Needs of electricity, hydrogen and carbon infrastructures for greenhouse gas neutral heavy industry clusters in the EU 2050

Frank Merten, Arjuna Nebel,
Christine Krüger, Clemens Schneider,
Alexander Scholz & Ansgar Taubitz
Wuppertal Institute for Climate, Environment, Energy
Department "Future Energy and Industry Systems"
Döppersberg 19
D-42103 Wuppertal
Germany
frank.merten@wupperinst.org
arjuna.nebel@wupperinst.org
christine.krueger@wupperinst.org
clemens.schneider@wupperinst.org
alexander.scholz@wupperinst.org
ansgar.taubitz@wupperinst.org

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Abstract

The reduction of greenhouse gas (GHG) emissions by energy-intensive industries to a net zero level is a very ambitious and complex but still feasible challenge, as recent studies show for the EU level. "Industrial Transformation 2050" by Material Economics (2019) is of particular relevance, as it shows how GHG-neutrality can be achieved in Europe for the sectors chemicals (plastics and ammonia), steel and cement, based on three main decarbonisation strategies. The study determines the resulting total demands for renewable electricity, hydrogen and for the capture and storage of CO_2 (CCS). However, it analyses neither the regional demand patterns that are essential for the required infrastructure nor the needed infrastructure itself.

Against this background the present paper determines the regional distribution of the resulting additional demands for electricity, hydrogen and CCS in Europe in the case that the two most energy and CCS intensive decarbonisation strategies of the study above will be realised for the existing industry structure. It explores the future infrastructure needs and identifies and qualitatively assesses different infrastructure solutions for the largest industrial cluster in Europe, i.e. the triangle between Antwerp, Rotterdam and Rhine-Ruhr. In addition, the two industrial regions of Southern France and Poland are also roughly examined.

The paper shows that the increase in demand resulting from a green transformation of industry will require substantial adaptation and expansion of existing infrastructures. These have not yet been the subject of infrastructure planning. In particular, the strong regional concentration of additional industrial demand in clusters (hot spots) must be taken into account. Due to their distance from the high-yield but remote renewable power generation potentials (sweet spots), these clusters further increase the infrastructural challenges. This is also true for the more dispersed cement production sites in relation to the remote CO_2 storage facilities. The existing infrastructure plans should therefore be immediately expanded to include decarbonisation strategies of the industrial sector.

Introduction

The entire industrial sector is responsible for about 19 % (860 Mt/a) of the total GHG emissions (4,470 Mt/a) in the EU-28 as of 2015 (EEA, 2019a) (EEA, 2019b). The three sectors steel, chemicals (plastics and ammonia) and cement production alone account for approximately 62 % (536 Mt/a) of industrial emissions in 2015 (Material Economics, 2019). The special feature of these three sectors considered here is that their CO_2 emissions are largely process-related (approx. 42 %) and fuel-related (approx. 36 %) but only about 12 % result from their electricity demand (Material Economics, 2019). Their decarbonisation will therefore require a bundle of different, sector and process-specific measures and strategies. These include in particular the introduction and use of new processes such as hydrogen direct reduction of iron (steel production), the electrification of process heat generation and steam crackers (chemicals production) as well as electrification of sintering and calcination processes (cement production), while using renewable electricity and renewable gases such as hydrogen. Nevertheless, there will still remain significant process-related CO_2 emissions, in particular from cement making, that need to be captured and stored (CCS)[1] in any case (Material Economics, 2019).

A comprehensive and consistent use of those strategies could fulfil the decarbonisation of the chemicals, steel and cement production, but leads at the same to considerable higher demands for renewable electricity, for hydrogen as feedstock and for CCS throughout of Europe. Depending on the strategies analysed in (Material Economics, 2019), the electricity demand of the three branches will raise by about 450–750 TWh_{el} until 2050 compared to 2015, including the electrical production of about 114–287 TWh_{th} of hydrogen needed. The remaining annual CO_2 emissions for CCS use will be about 45–235 Mt from 2050 onwards.

This new industrial electricity demand alone equals to a significant increase of up to 26 % (or 0.66 % per year) compared to the total electricity demand of approx. 2,900 TWh_{el} in the EU 2015 (eurostat, 2019). However, this demand is not included yet in the relevant reference scenarios for infrastructure planning and foresight analyses like (ENTSO-E & ENTSO-G, 2019) and (e-Highway 2050, 2014), which already lead to substantial grid expansion needs in Europe until 2040 and 2050 at otherwise comparable increase-rates of electricity demand. Hence, the decarbonisation of the three industry sectors alone will require a significant enhancement of the existing European power grid, which is not sufficiently reflected yet in the current networking planning. Furthermore, the infrastructure needs by decarbonising the energy intensive industry are not reflected in other industry transformation studies like (EURELECTRIC, 2018) and (McKinsey, 2010).

