

Infrastructure needs for deep decarbonisation of heavy industries in Europe



Key results and conclusions

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Foreword

The study behind this policy brief has been conducted in 2019, before the new European Commission announced the "European Green Deal" for a climate neutral EU as its core political project. Since then the global spread of the COVID-19 virus at the beginning of 2020, led to a worldwide reduction of industrial production and of global trade. Both events highlight why we are now simultaneously facing two huge, at first sight different challenges: 1) The "green" transformation of the existing heavy industry structures through replacing fossil fuels, raw materials and established process technologies by renewable energy sources and by low-carbon technology alternatives and 2) a quick recovery of today's industrial production and global trade, in order to stabilise the European and global economies.

However, both challenges could and should be seen as interlinked and solved together, in order to avoid fuelling the much bigger global crisis of climate change by solving the current global health crisis and economic downturn. That is why we think, that the results of this study are even more important than before the COVID-19 caused economic crisis hit. Our study underlines the urgent need to think about the green transformation of industry, energy supply and infrastructure together and thus to create the conditions for maintaining heavy industry in Europe, not despite, but because of decarbonisation and by this to become a pioneer in climate-neutral system innovations. This will be an important basis, not only for global climate mitigation strategies, but also for future competitiveness of European industries. Solutions must be sought both at EU and regional level, because the impact of industrial transformation and infrastructure requirements vary greatly between regions, as the study shows.

The current economic crisis calls for huge investments into industrial recovery, the more future proof they are, the better. Accelerating the climate neutral transformation of industry together with the related infrastructure upgrading (expansion of renewables and the electricity grid as well as the conversion of parts of the natural gas to hydrogen grids) can contribute to considerable investment and to added value in the short term.

Heavy industry at the heart of the creation of the EU and is still an important part of the European economy. In order to make it a driver for climate neutrality, innovation and competitiveness, it needs dedicated and coordinated planning, policy and investment support towards a secure supply of green energy and raw materials as well as a strong and secure infrastructure based on renewable energies. This report tries to support this transition by relevant insights and recommendations.

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Executive summary

A climate-neutral transformation of heavy industry in Europe is feasible (Material Economics 2019), but poses a major challenge for the respective industries, the entire energy and the feedstock supply system. The central prerequisites for success are renewable energies and low-carbon raw materials, increasingly circular value chains as well as strong infrastructures. The challenges to develop the necessary infrastructures for renewable electricity and green (i.e. renewable electricity based) hydrogen as well as for CO₂, differ among regions according to regional potentials and decarbonisation strategies chosen.

The study "Infrastructure needs for deep decarbonisation of heavy industries in Europe"¹ shows how industrial transformation strategies in materials processing industries such as steelmaking, cement and basic chemicals production may affect future regional demand for electricity, green hydrogen and Carbon Capture and Storage (CCS) technologies and thus the relevant infrastructure requirements for Europe. The main findings as well as conclusions and recommendations of this study are presented in this policy brief. Further information and results, in particular for the three selected industrial focal regions (southern France, southern Poland and northwest Europe) can be found in the corresponding workshop reports².

Scope and approach

The study focuses on the three carbon- and energy-intensive industrial sectors chemicals (plastics & ammonia), steel and cement based upon their existing production structures in the base year 2015 and determines their future demand for electricity, green hydrogen and CCS and the related infrastructures as well as the spatial distribution of the technical potential for renewable electricity generation. The analyses rely on two existing studies (Material Economics 2019) and (ENTSO-E 2014a) and use their relevant scenarios (see below) as references. The study area covers Europe and the time horizon focuses on the years 2050 (and comparisons to 2015). The analyses were carried out for three different regions (southern France, southern Poland and North Rhine-Westphalia) and with the participation of regional stakeholders in on-site workshops.

Main findings

The climate neutral transition of European heavy industry needs a large amount of green electricity and green hydrogen as well as some carbon capture and storage. The volumes needed (i.e. 419-809 TWh_{el}/a renewable electricity, 114-398 TWh_{th}/a green hydrogen and 45-235 Mt CO₂/a for CCS in 2050), however, depend strongly on how efficient materials will be used and recycled in a future, much more circular, economy. As some process emissions cannot be fully avoided there will remain some need to capture and store CO₂, e.g. from larger parts of cement manufacturing.

¹ The study was funded by EIT Climate-KIC under Task ID: TC_2.11.1_190229_P259-1B. The workshop reports and other information can soon be found here: <https://wupperinst.org/en/p/wi/p/s/pd/818/>

² The regional workshop reports are available for download at the project website above.

The green transformation of basic materials industry in Europe will lead to spatially concentrated demand increase for green electricity, assuming today's industry structures and locations and even including benefits from increased circularity of basic materials. This requires significant expansion of the electricity infrastructure in addition to current expansion plans, especially to supply core industrial regions. Hence, the climate neutral electricity supply requires a rapid and strong but feasible expansion of the regional as well as the transnational electricity infrastructures. This needs to go far beyond the level of the current expansion plans in the Ten-Year Network Development Plan (TYNDP) and will increase further, if the green hydrogen is to be produced in Europe.

In order to keep the increase in electricity demand as low as possible and to be able to cover it sufficiently with renewable electricity, **both the energy saving potential and the renewable generation potential in Europe (especially from offshore wind) must be realised as quickly and comprehensively as possible**. For the additional electricity demand of the three industrial sectors under consideration alone, at least 419 TWh_{el}/a (without hydrogen) to 809 TWh_{el}/a (with hydrogen) are needed. The latter corresponds to approx. 32% compared to today's renewable electricity generation, while the resulting future total electricity demand (incl. industrial hydrogen) in 2050 amounts to approx. 72% of the assumed total renewable electricity production potential in Europe. In view of the growing demand for renewable electricity also from other sectors, the existing potential must be exploited quickly and to the greatest possible extent.

National or regional expansion of electricity and hydrogen production is seen as important to European value creation and security of supply. This assessment was consistently expressed at all three regional stakeholder workshops on the topic, even though energy and raw material imports can be regarded as economically more favourable. Political decision-makers and transport system operators (TSOs) should therefore pay attention to the right balance between self-sufficiency (added value) and imports (costs). In the case of imports, it must also be ensured that the GHG reductions are actually realised (also in the upstream chain).

Some regions with the highest increases in demand will need new, high-performance import structures for electricity and hydrogen, while most heavy industry clusters in Europe would be able to meet the additional demand to a sufficient extent by renewable energy from their vicinity. northwest Europe, however, as Europe's prime heavy industrial cluster will most likely need to rely on significant imports of green energy from other parts of Europe and the world. Less pronounced, this also applies to Europe as a whole, i.e. new import infrastructures will become an indispensable part of a secure and inexpensive supply of climate neutral energy carriers and feedstocks, in particular for basic industries.

For the supply of the necessary amount of green hydrogen to energy intensive industries, parts of the existing natural gas grids and storage facilities can serve as important assets and should be repurposed.

Processing industries such as steel mills or basic chemical production sites need high amounts of green hydrogen (up to 398 TWh_{th}/a) to be supplied best via dedicated hydrogen pipelines. Developing a hydrogen pipeline network can benefit from the conversion of existing and potentially idle natural gas infrastructures. Particularly the

northwest of Europe obtains of a significant transport and storage infrastructure that could be converted. It could diversify hydrogen supply for the industries connected and offer significant storage capacity to the energy system.

