transport costs going through ports (Wilmsmeier, Hoffmann and Sanchez, 2006[25]). Hinterland transport costs, on average, constitute 80% of the total transport cost of intermodal shipment, while it covers only 10% of the total transport distance (Notteboom and Rodrigue, 2012[26]).

In the EU, regions differ in the density of their rail networks and therefore in their ability to substitute rail for road (Figure 3.17). Regions in the periphery of the EU, in particular in far northern regions, in Southwest and Southeast Europe have low rail densities, especially in regions which do not have maritime ports or capital cities in their proximity.

Figure 3.17. Rail network density and maritime port throughput across EU regions



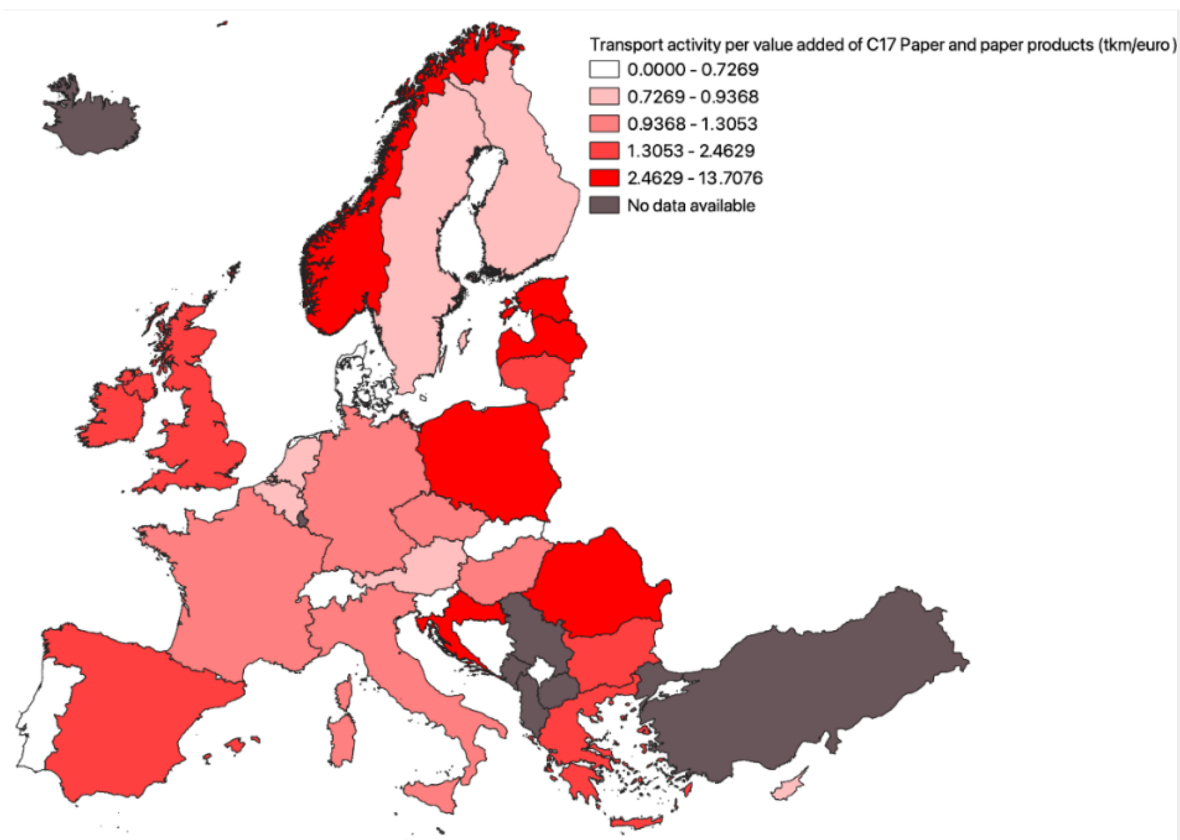
Source: Eurostat and Equitable Maritime Consulting.

Across the key manufacturing sectors identified in the first chapter, paper and pulp (NACE 17) and non-metallic mineral products (NACE 23) tend to be the most intensive in road freight use to transport their output, as measured by road freight tonne-kilometres invoiced by businesses producing goods in this sector relative to value-added.