In order to close this gap and to explore the infrastructure needs for a green industrial transformation in Europe, we are building on the relevant industry study (Material Economics, 2019) and link it to the relevant power grid study (e-Highway 2050, 2014). In this way, we gain an overall systemic view of the respective developments and challenges and how they relate to each other. For the exploration of industrial infrastructure needs, we focus on selected regions with particularly significant industrial clusters in Europe with the help of our own industry model WISEE, cf. (Schneider et al., 2020)(van Sluisveld et al., 2018). It is a bottom-up energy system model representing production technologies in the context of value chains which are linked via product, energy and resource flows. The EU industrial production stock is represented in a database with commissioning date, actual capacity and the production site (GIS coordinates). In the context of the study at hand we set future technology choice exogenously following the pathways of the study by (Material Economics, 2019).

The focal regions include particularly the industrial hot spot region in North-West Europe, which covers the triangle between Antwerp, Rotterdam and Rhine-Ruhr, being the most important cluster of steel and chemical industry in Europe. Hence, the results of this paper concentrate on this region, but are complemented by more rough examinations of two other hot spot regions (Southern France as a proxy for the Mediterranean area and Poland as a proxy for central European industrial regions).

Scope and Approach

This paper focuses on

- the three carbon- and energy-intensive industrial sectors chemicals (plastics & ammonia), steel and cement,
- their existing production structures (of which three cluster regions are selected) in the base year 2015,
- their future demand for electricity, hydrogen and CCS,
- the related energy infrastructures and the spatial distribution of the technical potential for renewable electricity generation, and
- the two reference studies (Material Economics, 2019) and (e-Highway 2050, 2014).

The study area covers the EU plus non-EU member states and the time horizon focuses on the years 2050 and 2015 (for comparison purposes).

Figure 1 shows the basic procedure for our own analyses and results. The (Material Economics, 2019) study provides the industrial needs for electricity, hydrogen and CCS expected in 2050, aggregated at EU level. Of the three underlying decarbonisation strategies, the "New Processes" (NP) scenario is used for the analyses of electricity and hydrogen demand and the "Carbon Capture and Storage" (CCS) scenario for the CCS demand, as these are the two with the highest specific demand figures. The aggregated demand values are broken down into site-specific demand values using the detailed site data and knowledge of the WISEE model and additional specific assumptions. For steel making at EU level (182 Mt in 2050), for example, it is assumed that CCS-based production (10 Mt) will then exclusively take place in the Visegrad states. The remaining 172 Mt are covered by shrinking primary and increasing secondary production according to the recycling potentials identified by Material Economics for the whole EU. Primary and secondary production are distributed to all other sites in Europe. Current primary and secondary production shares of countries and regions are regarded in this distribution. 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 overall equal all over Europe, as the product portfolio differs. In particular regions with high shares of flat steel production like North-West Europe (i.e. here Belgium, the Netherlands, Luxembourg and North Rhine-Westphalia) keep higher shares in primary production than other regions. For this particularly relevant focus region it was assumed that the current primary production of 24.9 Mt crude steel will be replaced by approx. 32 % using the "steel scrap" (Secondary steel) route and by approx. 68 % using the "direct reduction" (Primary steel production route using hydrogen) route in 2050 (Wuppertal Institut & ECF, 2020). Similar sector-specific considerations based on existing structures underpin the transformation paths for climate-neutral chemical and cement production.

1. In the case of new steel production processes such as smelting reduction, carbon capture and use (CCU) will also play a certain role, e.g. for recycling and reprocessing of exhaust gases for chemical production.

From the resulting regional distribution of demand, those industrial focus regions ("hot spots") are then identified that are characterized by particularly high consumption and at the same time by the proximity of different industries (cf. results).

The necessary data for the generation and infrastructure of electricity as well as for the "conventional" remaining total electricity demand, which depends negligibly small on industry decarbonisation, are taken from the study (e-Highway 2050, 2014) and scenario X-7 (100 % RES electricity). These are spatially broken down into 113 clusters, to which the additional industrial power requirements from (Material Economics, 2019) are allocated. This resolution enables the necessary data to be generated and evaluated in the form of maps for infrastructure analyses throughout Europe (cf. results). Particularly helpful is the presentation of total demand (including decarbonised industrial sectors), the remaining potential for renewable electricity generation and the balances of maximum potential electricity generation and total electricity demand (with and without electricity for hydrogen production).

With regard to the results, it should be noted that a sensitivity analysis was not performed in this study. Since rather ambitious scenarios have been chosen as the base for deriving the infrastructure needs, the following results can be regarded as in the upper range of the possible bandwidth of necessary transport infrastructures. If the additional demands for electricity, hydrogen, and CCS are assumed to be lower (e.g. because less low carbon technologies are applied or the production rates decline), the transport needs will be accordingly lower as well. That is, in the first approach, a linear correlation. But if the demand for hydrogen and carbon dioxide falls below a certain threshold, possible pipelines could be replaced by less capital cost intensive alternatives (e.g. truck transport).