Infrastructure development for abatement of unavoidable industrial CO₂ emissions with CCS, will need access and connection to suitable (large) storage sites and should be coordinated at EU level to reduce regional disparities. CCS is required in all decarbonisation strategies for heavy industry, and most importantly for the climate-neutral transformation of cement production. The average quantities to be managed range from 0.6 Mt/a for many cement sites to 2 Mt/a for a few chemical/steel sites. The suitable storage facilities across Europe promise sufficient potential at an aggregated (national) level. Regional storage capacities are often too small and diffusely distributed and rarely located near the emission sources. Therefore, with the exception of the Netherlands, which has its own coastal reservoirs, CO₂ storage solutions for each assessed region can best be found in a European context (e.g. with development of inter-regional infrastructures and connection to the Norwegian storage sites).

Main conclusions & policy recommendations

The industry, energy and infrastructure transitions towards climate neutrality are interdependent and strongly interlinked between the three transitions and across the EU. They therefore need forward-looking and integrated planning. Energy and resource efficiency as well as circular economy strategies will lower the increase in energy and resource demand. By this they partly mitigate the challenges to ramp up green energy supply and in this way relieve the need to expand and reconstruct infrastructures. **In view of the long lead times, the adjustment of infrastructure planning and implementation to industrial decarbonisation must begin today.**

Recommendations for industry transformation

- Decarbonisation strategies of the various industrial clusters in the EU should be coordinated and supported on the regional, national and European level in order to enable the regions and their stakeholders to develop such strategies, foster their implementation and adapt the necessary infrastructure to them.
- Strategies to improve resource efficiency and recycling management should be demanded and promoted by policymakers as a matter of priority. These should be emphasised as important enablers of innovative and competitive industries and regions.
- Policy makers should give concrete and unambiguous guard rails and support for the industrial decarbonisation like efficiency and use of excess heat first, switching to renewable electricity wherever it is possible and otherwise to make use of green hydrogen, to accelerate corporate decisions. This allows TSOs to plan the necessary infrastructure in a more forward-looking manner.

The additional and in some industrial core regions concentrated demands for electricity and hydrogen by industrial decarbonisation are not sufficiently taken into account in the current long-term infrastructure development plans, because the plans do not consider other strategies than CCS for industry decarbonisation and do not extend to

the year 2050. They therefore underestimate the need to expand renewable energies and the electricity grid as well as the challenge of converting parts of the gas grid from natural gas to hydrogen.

The growth in electric demand will be moderate in most regions, so that an expansion of the electricity grid within the current grid structure should be adequate. The technical potential for annual renewable electricity generation would be sufficient to cover the additional industrial electricity requirements in Europe itself. Most regions with heavy industry could meet their needs with renewable electricity from the surrounding area if the remaining potentials were developed. **Only the regions with the highest production volume today and the highest to be expected increase in electricity demand need long-distance transport from the far-off sweet spots.**

In the natural gas network, there is in principle enough capacity for the intake and transport of the industrial hydrogen required if the pipelines are converted to use hydrogen. However, regions with very high hydrogen demand will probably still need additional new hydrogen pipelines due to the lower energy density of hydrogen. In particular, coastal locations are also suitable for hydrogen imports from distant sweet spots. However, these imports are in competition with the value added by own production and the current plans for LNG imports, whose assets are not considered compatible with those for hydrogen.

Recommendations for electricity infrastructure

- The scenario framework for the electric TYNDP should already be expanded in the current version to 2050 and to include various industrial decarbonisation strategies beyond CCS (i.e. electrification and hydrogen) with different levels of electricity intensity.
- The expansion of the electricity grid should be accelerated overall, but above all in the sweet (especially offshore wind) and hot spot regions, and increased to meet the higher regional electricity demand expected in the long term.
- The expansion of renewable electricity generation in Europe (especially offshore wind power generation in the North Sea) should be accelerated.
- The expansion of the electricity grid must be more closely coordinated with the transformation of the natural gas grid towards hydrogen, in order to achieve more synergy effects in terms of capacity utilization and relief as well as system costs.
- When planning electric infrastructures, local industrial actors in particular should be involved.
- In line with the previous points, the current PCI projects that have been delayed or are still being approved should be implemented more quickly.

Recommendations for natural gas and hydrogen infrastructure

- Similar to above, the scenario framework for the gas TYNDP should be expanded to reflect the consequences of industrial decarbonisation strategies beyond CCS with different levels of hydrogen use intensity and more closely coordinated with the electric TYNDP.
- Furthermore the total gas grid planning and expansion should be reassessed in the context of the 2050 climate neutrality targets and under the premise of an overall

gas demand reduction and a shift to climate-neutral gases, especially green hydrogen for industry and heavy duty transport.

- For climate-proof planning and conversion of natural gas networks to hydrogen networks, transformation and verification criteria must be developed and established in a timely manner to ensure that gases are CO₂-free along the entire process chain.
- Additional costs for the future-proof conversion of natural gas networks to hydrogen should be given special consideration in regulation if the costs comply with the transformation criteria developed previously.
- The Trans-European Networks for Energy regulation (TEN-E) as well as the planning of LNG and hydrogen imports should be reassessed in the light of those criteria, in order to enhance the build-up of a European hydrogen economy.
- Windows of opportunities (e.g. planned replacements of pipelines and equipment and foreseeable idle capacity) for the conversion of pipelines to hydrogen are to be identified and reported by the Gas-TSO, in order to better coordinate, push and support the transformation of the gas grid.
- When planning hydrogen infrastructures, local industrial actors should be involved.
- The European Commission should support and accelerate the European scale up of electrolyser capacities (together with the European expansion of renewable energies), in order to contribute to added values, jobs and industrial leadership in the global market.

With regard to CCS, particular attention should be paid to the frequent discrepancies between CO₂ sources and storage sites. For regions with unfavourable storage situation (e.g. southern France and southern Poland) this could rather lead to a wait-and-see approach instead of an own building-up infrastructure strategy. This bears a high risk that the required solutions will not be available in time and underlines the importance of coordination at the European level. Furthermore it remains to be seen which transport infrastructures are best suited for CCS, but pipelines are necessary in any case. Due to competition with future transport of hydrogen, it is not expected that the existing natural gas networks will be used for CO₂ on a large scale.

Recommendations for Carbon Capture and Storage (CCS) infrastructure

- CCS should be planned and supported exclusively for unavoidable process emissions from industry like cement kilns. This is important, due to the scarce storage facilities, high transport costs, lack of social acceptance in some regions and substitution possibilities in other sectors as well as in order to prevent lock-in effects on other potential users.
- In this sense, CCS should also be explicitly banned for coal-fired power plants, as concerns have been repeatedly expressed by several workshop participants that developments of CCS in industry may be taken up by the coal-based energy sector.
- CCU should only be allowed under strict criteria-based limitations as it is unlikely to contribute to long-term avoidance of CO₂ (with few exceptions, such as comprehensive chemical recycling).
- Rapid action (e.g. successful demonstration projects) is needed if a future-proof European CCS infrastructure is to be established by 2050 at the latest, as its build-up poses long and complex lead times.

Introduction

Today's big industrial sites were built largely with fossil fuels and resources in mind, which must be completely replaced by renewable energy sources in order to achieve a climate-neutral economy. The same applies to today's gas and electricity supply infrastructures, which have been planned, constructed and operated mainly for the use of natural gas and large conventional steam and gas power plants. Both transformations towards climate-neutral industrial production and renewable energy supply require considerable investment and time.

There are different studies and strategies for both transformations, which show that and how they could be realised. An integrated view of industrial and infrastructure transformations in Europe has, however, hardly taken place to date. Studies and strategies for industrial transformation, e.g. (Material Economics 2019), (EURELECTRIC 2018), (McKinsey 2010) and (European Commission 2018) show how the energy-intensive primary industry in Europe can be decarbonised (i.e. CO₂ emissions reduced to net zero). The necessary infrastructures are hardly or not at all investigated. Conversely, studies and network development plans such as (ENTSO-E 2015) and (ENTSO-E und ENTSO-G 2019) deal in detail with the energy infrastructures for renewable/climate neutral electricity and gas supply, but little differentiated with the industrial sector. Strategies beyond Carbon Capture and Storage (CCS) and Power-to-Heat hardly play a role in industrial decarbonisation.