The dependency on road transport measured in this way also varies across countries. Regional data for road freight use are not available. Indeed, as Figures 3.18 and 3.19 show, road freight dependence of both these sectors tends to be particularly strong in Southern and Central Eastern Europe. Some of these countries, such as the Czech Republic, also stand out for their long distance to maritime ports and high shares of employment in non-metallic minerals production. As shown in the following section, regions with these characteristics may suffer substantially higher increases in transport costs, if the decarbonisation of road freight turns out to be costly and substitution by rail is not readily available. By contrast, regions with strong paper and pulp production in Finland and Sweden appear to be less road freight dependent. In the non-metallic minerals industry, some regions with high-emission activity and employment in Poland, as shown in Chapter 2, appear to be in countries with relatively strong road freight dependence. A forthcoming working paper illustrates road freight dependence for the other key manufacturing industries (Fuentes Hutfilter et al., 2023[3]).

Figure 3.18. Road freight intensity in paper and pulp production

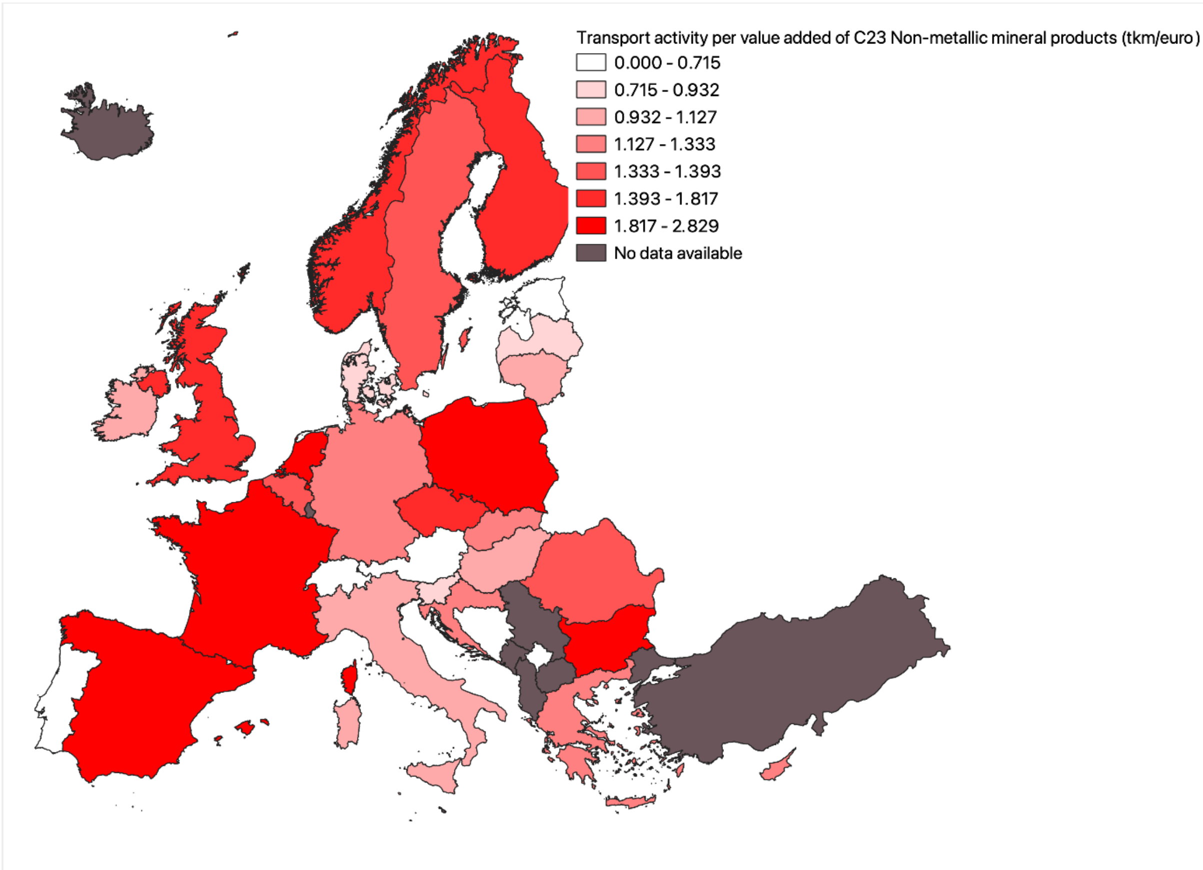
Tonne-kilometres of output transported on roads relative to value-added



Note: Tonne-kilometres refer to road transport services invoiced by businesses in the respective countries.
Source: Eurostat and Equitable Maritime Consulting.