Results for industrial hot spot regions in Europe

Figure 2 illustrates the resulting regional distribution of the additional industrial electricity demand (in total 750 TWh_{el}/a), if the decarbonisation strategies of the NP scenario are broken down from (Material Economics, 2019) to the current production sites of the considered industrial sectors according to their characteristics. This leads to an exceptionally large and concentrated increase in electricity demand in north-western Europe, especially in the region of Belgium, the Netherlands and the neighbouring German federal state of North Rhine-Westphalia. It amounts to a total of 263 TWh_{el}/a (incl. H_2 production), contributes 35 % to the Europe-wide increase in demand and is determined by the few but large production sites for chemicals and steel (see Figure 4) there. This region therefore determines to a large extent the future requirements for the necessary infrastructure (due to its size not only locally but also in the larger environment) and is therefore focused in the following section. In addition the relatively strong increase in electricity demand in the immediate vicinity (northern and southern Germany and northern France) should also be taken into account.

In addition, there are a number of other noteworthy industrial regions with relatively 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. Of these, southern France (+54 TWh_{el}) and southern Poland (+6 TWh_{el}) are selected as further focus regions for complementary infrastructure analyses, since all or several of the industries under consideration are represented there and they have a special, interesting location in terms of infrastructure (Mediterranean port or eastern European hinterland, each with national pipeline connections).

Another reason shows the right side of Figure 2, indicating the resulting electricity balance in 2050 by clusters, which would result from the total possible electricity production according to (e-Highway 2050, 2014)-X7 minus the total electricity demand (including decarbonised industries) according to (e-Highway 2050, 2014) and (Material Economics, 2019). In the future, southern Poland will already have a balance sheet shortfall of a few TWh_{el} per year even without additional industrial electricity demand, which will be moderately intensified by decarbonisation through electrification. In contrast, southern

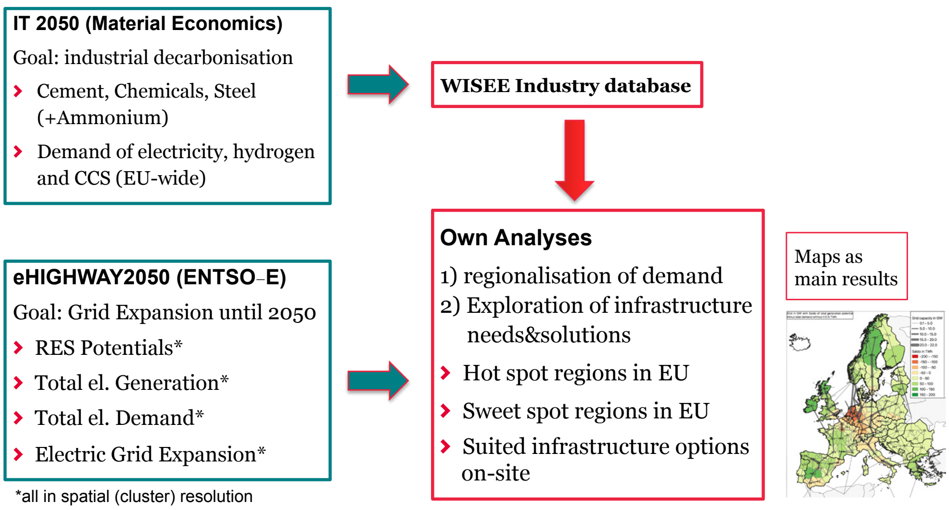


Figure 1. Overview of the usage of the two reference scenarios and their parameters for own analyses.