Against this background, the study "Infrastructure needs for deep decarbonisation of heavy industries in Europe"³ combines existing ambitious strategies for industrial decarbonisation with an exploratory analysis of the necessary infrastructure requirements. It geographically localises industrial demands for power, gas and CCS in Europe 2050, which result from existing decarbonisation scenarios by (Material Economics 2019), and explores which infrastructure solutions for electricity, hydrogen (H₂) and CO₂ would be necessary to cover these demands for three selected industrial regions.

This policy brief complements the results of the workshop reports (see bibliography) on the selected and more closely examined three industrial regions in southern France and Poland as well as northwest Europe with politically relevant conclusions and recommendations. It is structured in the following sections: scope & approach, main results and conclusions and recommendations.

³ The study was funded by EIT Climate-KIC under Task ID: TC_2.11.1_190229_P259-1B. The workshop reports and other information can be found here: <https://wupperinst.org/en/p/wi/p/s/pd/818/>

Scope, approach and main assumptions

The study examines the decarbonisation of the industrial production sectors for chemicals, steel and cement in Europe in 2050 in the context of the overall electricity supply system as well as gas and electricity infrastructures. To this end the following five research steps were conducted:

- 1 | Localisation of relevant industrial clusters and their current and future demands of electricity and hydrogen (industrial hot spots)
- 2 | Localisation of high-yield renewable energy potentials (sweet spots)
- 3 | Localisation of well suited carbon storage potentials
- 4 | Infrastructure analyses for three selected hot spot regions in Europe
- 5 | Interactive workshops for exploration and evaluation of possible infrastructure solutions

The analyses about the hot and sweet spots are carried out at both the European and the regional level, while the exploration of infrastructure needs and solutions is performed only for three selected hot spot regions as semi-quantitative case studies. These hot spot regions are southern France, southern Poland and the industrial triangle in northwest Europe (Belgium, the Netherlands and North Rhine-Westphalia in Germany). In each of these regions, a workshop was held with local stakeholders to discuss the backgrounds and findings of the study. A more detailed description of the research design, background, the developed infrastructure storylines and their evaluation can be found in the workshops' documentations⁴.

The analyses are mainly built on the following two studies and their data:

- The study “Industrial Transformation 2050” (Material Economics 2019), which determines three different scenario strategies for the decarbonisation of three industry branches (chemicals, steel and cement) on EU-level and gives us the aggregated industrial demand data by processes and decarbonisation strategies. These together with our own industry database and industry model (cf. Schneider et al., 2014) are used to determine both the total demand for electricity and hydrogen as well as the additional demand compared to 2015 and the remaining CO₂ emissions in 2050 by the three considered branches at their production sites.
- The study “e-HIGHWAY 2050” (ENTSO-E 2014a), which assesses future transmission system structures for five different ambitious scenarios, in order to reach European climate targets (minus 80-95% of CO₂ emissions in 2050 vs. 1990). Of the five scenarios, scenario X7 was selected, which represents a power supply system based on 100% renewable energies and poses the greatest challenge for the future power grid. It supports our analyses with data of renewable energy generation and potentials as well as “conventional” electric demand and NTC-expansion, with a spatial resolution of 106 clusters for Europe. This allows to determine the additional electric demand caused by industry decarbonisation compared to the total conventional demand and, based on that, to calculate the resulting new electricity balance and the remaining potential for renewable electricity production in the clusters that belong to the hot spot regions.

⁴ (Wuppertal Institut und ECF 2020a), (Wuppertal Institut und ECF 2020b), (Wuppertal Institut und ECF 2020c) and (Wuppertal Institut und ECF 2020d) for download at the website <https://wupperinst.org/en/p/wi/p/s/pd/818/>

The **main assumptions** of the two reference studies are summarised in Table 1. Of the three industry scenarios, we use the NP scenario for the analyses on electricity and gas requirements and the CC scenario in analogy for the CCS analyses, as these each pose the greatest challenge to the corresponding infrastructures⁵.

Table 1: Main assumptions of the reference studies

Material Economics 2019: Industrial Transformation 2050			
Scenarios	New Processes (NP)	Circular Economy (CE)	Carbon Capture (CC)
Ind. electricity demand	965 TWh _{el} /a	659 TWh _{el} /a	693 TWh _{el} /a
Hydrogen demand	433 TWh/a	293 TWh/a	226 TWh/a
CO ₂ capture	45 Mt/a	47 Mt/a	235 Mt/a
ENTSO-E 2014: eHighways 2050 – Scenario X7 100% RES electricity			
Neither nuclear nor fossil fuels (+CCS) but all RES options incl. CSP (MENA) are used in this scenario.			
Total electricity demand: 4329 TWh _{el} /a, with higher demand by industry due to 60% of "heat" is converted from other fuels to electricity and 10% of the processes are electrified. As these figures could not be broken down further, we assume that demand from decarbonisation can be added to total demand.			
Wind is the most important RES source High power exchanges are required Peak units of ~73 GW _{el} are needed			

Source: own presentation after (Material Economics 2019) and (ENTSO-E 2014a)

The regional breakdown of the aggregated data from (Material Economics 2019) is similar to the following example for steel. It is assumed that CCS-based production of 10 Mt/a steel will exclusively take place in the Visegrad states, while the remaining 172 Mt/a are covered by shrinking primary and increasing secondary production according to the recycling potentials identified for the whole EU. The primary and secondary production is distributed to all other sites in Europe, taking into account the current shares of the countries and regions. So increase in secondary production is lower in regions with high shares of secondary today. Thus deviations in secondary shares all over Europe decline, but still the share of secondary is not equal all over Europe, as the product portfolio differs. In particular regions with high shares of flat steel production like northwest Europe (i.e. here Belgium, Netherland, Luxembourg and North Rhine-Westphalia) keep higher shares in primary production than other regions. Similar sector-specific considerations based on existing structures underpin the transformation paths for climate-neutral chemical and cement production.

Limitations of the study

The analyses were carried out for the existing industrial structures in Europe. However, the availability of infrastructure and green energy will also significantly affect the future development and location of energy intensive processing industries in Europe. The existence of such feedbacks shows how complex and how important the issue of

⁵ It should be noted that the demands here are in part significantly lower than in other (industrial) studies, e.g. (Alexis Michael Bazzanella und Florian Ausfelder 2017)

infrastructure development and planning is. As a deeper understanding of these feedbacks was not part of this study it has to be analysed in following in-depth studies.

Furthermore, it was not possible to carry out cost-benefit analyses, modelling or optimisation within the framework of the study. As economic evaluations could lead to different or new conclusions, they should therefore also be supplemented.

Results

The green transformation of basic materials industry in Europe will lead to spatially concentrated demand increase for green electricity

Decarbonisation strategies of energy and feedstock intensive industrial processes will always be related with an increase of industrial electricity demand. Main drivers are fuel switches from fossil to renewable electric energy and new processes like electric steam cracker and direct reduction of iron ore by electricity based hydrogen.