Figure 3.19. Road freight intensity in non-metallic minerals production

Tonne-kilometres of output transported on roads relative to value-added



Note: Tonne-kilometres refer to road transport services invoiced by businesses in the respective countries.
Source: Eurostat and Equitable Maritime Consulting.

Impact of road freight carbon taxes on freight transport costs in selected EU regions

This section illustrates the potential impacts of road freight carbon taxes on transport costs for selected commodities produced by key manufacturing sectors in selected European regions, drawing on one example region. The analysis highlights the importance of road freight, especially in regions distant from maritime ports. A fuller analysis with a range of different regions is contained in a forthcoming working paper (Fuentes Hutfilter et al., 2023[3]). Road emerges as the cheapest land-based freight transport mode in all examples. The transport model optimes transport modes and routes, minimising transport cost, between a key sector-producing region and a major export destination. Modelled costs include fuel costs, transport tolls and taxes, operating and capital costs of transport equipment as well as labour costs and other time-related costs. However, for simplicity, no behavioural response is assumed in response to the carbon tax increase, for example from the substitution of road by rail or from fuel-saving. The Annex to this chapter contains a more detailed description.

The carbon tax increases considered include an increase of 50% and 100% in fuel costs respectively. Based on the assumption that, on average, a heavy duty vehicle (HDV) consumes 3.45 L/100 km, a 50% and 100% increase in the fuel price is approximately equivalent to a carbon tax of 58 USD/tonne CO_2 and 116 USD/tonne respectively. A carbon price of EUR 60 (66.70 USD/ tonne) per tonne of CO_2 would be consistent with a scenario of slow decarbonisation by 2060, and a carbon price of EUR 120

(133.40 USD/tonne) per tonne of CO_2 is a central estimate of the carbon price needed to decarbonise by 2050 (OECD, 2021[27]). However, the German Environmental Protection Agency estimates that the social damage per CO_2 tonne released is EUR 180 in 2016, implying that the assumed fuel prices may still be too low to include all costs (OECD, 2021[27]).

The modelling results suggest that land-locked regions supplying or receiving basic materials produced by key industries may face substantial freight cost increases from carbon taxes on road freight. This is shown in the example of cement exports from Krakow, Poland, below. Cost impacts may be lower if the cost of introducing zero-emission road freight technologies or the shift to rail can be achieved at a lower cost than the assumed carbon prices.

Export of cement from Krakow to Los Angeles, United States

For destinations that are geographically far away, intermodal maritime transport is the main mode. There are several alternative routes to ship goods through 2 ports: the port of Gdansk (344 km) and the port of Szczecin (407 km). The transport from Krakow to both ports is mainly carried out using road freight (Figure 3.20, Panel A).

From Table 3.2, it is apparent that hinterland transport costs represent the highest fraction of total transport costs. Under the baseline scenario, road transport from Krakow to major Polish ports constitutes 68-70% of transport costs to Los Angeles. The application of carbon tax on road transport will amplify the costs of hinterland transport to USD 52/tonne (low scenario) and USD 60/tonne (high scenario). In comparison to hinterland transport, maritime transport costs are a lot lower. This is due to the economy of scale offered by large ships that serve the Poland-US route (Figure 3.20, Panel B). Improving hinterland transport infrastructure to make it climate neutral is most important. For instance, improving the availability of rail could help to attain this objective.

Table 3.2. Breakdown of intermodal maritime transport costs from Krakow to Los Angeles