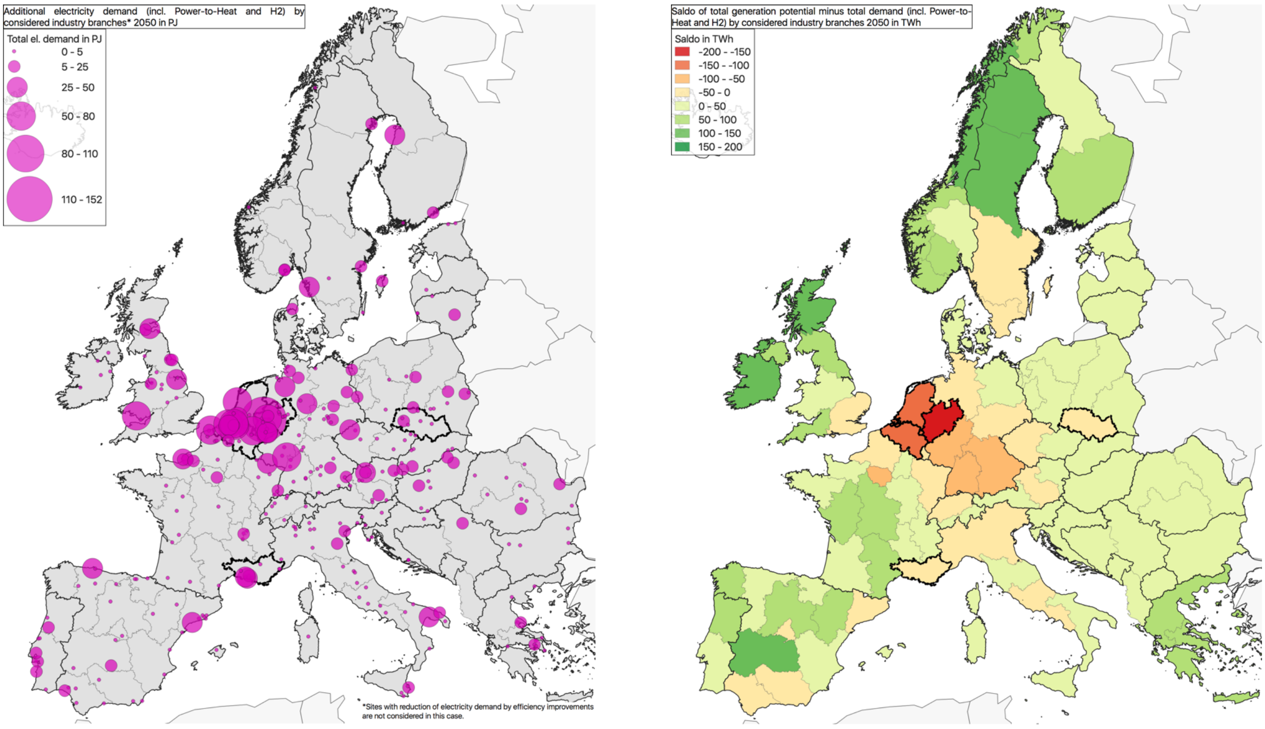


Figure 2. Left: regional distribution of the additional electricity demand (incl. Power-to-Heat and hydrogen) in PJ/a by decarbonised industry branches in 2050 after ME-scenario "NP"; right: regional distribution of the balance between maximum potential electricity generation and total electricity demand in TWh_{el} after -"NP" and (e-Highway 2050, 2014)-X7.

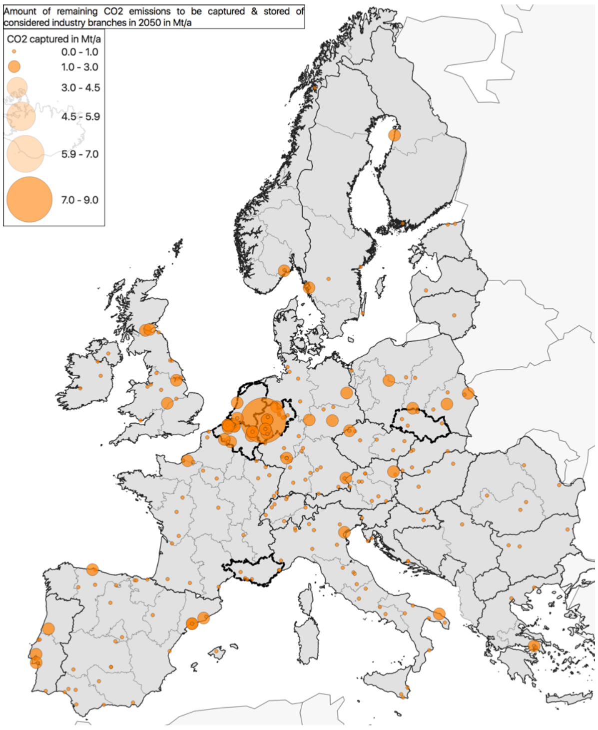


Figure 3. Regional distribution of the remaining CO_2 emissions in 2050 after the ME-Scenario "CCS".

France is changing from a slightly covered region (+1.5 TWh_{el}) to a significantly under-covered region (-18.8 TWh_{el}). A particularly strong deterioration of the electricity balance in 2050 occurs in the focus region BENELUX+NRW. Due to the high consumption densities in the other sectors, this region will already have to compensate for a strong under-coverage of about minus 244 TWh_{el}/a in total. Industrial decarbonisation according to the NP scenario will increase this significantly to minus 325 TWh_{el}/a (without H_2 production) or minus 467 TWh_{el}/a (with H_2 production). It would thus account for around 40 % of the total current (as of 2018) electricity generation in the region or exceed that of the countries of Belgium and the Netherlands together by 70 %. This poses a considerable challenge for the future transport of the required electricity to the region, especially since, unlike in the other two focus regions, the neighbouring regions would no longer have a sufficiently high RE potential to compensate. This suggests that good solutions are better found in the EU interconnected system than in regional or national stand-alone projects.

As can be seen in Figure 2, the region around Belgium, the Netherlands and North Rhine-Westphalia is also particularly relevant with regard to CCS. Of the 235 Mt CO_2, which will have to be captured in Europe and stored underground annually as of 2050 according to the "carbon capture pathway" in (Material Economics, 2019), 32.1 Mt or almost 14 % are concentrated here. But also southern Poland faces the challenge of addressing 9.3 Mt CO_2/a by CCS (~4 % of the total European 235 Mt/a), mainly due to its steel sites. Southern France, whose selection was more strongly driven by the electricity/H_2 consideration, has relatively low remaining emissions of 4 Mt CO_2/a as of 2050 (~2 % of the total European 235 Mt/a).