Industrial sites with (very) large production capacities will especially lead to a locally concentrated increase in electricity demand, as Figure 1 shows. Most locations with lower production capacities show a small absolute increase of less than 1.8 TWh_{el} (on average 0.97 TWh_{el}). However even these increases can trigger a significant expansion of the local power grid in the case of an extensive fuel switch or of clusters. In addition, there are a number of particularly noteworthy industrial regions with strong, spatially concentrated consumption growth, such as the east and south-west of the UK, the north-west and north-east of Spain, western Portugal and southern France as well as Italy, Poland, Austria and Hungary. All these regions will pose particular challenges for the electricity grid.

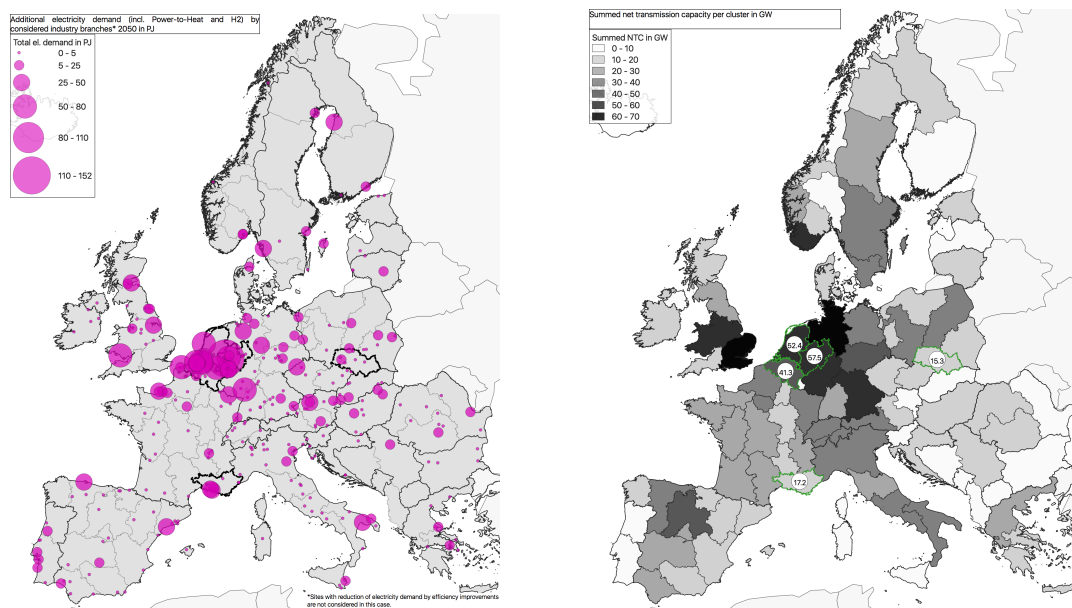


Figure 1: Left: Regional distribution of additional industrial electricity demand in 2050 incl. steam and H₂ production after scenario NP; Right: Regional distribution of cumulated additional net transfer exchange capacities 2050 in the power grid after scenario X7

Source: own graphs based on (Material Economics 2019) and (ENTSO-E 2014b)

By far the greatest challenge for the electricity grid is the region in the northwest of Europe (Belgium, the Netherlands and North Rhine-Westphalia). Here alone, the increase in electricity consumption is between 121 TWh_{el} (without H₂) and 263 TWh_{el} (with H₂) and thus accounts for between 29 and 33% of the total increase in demand. The average rate of increase is up to 4.2%/a (without H₂) compared to today and is thus significantly higher than the assumption for total electricity consumption (approx. 0.9%/a until 2040) in TYNDP 2020 (ENTSO-E und ENTSO-G 2019). For an assumed base load (8000 h/a), this demand leads to a total increase of 15 GW_{el} (without H₂) to

33 GW_{el} (with H₂) of the industrial load in the region, requiring according additional transport capacities. Compared to the already very ambitious grid expansion requirement without industrial decarbonisation in the "100% RES electricity" scenario of (ENTSO-E 2014a) (see Figure 1), this means a significant additional demand.

Both the energy saving potential and the renewable generation potential in Europe (especially from offshore wind) must be realised as quickly and comprehensively as possible

In order to bring the CO₂ emissions of the three industrial sectors under consideration to net zero, a mix of the following main strategies must be pursued in (Material Economics 2019) in each of the three scenarios, in combination with a complete change in energy supply from fossil to renewable sources:

- Increasing material efficiency and recycling (focus in CE scenario),
- introduction of new, efficient process technologies based on renewable electricity or green hydrogen (focus in NP scenario) and
- the use of carbon capture in relation to the remaining process emissions (focus in CC scenario).

The resulting energy requirements (see Table 1) and the associated requirements for the expansion of renewable energies and on CC systems as well as the necessary infrastructure vary in size depending on the scenario focus selected. In this respect they will be significantly lower in the CE scenario than in the other two scenarios. However, the realisation of comprehensive efficiency improvements are important in all scenarios in order to reduce future resource and energy requirements to below today's levels. The pressure for action on the energy infrastructures, which is examined below on the basis of the more ambitious NP scenario, can be reduced by setting greater priorities in favour of efficiency.

The decarbonisation of the industry sectors steel, cement and chemicals will lead to an additional demand of renewable electricity of up to 419 TWh for direct electricity and steam appliances and another 390 TWh for hydrogen production⁶. Both together correspond to approximately 85% of the EU's renewable electricity generation of about 951 TWh in 2016 according to (EEA 2020). At the same time, the surrounding energy system will be decarbonised, as foreseen in the EU's „A Clean Planet for all“ (European Commission 2018). This means that renewable energies will need to cover all energy demands. Since electricity can be decarbonised more easily than fuels, the sectors of heat and transport will most likely have a high degree of electrification, resulting in an even higher demand for renewable electricity. Overall, this could lead to a European electricity demand in the range of 5000 TWh (compared to ca. 2800 TWh in 2018 (eurostat 2020)). In the underlying study eHighway2050 (ENTSO-E 2014a), a total renewable electricity generation potential (technical potential) of about 6900 TWh is assumed. Covering the electricity demand by European renewable electricity will accordingly imply to use about 72% of the overall renewable generation potential. Especially the supply for northwest Europe poses a major challenge, since there is

⁶ These analyses are based on the new processes scenario of (Material Economics 2019), which has the highest additional electricity demand. In the lowest case (scenario circular economy), additional electricity demand (incl. H₂) is 659 TWh.

already a spatial concentration of electricity demand there, which will increase further due to decarbonisation. Offshore wind energy in the North Sea therefore is a very important resource which will need to be deployed to a large extent.

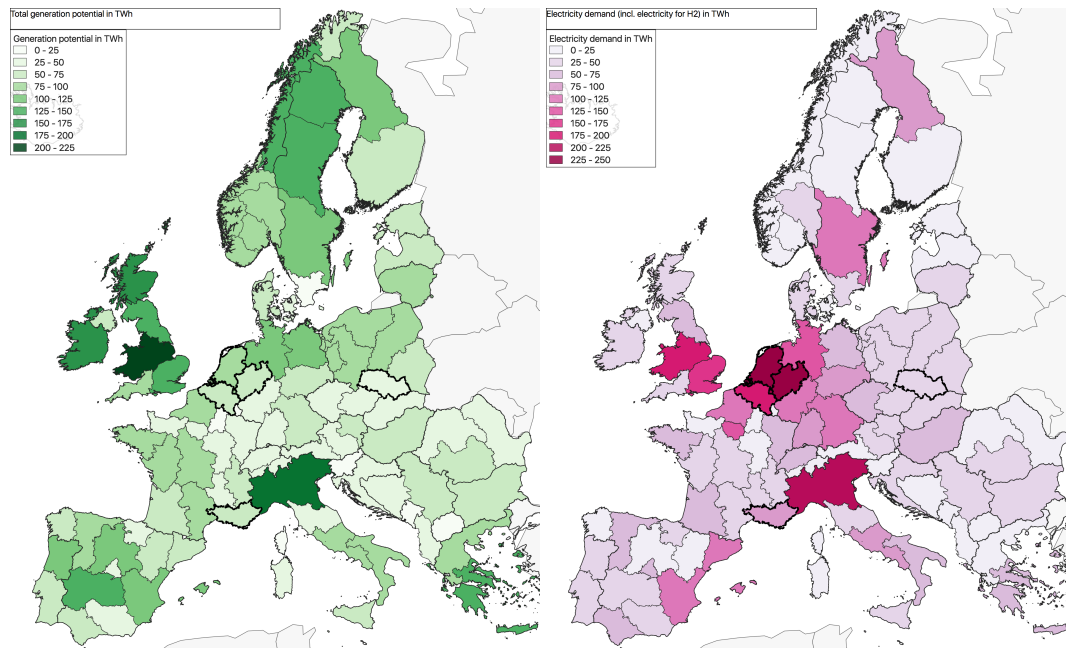


Figure 2: left: renewable generation potential (wind offshore potentials are assigned to the respective surrounding regions); right: electricity demand including industrial decarbonisation