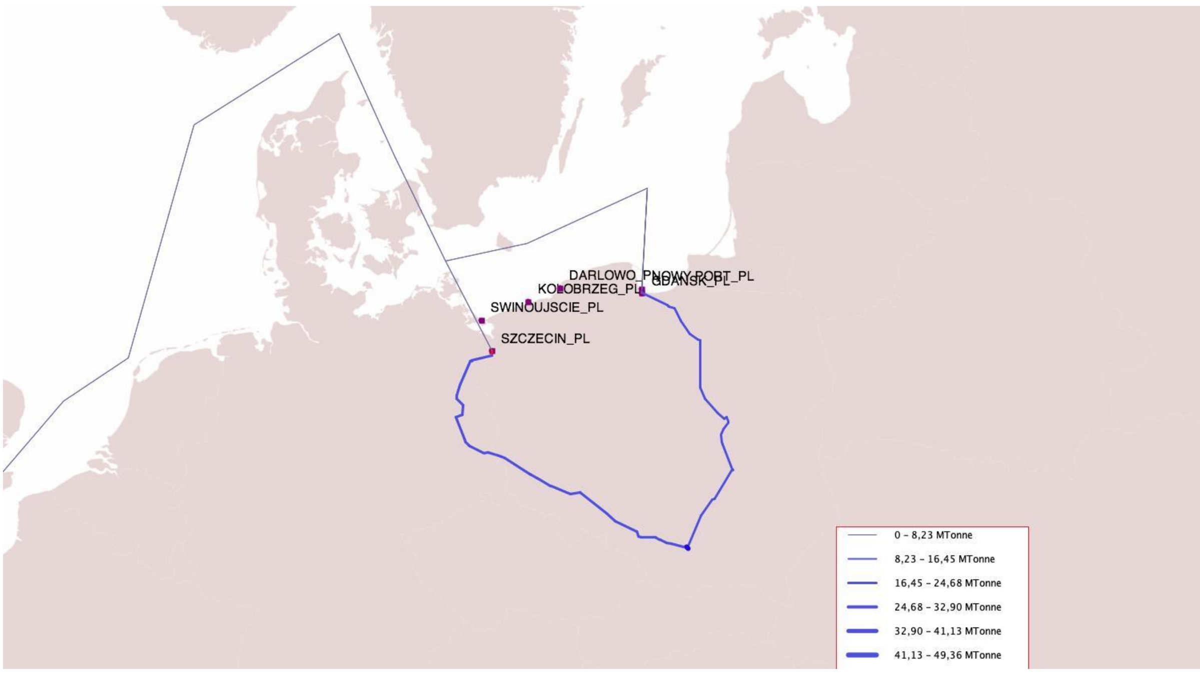
USD per tonne unless indicated otherwise

Hinterland connection	Scenario	Road freight cost from origin-to-origin port	Maritime transport cost	Road freight cost from destination port to destination	Total cost	Fraction of origin road freight costs, per cent
Krakow-Gdansk	Base case	42.97	17.34	2.51	62.82	68.41
	Low tax	51.56	17.34	2.51	71.41	72.21
	High tax	60.16	17.34	2.51	80.01	75.19
Krakow-Szczecin	Base case	46.65	17.34	2.51	66.50	70.15
	Low tax	55.98	17.34	2.51	75.83	73.83
	High tax	65.31	17.34	2.51	85.16	76.69

Figure 3.20. Transport routes from Krakow to Poland’s main ports and from Krakow to main regions in the US

Annual transport volumes along cost-minimising routes

A. From Krakow to Poland’s main ports



B. From Krakow to main regions in the US

Source: Equitable Maritime Consulting.

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Note

[1] The characteristics of hydrogen lead to a higher fatigue of pipeline material. This can be countered with various measures such as adaptions in compressor stations, coatings or pipe-in-pipe solutions (Gillessen et al., 2020[31]).

Annex 3.A. Road freight carbon tax impacts on transport costs: Methods and further examples

For road transport, we use the cost specification as described by Persyn, Diaz Lanchas and Barbero Jimenez (2020[28]) to test the impact of carbon tax scenarios on road transport costs within EU regions. We assume shippers would opt to use the route with the lowest costs $R_{o,d}$, which is described by the following equation:

$$C_{o,d,road} = \min(DC_{o,d,road} + TC_{o,d,road}) + Tax_o + Vignette_{o,d,road} \quad (1)$$

In Equation (1):

- $C_{o,d,road}$ is the unit cost of the route from the location of origin o to destination d (USD/tonne).
- $DC_{o,d,road}$ are the distance-related costs for origin o, destination d, using road transport.
- $TC_{o,d,road}$ are the time-related costs for origin o, destination d.
- Tax_o are the taxes added to road freight from the location of origin o.
- $Vignette_{o,d,road}$ is the cost of vignettes between any pair of origin and destination locations.