Hot-spot region North-West Europe

INDUSTRIAL STRUCTURE IN NORTH-WEST EUROPE TODAY

The focal region "North-West Europe" at first consists of the Netherlands with a high density of heavy industry in the province of South Holland around the Rotterdam harbour with refineries and petrochemical industry (cf. Figure 4). In the immediate vicinity is the Flemish heavy industry cluster around the port of Antwerp – another petrochemical cluster – and the steel plant at Ghent in Belgium. The third corner of this heavy industry cluster is the Rhine-Ruhr area, which is located in the West of the German federal state North Rhine-Westphalia. The Rhine-Ruhr area comprises a petrochemical cluster around Cologne and another around Gelsenkirchen. Duisburg is the spot in Europe with the highest crude steel production.

In between these corners there are other major petrochemical sites e.g. at Beringen (Belgium) and Geleen (Netherlands). Taking that altogether the region is unique within the EU in regard to the density of heavy industry and the linking infrastructure as well as in regard to the energy requirements of industry. All in all this region comprises almost 50 % of the EU's petrochemical production and about a quarter of European primary steel production.

INFRASTRUCTURE FOR INDUSTRIAL ENERGY DEMAND IN NORTH-WEST EUROPE 2050

Energy demand and generation potentials

The industrial electricity demands of the considered sectors in the region 2050 (incl. steam by Power-to-Heat but without electricity for hydrogen) rises from 28 TWh/a to 147 TWh/a. These numbers result from analyses based on the scenario "new processes" (Material Economics, 2019), which is the scenario with the highest additional electricity demand. The production of high-value chemicals, electric-arc furnaces, clinker ovens and production of chlorine are the most prominent electricity consumers in the decarbonised industry.

These demands result in an additional necessary electricity transport capacity of 15 GW, when this extra load is assumed to be close to baseload (8,000 full load hours). On top of that, decarbonised industry will cause a significant demand for hydrogen, especially for high value chemicals, direct reduced iron and ammonia production. This demand is expected to be up to 106 TWh_{th} (35,333 Mio Nm^3), which results in 141 TWh electricity needed to produce that hydrogen at an assumed electrolysers' efficiency of 75 % (which is a rather optimistic assessment). This would result in an additional electricity transmission capacity of 18 GW.

In addition to these industrial demands, hydrogen will most likely also be needed in other sectors, e.g. for transport or heat. These demands are not considered here, but must be taken into account in the design of energy infrastructures.

The spatial distribution of the electricity and hydrogen demands for decarbonised industry is shown in Figure 3 on the left side. The right picture in Figure 3 shows the technical potentials for generating renewable electricity, which remains according to the study (e-Highway 2050, 2014). In the region of Netherlands, Belgium and North-Rhine Westphalia, this potential is 40 TWh in sum. This illustrates the fact that the available potential in the region is not sufficient to meet the additional demands and that further energy infrastructures are necessary.

Storylines for energy infrastructures

For both electricity and hydrogen, different infrastructure storylines were prior to the regional workshop developed, which then have been discussed and evaluated there. These storylines are rather prototypical options that show the range of possible infrastructure solutions.