Source: own graphs based on (ENTSO-E 2014a) and (Material Economics 2019)

National or regional expansion of electricity and hydrogen production is seen as important to European value creation and security of supply.

The individual workshop assessments of the infrastructural challenges and solution options in the three hot spot regions investigated led to the following fundamental dilemma. On the one hand, significant potentials for the regional or national expansion of renewable energies for electricity generation are still seen, which should be further developed in order to contribute positively to domestic value creation and independence from foreign countries. At the same time, the expansion is not considered realistic due to social and partly regulatory obstacles as well as cost disadvantages compared to foreign sweet spots.

There is also a risk that imports will probably not only be limited to energy sources but will also extend to products (e.g. platform and specialty chemicals as well as crude steel and steel products) that are still produced or processed in Europe today. In addition to a weaker security of energy supply, this also entails the risk that domestic production facilities will lose their importance in the long term and may be lost. For this reason, large domestic electricity and hydrogen production is seen as advantageous from a macroeconomic point of view. Decarbonisation in Europe would be an important win-win opportunity to reduce European import dependency and at the same time to achieve global leadership in key technologies such as electrolyzers.

Policy makers and transmission system operators (TSO) should therefore pay attention to the right balance between sufficiently high but more expensive self-supply (which is preferable for the above reasons) and high but cheap imports with more dependencies.

Some regions with the highest increases in demand will need new, high-performance import structures for electricity and hydrogen, while most heavy industry clusters in Europe would be able to meet the additional demand to a sufficient extent by renewable energy from their vicinity

Applying the decarbonisation strategies according to the NP scenario of the (Material Economics 2019) study to the current industrial structures and their regional characteristics would lead to the regional distribution of electricity balances in Europe shown in Figure 3. These contain both the total renewable electricity generation potential and the total electricity demand based on EHY2050 plus the additional industrial electricity demand including hydrogen production.

One can see that the electricity balances are positive in most regions and that it would be possible to meet demand despite additional industrial demand if the electricity grid was adjusted accordingly. In addition, most regions have such a high generation potential that even the electricity deficits of many regions could be compensated regionally. Overall, the remaining electricity generation potential is so high that theoretically the entire residual electricity demand in Europe could also be met.

However, it is also evident that in northwest Europe a very deep electricity sink ("deep hole") would be caused with an electricity deficit of 325 TWh_{el}/a (without hydrogen) to 467 TWh_{el}/a (with hydrogen). An ambitious, conventional expansion of the power grid will therefore no longer be meaningful for the power supply of this highly industrial region. For the supply of hydrogen, however, the existing natural gas pipelines can and should first be converted for use with green hydrogen. However, they will also have to be additionally reinforced due to the two-thirds lower energy density of hydrogen. Therefore, it appears necessary, at least for the industrial region in northwest Europe, to establish sufficiently powerful and secure import and transit structures for electricity and hydrogen to relieve the strain on the electricity grid. Due to the long lead times for implementation, planning should already begin today.

The import structures should enable both the intra-European import of remote sweet spots for renewable electricity and hydrogen production (e.g. in Spain and Scandinavia) as well as the import of sweet spots outside Europe (e.g. from North Africa). The large seaports in northwest Europe (Antwerp, Rotterdam) and on the Mediterranean (Barcelona, Marseilles) are of great advantage for imports by sea in combination with domestic gas and electricity pipelines for supplying the hinterland or even more distant European deficit regions.

Regardless of the exact design of energy import infrastructures, they will play a key role for the decarbonisation within Europe.

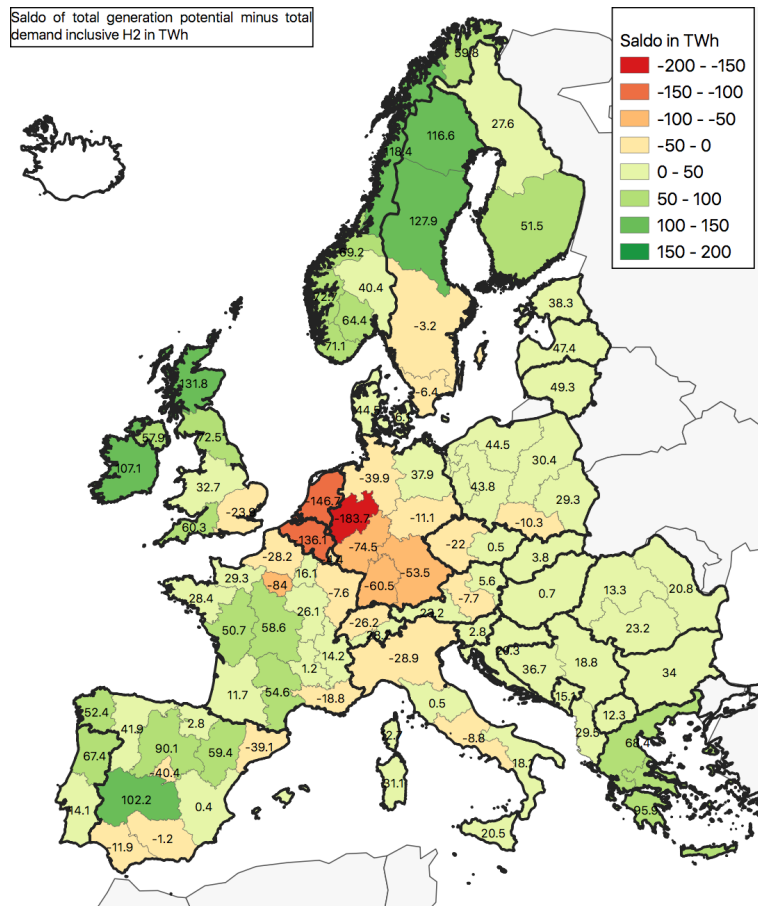


Figure 3: Balance of renewable generation potential and demand with electricity for hydrogen in Europe 2050

Source: Own graph after (Material Economics 2019) and (ENTSO-E 2014a)

However, today's "fossil-fuelled" industrial structures can (and will) also change as a result of the transformation towards renewable energies and raw materials, and possibly orient themselves more towards European sweet spots for electricity and hydrogen. In principle, this could involve many new regions that still have great potential for renewable electricity generation in the long term (see Figure 3). This also includes the entire eastern and south-eastern European region with almost area-wide high remaining renewable generation potentials. Strengthening the energy infrastructures and the expansion of renewables there could contribute to the development of future-proof industrial structures for the whole of Europe and, in particular, to strengthening the economy in these regions.