Distance-related costs can be broken down into the following components:

$$DC_{o,d,road} = \sum_{a \in R,o,d} (fuel_a + toll_a)\, d_a + (tireCS + mainCS)\ (fuel_a\ d_a) \quad (2)$$

where $fuel_a$ are fuel costs for travelling via road connections a that make up the cheapest route $R_{o,d}$. $toll_a$ are toll costs associated with the use of toll roads in a specific country. d_a is the distance travelled on road connections. $tireCS$ is the cost of tire replacement, which is defined as a share of fuel costs. $mainCS$ are maintenance costs which represent a small fraction of total transport costs.

Time-related costs are composed of the following components:

$$TC_{o,d,road} = \sum_{a \in R,o,d} (1 + amortFinCS + insCS + indCS)\ (t_a\ lab_{od}) \quad (3)$$

The main components are the labour costs of the driver $t_a\ lab_{od}$. lab_{od} represents the hourly wage of the driver and t_a is the total travel time on a road connection. For more detailed descriptions of labour cost components, readers can refer to Persyn, Diaz Lanchas and Barbero Jimenez (2020[28]). The remaining components include amortisation and financing costs $amortFinCS$ of the vehicle, insurance $insCS$ and indirect costs $indCS$. For the sake of simplicity, they are assumed to be proportional to labour costs.

For transport between the location of origin and the destination using intermodal maritime transport, the analysis uses the costs specification described in Halim et al. (2018[29]) and builds on the road transport cost specification in Equation (1). Annex Figure 3.A.1 provides a schematisation of the components of intermodal transport costs.

$$C_{o,d,intermodal\_sea} = \min(C_{o,origin\_port,m} + C_{origin\_port,destination\_port,maritime} + C_{destination\_port,d,m}) \quad (4)$$

where:

- $C_{o,origin\_port,m}$ is the unit cost of the route from origin location o to the port of port (USD/tonne), using transport mode m.
- $C_{origin\_port,destination\_port,maritime}$ is the unit cost of the route from port of origin to the destination port (USD/tonne), using maritime transport.

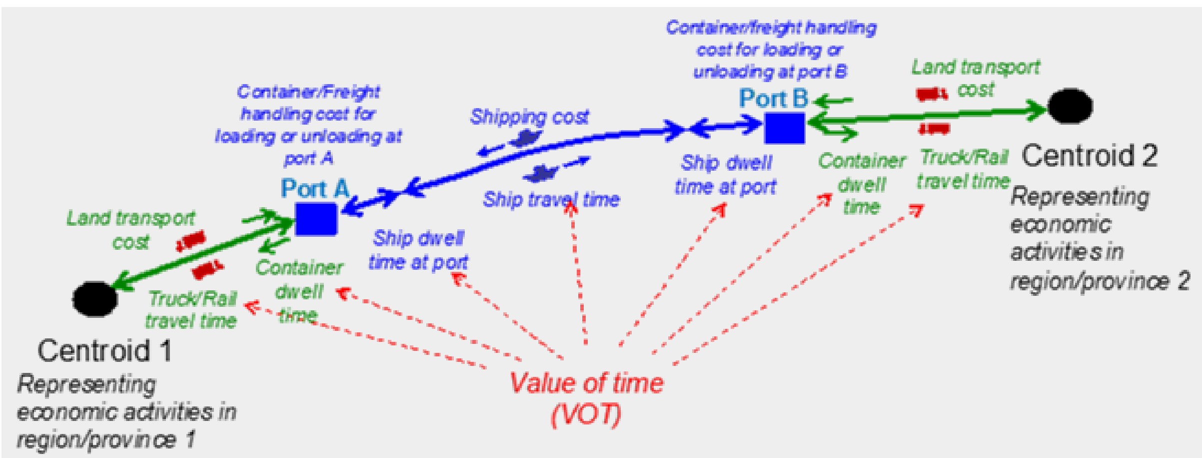
- $C_{destination\_port,d,m}$ is the unit cost of the route from the destination port to the destination location o (USD/tonne), using transport mode m.

Maritime transport costs are calculated by multiplying maritime transport costs (in USD/km) by the distance travelled (in km) between the port of origin and the port of destination:

$$C_{origin\_port,destination\_port,maritime} = \sum_{a \in R,o,d} maritime\_cost_a \, d_a \qquad (5)$$

Maritime transport costs include fuel, labour and maintenance costs, as well as the time value of goods shipped (Halim et al., 2018[29]).

Annex Figure 3.A.1. Schematisation of components of intermodal transport costs



Source: Equitable Marine Consulting.