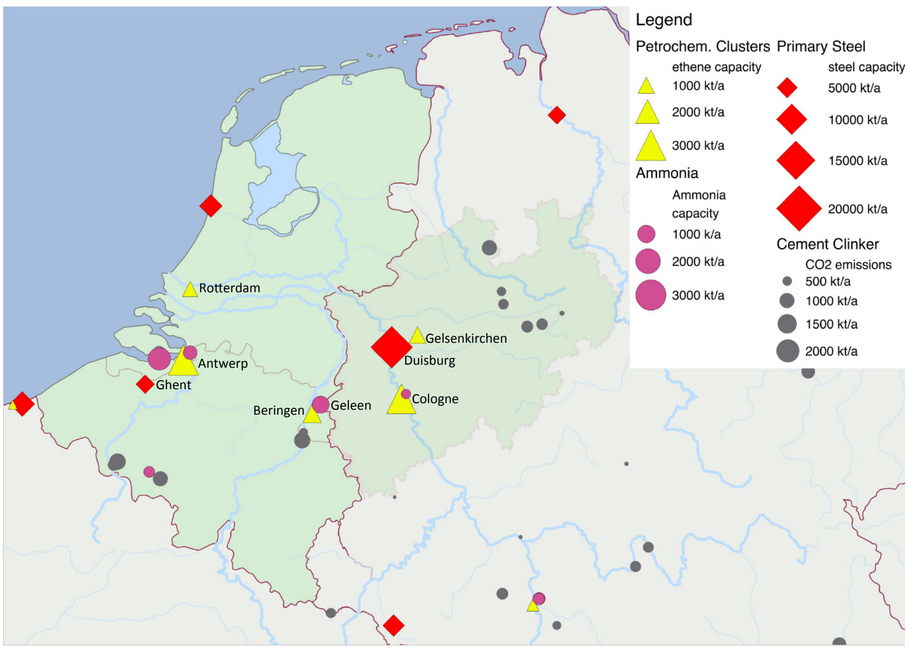
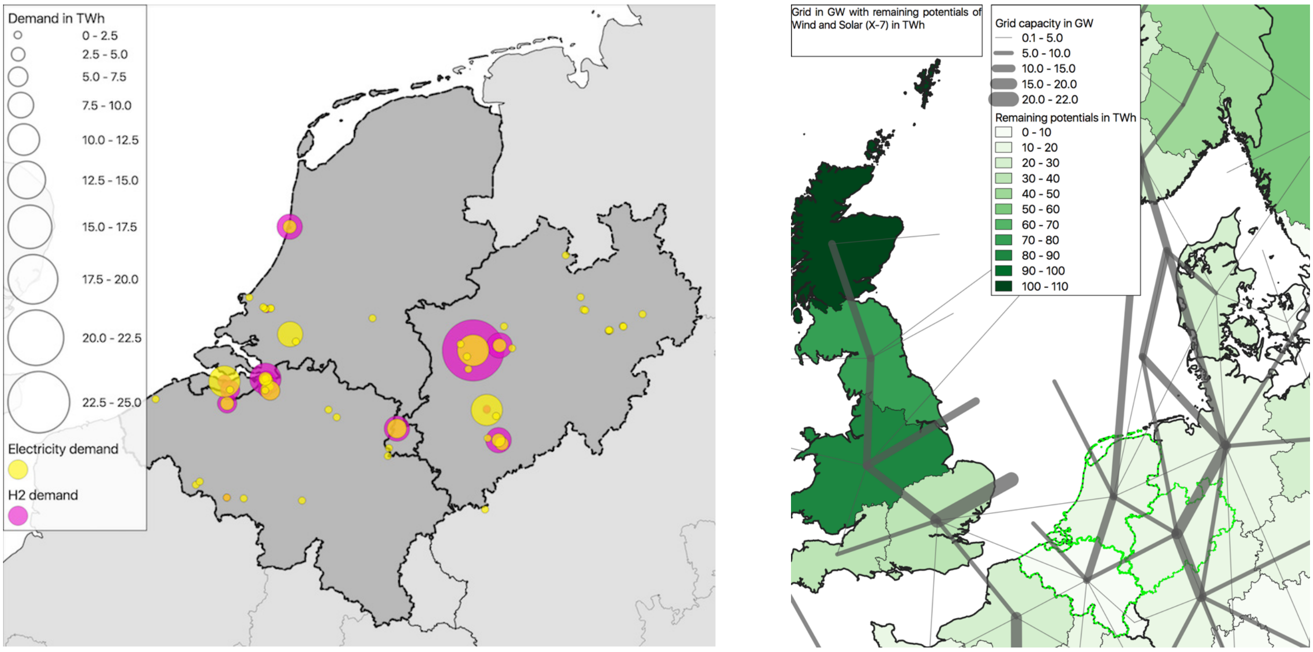


Figure 4. Production capacities at sites for steel and chemicals and CO_2 emissions at sites of cement production.



(a) (b)

Figure 5. (a) Electricity and hydrogen demand at sites in TWh. (b) Remaining renewable electricity potentials according to underlying scenario in the surrounding regions. Offshore potentials are assigned to the according bordering regions.

Storyline Electricity 1: import from northern Europe (Scandinavia, UK)

The study (e-Highway 2050, 2014) already assumes an expansion of the capacities to Scandinavia and the United Kingdom. In addition, another 15 GW of transmission capacity are necessary for decarbonised industry (without electricity for hydrogen). These additional transport capacities would need to strengthen the connection between North-Western Europe and Norway, to connect offshore wind parks in the North Sea, especially to the large potentials that belong to UK territory, and to enhance the connection between Germany, the Netherlands and Belgium.

Storyline Electricity 2: import from MENA

Another possible source of imports could be the MENA (Middle East North Africa) region. There are large renewable potentials, especially the resources of solar, but also of wind at the coasts are very high. If this potential is to be tapped for use in Europe, the local interests and needs of the MENA region must of course be taken into account. An exemplary import route could be to transport electricity, which is generated in Algeria, via eastern France to North-West Europe.

Storyline Hydrogen 1: generate hydrogen at site, transport electricity

There is a limited number of industrial sites which are assumed to have a need for hydrogen in the future (see Figure 4), especially the steel sites at Duisburg, Ijmuiden and Ghent as well as several sites for production of high value chemicals and ammonia. These hydrogen demands could be covered locally, with electrolysers located directly at the sites. In this case, electricity would have to be transported there. The overall hydrogen demand for decarbonised industry is 106 TWh (33 TWh Belgium, 29 TWh the Netherlands, 44 TWh NRW), which results in an overall electricity demand of 141 TWh. If these are assumed to be close to baseload (8,000 full load hours), this results in 18 GW of electrolysers' capacity and also of additional electricity transmission lines (6 GW to Belgium, 5 GW to the Netherlands, 7 GW to NRW). If electrolysers are to be used more flexibly, e.g. at 4,000 full load hours, the necessary capacity would double accordingly.