For the supply of the necessary amount of green hydrogen to energy intensive industries, parts of the existing natural gas grids and storage facilities can serve as important assets and should be repurposed

The gas pipelines in the EU today have a total length of at least 2.2 million km (as of 2014) (Eurogas 2015). In the last 10 years (2008-2018) they covered an annual gas consumption of between 402 and 521 billion Nm³ (i.e. 4342 and 5627 TWh) (Statista 2019). The industrial sector accounts for approximately 34% or 1471 TWh (2014) (Statista 2016). Natural gas storage facilities with a working gas volume of 1110 TWh are also connected to the gas network (gie AGSI 2020). The phasing out of fossil fuels

such as natural gas can basically make these infrastructures available for the use of renewable gases such as green hydrogen produced from renewable electricity.

Depending on the strategy chosen (Material Economics 2019), decarbonisation of steel and chemical (plastics and ammonia) production in the EU will require between 114 and 398 TWh_{th} (or 32 to 112 billion Nm³) of green hydrogen in 2050⁷. From an aggregated energetic point of view, the capacities currently available in the gas network are therefore principally sufficient to transport the green hydrogen for these industrial sectors. It is also an advantage that the future industrial hydrogen hot spots in the regions under consideration are already in the immediate vicinity of today's natural gas pipelines (see Figure 4). The gas network at coastal locations such as Marseille or Rotterdam is of particular importance in this respect, as it is also suitable for the import, intermediate storage and domestic transport of hydrogen.

A broad, strong expansion of the gas network therefore does not appear to be basically necessary, in contrast to the electricity network.

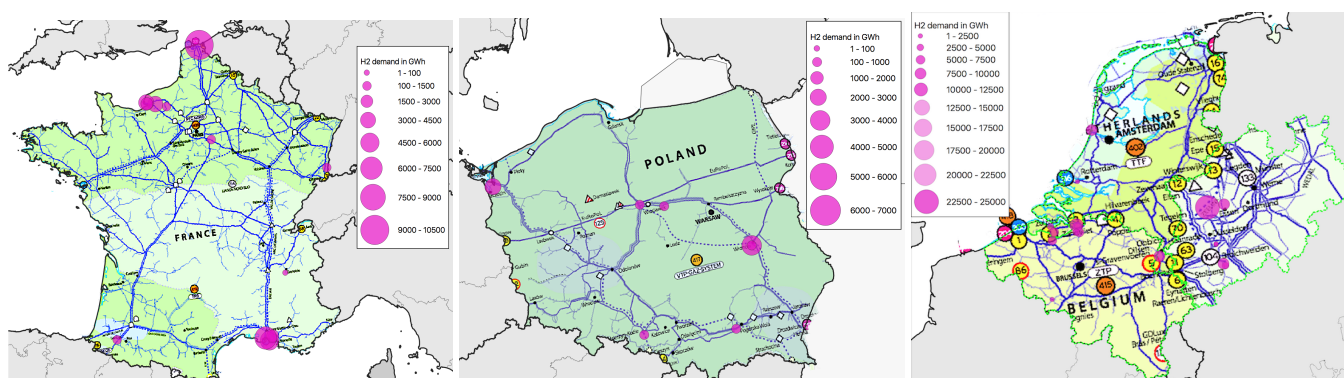


Figure 4: Locations of future industrial H₂ demand in relation to the existing natural gas grid in three selected industrial cluster regions (southern France, southern Poland and northwest Europe)

Source: own graphs combined with map sections from (entsog Map 2017)

However, the concrete utilisation of natural gas pipelines, including operating resources for green hydrogen, is a difficult and complex endeavour in practice. On the one hand, it must be carried out during ongoing operation (with seasonally fluctuating and overall decreasing natural gas quantities) and at the same time be oriented to different transformations in terms of both space and time. This includes the regionally and temporally varying development of renewable production quantities as well as the industrial demand quantities of hydrogen. An additional challenge arises from the fact that the increase in industrial demand for hydrogen will be rather in large steps (due to large units of production capacity) than continuously and will not be synchronized with the decline in demand for natural gas. The transformation of the natural gas networks therefore requires coordination at all levels, with the participation of the affected stakeholders and supplemented by overarching control at European level.

In particular, the concentrated demand rise in certain industrial regions must be taken into account, as it may exceed the local capacity of existing gas networks (cf. Figure 5). This is due to the lower energy density of hydrogen (being only one third of natural

⁷ According to (Simon 2020), the TSO's expect to feed 300 to 800 TWh of hydrogen into the gas grid for the decarbonisation of gas using power-to-gas plants, which does not yet include the actual demand in future.

gas), which requires higher transport volumes and/or operating pressures than today. This applies in particular to the industrial hot spot region in northwest Europe.

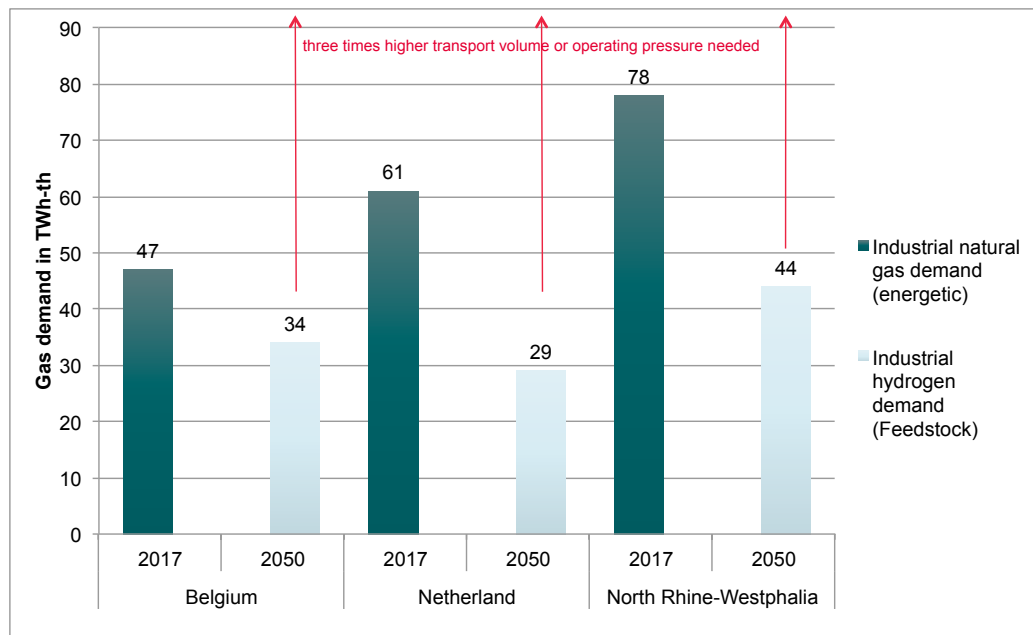


Figure 5: Comparison of today's industrial natural gas demand in 2017 with the future hydrogen demand in 2050 in the northwest Europe.

Source: own graph based on (eurostat 2017) and (IT.NRW 2020)

The regional strategies for the transformation of the natural gas network must also take into account the existing networks for "grey" hydrogen (i.e. produced from fossil resources) in some regions. This applies in particular to the industrial region of northwest Europe which has the highest additional hydrogen demand. There are already two relatively extensive networks with approx. 240 km in North Rhine-Westphalia and approx. 1150 km in the Netherlands, Belgium and France (H2 Tools 2020). These are operated commercially by Air Liquide and Air Products and mainly connect different chemical sites

These H₂ networks could act as a starting point for expanding the supply from other locations in the region or for a relatively simple direct conversion from grey to green hydrogen. However, at least two aspects must be considered and governed. Firstly, an adequate linkage of private, non-regulated gas networks with public, regulated gas networks and their operation in accordance with regulatory and energy industry requirements, unless the expansion cannot be carried out on a purely private basis. Secondly, the decarbonisation of the grey hydrogen component, which is a by-product of conventional industrial processes.