Based on the analytical model above, the following subsequent computation steps are performed to estimate the total transport costs:

- Computation of travel time and travel distance between ports and hinterland destinations using a multimodal transport network model. The model will take into account available transport modes and predict shippers' choice of modes based on distance and time under the baseline scenario. For instance, if rail transport offers the shortest distance and time, the model will predict that a majority of goods will be shipped using rail instead of road.
- Computation of average unit transport costs per kilometre (USD/tonne-kilometre or USD/tkm) for road transport by dividing the average unit transport costs (USD/tonne) computed using Equation (1) with the average distance travelled by heavy duty vehicle (HDV) within a given country.
- Distance-related costs are computed by multiplying hinterland distance (km) with the unit cost of transport (USD/tkm) for each mode of transport that might be used to transport goods, such as rail or road (USD/km).
- Port handling costs are estimated by taking into account the observed port throughput and socio-economic variables of the port country.
- Transport costs are computed by summing up the hinterland and maritime transport costs in USD/tonne using Equation (4).
- The impact of carbon tax is calculated by computing the average increase in unit transport costs given a 50% increase in fuel price (low scenario) and a 100% increase in the high scenario.

This method has been used in various transport modelling literature such as in Tavasszy et al. (2011[30]) and Halim et al. (2018[29]).

Data used for transport costs calculation:

- Data for unit road transport costs (USD/tonne) between European regions at NUTS 2 level are obtained from the interregional transport costs dataset (Persyn, Diaz Lanchas and Barbero Jimenez, 2020[28]). The data used for computing costs are derived from empirical observations for HDVs compliant with Euro VI standards that transport goods across all commodity sectors in the EU. To date, data for road transport at the regional level for specific commodities are still scarce. A 50% and 100% increase in fuel price result in an 18% (low tax scenario) to 42% (high tax scenario) increase in total transport costs in different EU regions. The variation in the increase in transport costs is largely due to the different weights of fuel costs. Countries with higher labour costs such as Germany and the Netherlands tend to see a lower increase in total transport costs.
- Unit transport costs and the time value for goods for maritime transport have been obtained from the Equitable Maritime Consulting EMC) database. Transport cost data are estimated based on trade data obtained from the United Nations Comtrade database and United Nations Conference on Trade and Development (UNCTAD) global transport cost data.

Annex Table 3.A.1. Impact of carbon tax on fuel price and total road transport costs for selected countries in the EU

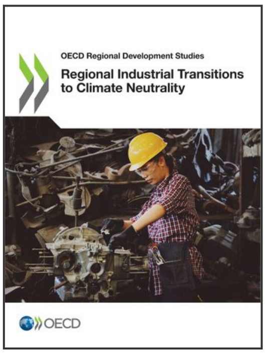
Region	Transport costs, baseline scenario (USD/tonne)	Increase in costs, low tax scenario (%)	Increase in costs, high tax scenario (%)	Average distance travelled (km)	Unit costs (USD/tkm), baseline scenario	Unit costs (USD/tkm) low tax scenario	Unit costs (USD/tkm) high tax scenario
Finland	28	21	42	298.00	0.0940	0.1137	0.1614
Germany	46	18	35	373.00	0.1233	0.1455	0.1965
Netherlands	21	18	35	181.00	0.1160	0.1369	0.1848
Poland	24	20	40	271.00	0.0886	0.1063	0.1488
Portugal	36	20	39	315.00	0.1143	0.1371	0.1906

Annex Table 3.A.2. Unit maritime transport costs for selected routes illustrated in the case study

Origin country	Destination country	Sector	Transport costs (USD/tonne)
Poland	United States	Petroleum chemical and non-metallic mineral products	17.34
Finland	United States	Wood and paper	13.79
Finland	Germany	Wood and paper	14.40
Portugal	Netherlands	Petroleum chemical and non-metallic mineral products	15.22
Portugal	Cameroon	Petroleum chemical and non-metallic mineral products	9.35

Furthermore, for the sake of simplicity and clarity, we adopt the following assumptions in carrying out our analysis:

- We apply a constant price for extra-EU components of transport costs and other modes of transport, notably maritime transport. We assume that transport costs for these other modes always follow the baseline costs assumption. Depending on the outcome of the International Maritime Organization (IMO) negotiation regarding market-based measures for emission reduction, non-EU costs of maritime transport might however increase due to the application of a carbon tax.



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