Storyline Hydrogen 2: central electrolysis to supply Belgium, the Netherlands and North Rhine-Westphalia

Another possibility is to produce hydrogen in one suited spot instead of decentralised generation at site. That spot would need to be connected to a strong electricity grid. From there on, hydrogen could be transported via a hydrogen grid. The necessary hydrogen grid could either consist of newly built pipelines, or parts of the natural gas grid could be repurposed (e.g. the grid for low-grade gas which will not be utilised in the future), or both strategies could be combined. There is a good spatial correlation between the possible industrial hydrogen demands and the existing natural gas grid.

Storyline Hydrogen 3: import hydrogen

A possible future hydrogen grid could not only be fed by central electrolysers, but also by hydrogen imports. The region under consideration here (Belgium, the Netherlands, NRW) is a hydrogen load focus, but there are further hydrogen demands in the surrounding areas. More than 50 % of the expected European hydrogen demand occur in the observed region and its surrounding clusters (158 TWh/a, 567 PJ/a). Therefore, hydrogen imports even over long distances could be worthwhile. Hydrogen could be produced in regions with high potentials for renewable electricity, for example in Norway or North Africa. Hydrogen could be transported via ship or via pipeline. A pipeline to cover the demand in the region of Belgium, Nether-

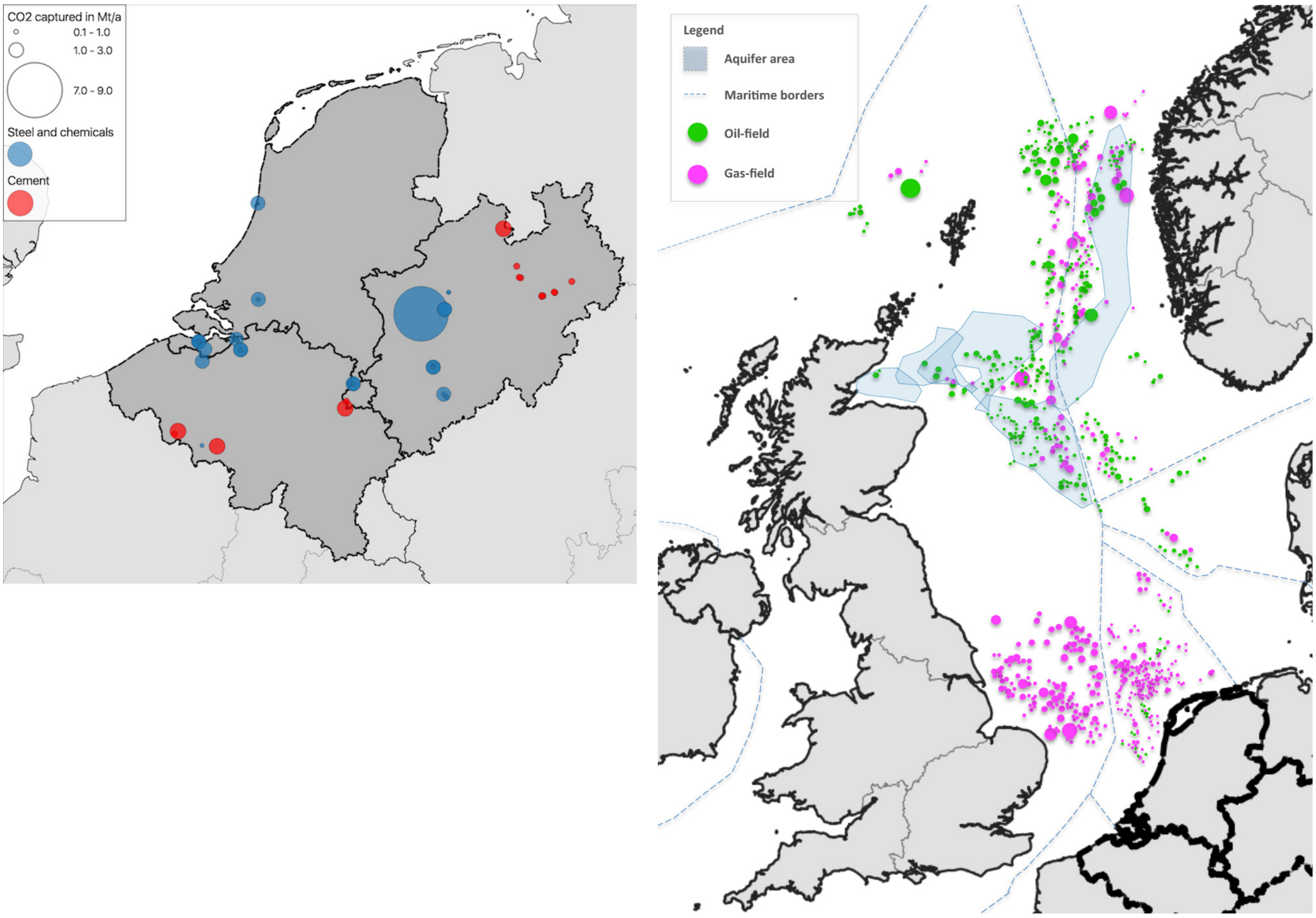


Figure 6. Sites and potential CCS demands of considered industry in Mt/a as of 2050 in CCS-intensive scenario (left). Offshore hydrocarbon fields in North-West-Europe, serving as potential future storage facilities (right). Source left: own graph based on own calculations and on (Material Economics, 2019). Source right: own graph based on (NLOG, 2020; NPD, 2020; OGA, 2020).

lands and NRW would need to have a diameter of 1.2 m; in case of transport by ship, about 320 shipments per year would be necessary[2]. To supply the region and the surrounding clusters, 1.5 m diameter or 475 shipments would be necessary.