Infrastructure development for abatement of unavoidable industrial CO₂ emissions with CCS will need access to suitable (large) storage sites and should be coordinated at EU level to reduce regional disparities

CCS is required in all decarbonisation strategies for heavy industry, and most importantly for the climate-neutral transformation of cement production. However,

depending on the strategic orientation of the steel and chemical industry as well as the level of ambition in circular economy, the quantities involved vary considerably (45 – 235 Mt CO₂/a to be stored as of 2050). In any case, the emissions to be managed are generated at a large number of locations (see left in Figure 6), posing a challenge for the development of CO₂ transport infrastructures. This is especially true for the typically decentralised distribution of cement plants in the hinterland, which also have rather low site-specific CCS demands of 0.6 Mt CO₂/a (compared to 2 Mt CO₂/a for steel sites; average values). However, these decentralised sites usually lack suitable (and socially accepted) regional CO₂ storage facilities and therefore need support for transport and access to the remote, central (offshore) CO₂ storage sites.

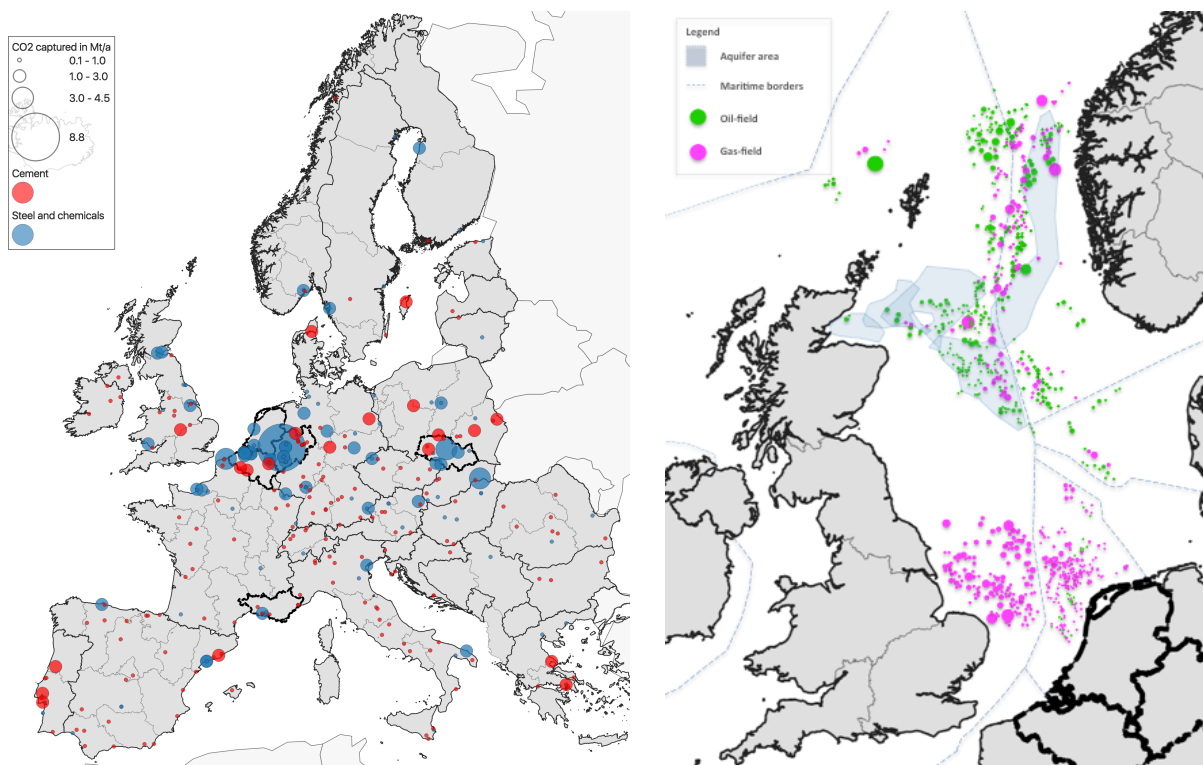


Figure 6: Remaining CO₂ emissions from considered industry sectors that need to be addressed by CCS in Mt/a as of 2050 according to CC scenario (left). Relevant aquifers and offshore hydrocarbon fields in North-West-Europe, serving as potential future storage facilities (right).

Source: Own graph and calculation based on left: (Material Economics 2019) right: (NLOG 2020), (Norwegian Petroleum Directorate 2019) and (OGA 2020)

Social acceptance of CCS is generally low in most European countries. Although research on the subject is diverse, onshore storage faces particular opposition, especially in areas close to settlements, and is therefore unlikely to play a major role in Europe (Schumann et al. 2014). The further analysis focuses on offshore storage, as projects in this area are generally considered to have higher probability of success (IOGP 2019) (Lofstedt 2015). Suitable offshore storage facilities close to the mainland promise comprehensive potential at an aggregated (national) level, but on closer examination they often turn out to be small and diffusely distributed. This is illustrated in the right of Figure 6 for the Dutch offshore fields, whose total effective storage capacity amounts to ~900 Mt CO₂, but is distributed over up to 150 fields. As can be

seen from the comparison of the two graphs in Figure 6, the storage sites are also rarely located in the immediate vicinity of the emission sources. Therefore, with the exception of the Netherlands, which has its own coastal reservoirs, CO₂ storage solutions for each assessed region can be best found in a European context (e.g. connection to the Norwegian storage sites).

Conclusions and recommendations

An integrated strategy for industrial, resource and energy transition is needed

Making European industries and particularly materials processing industries climate neutral is directly linked to the conversion of the European energy system towards renewable sources. Both transformations are interlinked and interdependent. On the one hand industry decarbonisation will need huge amounts of green energy and feedstock at competitive costs which requires a respective conversion and expansion of infrastructures as well as renewable generation. Energy infrastructures and the availability of green energies on the other hand also determine the future location of energy intensive materials processing industries in Europe. Material efficiency and circularity play an important role for making the industrial transition feasible and economically viable.

For a successful transition and implementation of the ideas of the European Green Deal, the EU and its industries need a coherent strategy and policy framework which integrates a strong innovation oriented industrial policy, a related policy on a circular economy as well as an enhanced energy and infrastructure policy (cf. Lechtenböhmer und Fishedick 2020).

Recommendations for industry transformation

- Decarbonisation strategies of the various industrial clusters in the EU should be coordinated and supported on the regional, national and European level in order to enable the regions and their stakeholders to develop such strategies, foster their implementation and adapt the necessary infrastructure to them.
- Strategies to improve resource efficiency and recycling management should be demanded and promoted by policymakers as a matter of priority. These should be emphasised as important enablers of innovative and competitive industries and regions.
- Policy makers should give concrete and unambiguous guard rails and support for the industrial decarbonisation like efficiency and use of excess heat first, switching to renewable electricity wherever it is possible and otherwise to make use of green hydrogen, to accelerate corporate decisions. This allows TSOs to plan the necessary infrastructure in a more forward-looking manner.

With regard to a coherent and future-proof design of the necessary climate-neutral transformations of heavy industry as well as of gas and electricity infrastructures, the following conclusions and recommendations are to be considered mainly from the perspective of the energy infrastructure policy as an important enabler of the industrial transition towards climate neutrality.

Electricity infrastructure

Current European plans to expand the electricity grids (TYNDP) underestimate the need for expansion, because they do not sufficiently reflect the necessary decarbonisation of industry. This is due to the fact that the underlying scenarios do not cover the decarbonisation of heavy industry in a sufficiently differentiated and ambitious manner. This results in a smaller foreseen increase in electricity

consumption than actually needed when deep decarbonisation of heavy industries is taken into account as well. In addition, the time horizon in the scenarios (until now) only extends to the year 2040 with an outlook to 2050.

Despite the considerable increase in demand and load, especially in the industrial hot spot regions, it will be possible to expand the electricity grid sufficiently within the existing structures by upgrading existing power lines or additional lines, with AC or HVDC technology. New topologies such as full HVDC overlay networks do not appear to be absolutely necessary for this purpose. However, they could be of (additional) benefit for an improvement of the security of supply if they help to connect European sweet spots (RES-export regions) and hot spots (high - industrial- demand regions) that are geographically distant.

Irrespective of the network topology, the priority for Europe-wide electricity network development should be in particular on the connections between the high-potential generation regions and the regions with high demand. This will ensure on the one hand that Europe's own renewable generation potentials can be used as comprehensively and effectively as possible for the necessary decarbonisation of industry. On the other hand, it will give the industry more security for its necessary large investments in decarbonisation. To this end, planning of the grid expansions especially for the hot spot regions to at least the year 2050 should already be started today.

The challenges and potential solutions for the electricity grid vary greatly from region to region, with solutions tending to be sought first in the individual regional or geographical environment (north, south, east and west). However, the long-term challenges, especially the spatially concentrated increases in demand in a few core industrial regions, exceed the regional RES potentials. Therefore, the design of electricity grids for comprehensive decarbonisation should be coordinated on a European-wide basis, with particular attention being paid a) to intra-EU electricity exchange with e.g. the North Sea region as well as with southern- and south-eastern European countries and b) to international energy partnerships with Ukraine, Belarus, Russia and MENA as well as the UK.

Even if the domestic potential for renewable electricity generation is much more limited in real terms than, for example, in sunny and windy North Africa, they can still make a much greater contribution than today to Europe's own security of supply and value creation. For this reason, the still very large and relatively inexpensive RE potential in Europe (i.e. offshore wind in the North Sea, onshore wind in the UK and Scandinavia, and solar energy in southern Europe) should be developed quickly and consistently.

Recommendations for electricity infrastructure:

- The scenario framework for the electric TYNDP should already be expanded in the current version to 2050 and to include various industrial decarbonisation strategies beyond CCS (i.e. electrification and hydrogen) with different levels of electricity intensity.
- The expansion of the electricity grid should be accelerated overall, but above all in the sweet and hot spot regions, and increased to meet the higher regional electricity demand expected in the long term.

- The expansion of renewable electricity generation in Europe (especially offshore wind power generation in the North Sea) should be accelerated.
- The expansion of the electricity grid must be more closely coordinated with the transformation of the natural gas grid towards hydrogen, in order to achieve more synergy effects in terms of capacity utilisation and relief as well as system costs.
- When planning electric infrastructures, local industrial actors in particular should be involved.
- In line with the previous points, the current PCI projects that have been delayed or are still being approved should be implemented more quickly.

Gas and hydrogen infrastructure

In the natural gas network, there is in principle enough capacity for the intake and transport of the industrial hydrogen required if the pipelines are converted to use hydrogen. However, regions with very high hydrogen demand will probably still need additional new hydrogen pipelines due to the lower energy density of hydrogen.

In particular, coastal locations are also suitable for hydrogen imports from distant sweet spots. They seem to be advantageous starting points for decarbonisation of gas and industry, as they usually have differentiated infrastructures (or conditions) for the reception of offshore produced hydrogen and hydrogen imports as well as for its further transport to the hinterland. Additional advantages result from the large wind power potentials near the coast, which can be used for hydrogen generation and feeding into the grid.

However, these imports are in competition with the value added by own production and the current plans for LNG imports, whose assets are not considered compatible with those for hydrogen, cf. (Union 2018, p. 48). In any case, it seems that import structures (including storage) for climate-neutral hydrogen must be established within the next 20 years, in order to supply industry sufficiently and safely with hydrogen from sweet spots beyond Europe.

Recommendations for natural gas and hydrogen infrastructure

- Similar to above, the scenario framework for the gas TYNDP should be expanded to reflect the consequences of industrial decarbonisation strategies beyond CCS with different levels of hydrogen use intensity and more closely coordinated with the electric TYNDP.
- Furthermore, the total gas grid planning and expansion should be reassessed in the context of the 2050 climate neutrality targets and under the premise of an overall gas demand reduction and a shift to climate-neutral gases, especially green hydrogen for industry and heavy-duty transport.
- For climate-proof planning and conversion of natural gas networks to hydrogen networks, transformation and verification criteria must be developed and established in a timely manner to ensure that gases are CO₂-free along the entire process chain.
- Additional costs for the future-proof conversion of natural gas networks to hydrogen should be given special consideration in regulation if the costs comply with the transformation criteria developed previously.

- The Trans-European Networks for Energy regulation (TEN-E) as well as the planning of LNG and hydrogen imports should be reassessed in the light of those criteria, in order to enhance the build-up of a European hydrogen economy.
- Windows of opportunities (e.g. planned replacements of pipelines and equipment and foreseeable idle capacity) for the conversion of pipelines to hydrogen are to be identified and reported by the Gas-TSO, in order to better coordinate, push and support the transformation of the gas grid.
- When planning hydrogen infrastructures, local industrial actors should be involved.
- The European Commission should support and accelerate the European scale up of electrolyser capacities (together with the European expansion of renewable energies), in order to contribute to added values, jobs and industrial leadership in the global market.

Carbon Capture and Storage (CCS) infrastructure

With only a few exceptions, the results show a mismatch between CO₂ sources and storage sites. Especially for regions with unfavourable storage situation, the discussion with representatives showed that a wait-and-see approach might be preferred to the build-up of own infrastructure. This bears a high risk that the required solutions will not be available in time and underlines the importance of coordination at the European level. This applies both to the development of necessary infrastructural solutions (especially for difficult regions/sites) and the clarification of related legal and financial issues, as well as to dealing with the lack of social acceptance, which constitutes one of the key obstacles for most workshop participants. In this context, the driving role of successful demonstration projects was highlighted as particularly important.

CCS is necessary for industrial decarbonisation at least in the cement sector (according to current knowledge). At the same time, due to its relatively small site-specific emissions and its typical geographical distribution in the hinterland, the cement industry in particular is not well placed to solve the challenges individually. At this point, dependencies on other industrial sectors arise as to whether a common approach to CCS could be established or not. It remains to be seen which transport infrastructures are best suited for CCS, but pipelines are necessary in any case. Due to competition with future transport of hydrogen, it is not expected that the existing gas networks will be used for CO₂ on a large scale.

Recommendations for CCS infrastructure

- CCS should be planned and supported exclusively for unavoidable process emissions from industry like from cement kilns. This is important, due to the scarce storage facilities, high transport costs, lack of social acceptance in some regions and substitution possibilities in other sectors as well as in order to prevent lock-in effects on other potential users and possible "keep coal alive" initiatives
- In this sense, CCS should also be explicitly banned for coal-fired power plants, as concerns have been repeatedly expressed by several workshop participants that developments of CCS in industry may be taken up by the coal-based energy sector.
- CCU should be only allowed under strict criteria-based limitations as it is unlikely to contribute to long-term avoidance of CO₂ (with few exceptions, such as comprehensive chemical recycling).

- Rapid action is needed if a future-proof European CCS infrastructure is to be established by 2050, as its build-up poses a complex and long-lasting challenge.

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