INFRASTRUCTURE FOR INDUSTRIAL CCS IN NORTH-WEST EUROPE 2050

Industrial carbon emissions and possible sinks

CCS is required in all decarbonisation strategies for heavy industry, at least 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 vary considerably. This results in a bandwidth of 6.1 to 32.1 Mt CO_2/a, which is to be captured in North-West Europe and stored underground, as of 2050 (own calculation based on the scenarios in (Material Economics, 2019)). Although the volume differs accordingly, the emissions to be managed generally occur at a large number of locations (see left of Figure 6). 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 0.7 Mt CO_2/a (compared to 2.7 Mt CO_2/a for steel sites; average regional values). 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, 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 in the North-Sea promise comprehensive potential at an aggregated (national) level, but regional storage capacities tend to be small and diffusely distributed (see right of Figure 6). The Dutch offshore hydrocarbon fields serve as an example here, whose total effective storage capacity amounts to ~900 Mt CO_2, but is distributed over up to 150 fields (NLOG, 2019).

Storylines for industrial CCS infrastructure

Prior to the workshop, three distinct storylines for the development of a possible CCS infrastructure in the region of North-West Europe were designed. The aim was to discuss these prototypical solutions with local experts in order to learn more about influencing factors, to explore the strengths and weaknesses of the respective strategies and to broaden the debate beyond purely cost-related aspects. In the following, these storylines are briefly presented.

2. Assumptions: 10,000 t per shipment according to (Sonal Singh et al., 2015); pipeline pressure 100 bar, velocity 10 m/s.

Storyline 1: joint strategy – joint usage of the Dutch storage sites
Industrial players from the Netherlands, Belgium and North Rhine-Westphalia (NRW) jointly use the Dutch CO_2 offshore storage capacities. The port of Rotterdam serves as a central CCS hub, from where the CO_2 is transported to depleted hydrocarbon fields off the Dutch coast. At some sites, the CO_2 needs to be bundled via pipelines (especially for the more scattered cement plants in the hinterland) before it is transported to Rotterdam, either via inland shipping on the river Rhine, or by a central pipeline. This makes particular sense for the NRW sites, which can establish and use a common transport infrastructure for large parts of the route. As the effective capacities of the Dutch gas fields (~900 Mt CO_2) will suffice for around 25 years (if used by all three countries and considering the 2050 capture demand of 32.1 Mt/a), this is only a medium term solution (NLOG, 2019). In the long term, there will be a joint move towards the large storage capacities further up the North Sea, e.g. to Norway with its effective storage potentials of ~21,000 Mt CO_2 (Viebahn et al., 2010).

Storyline 2: semi-individual strategy – exclusive use of the Dutch storage sites by the Netherlands, Belgium and NRW move to Norway
The Netherlands exclusively uses its local hydrocarbon fields for CCS, while Belgium and NRW transport their captured CO_2 to Norway right from the start. There are still opportunities for cooperation between the countries in the field of infrastructure development, as they both continue to use the port of Rotterdam as their joint CCS hub.

Storyline 3: individual strategy
This strategy was intended to illustrate possible effects if the steel and chemical sites in NRW decide against CCS. As the cement plants currently have no foreseeable technological alternative for their process-related CO_2 emissions, they continue to depend on CCS, but will now choose the shortest route to the coast by pipeline and set up their own CCS hub (for the case of NRW, in Wilhelmshaven), from where the CO_2 is shipped to Norway. Belgium also acts independently and transports the captured CO_2 to Norway via Antwerp. The Netherlands continues to use its local hydrocarbon fields. This individual strategy could also be seen as a more national, unilateral approach.

Hot spot region southern France

The Rhône delta region is one of the typical coastal industrial clusters in Europe that have been developed during the 1960s and 1970s. With Europe becoming more and more an importer of resources like crude oil, iron ore and coking coal the aim was to build up new conglomerates immediately at the sea with an easy and cheap access to the world markets. Other clusters of this type are Dunkerque in Northern France and Tarragona in Spain or Brindisi and Taranto in Italy. Although the Rhône delta region has a petrochemical "hinterland" it can be seen as a prototype, at least for the other Mediterranean port regions with a similar access to renewable energies or CO_2 storage options. Results for this region can thus be transferred to some extent to the other clusters of the same type.

In regard to petrochemicals the region has three major sites at Lavera, Berre l'Etang and Fos-sur-Mer. ArcelorMittal's primary steel plant is located at Fos as well. In the new processes scenario, there is an electricity demand of 6 TWh in the chemical industry which is partly due to existing electricity-"captive" processes like chlorine electrolysis, partly due to new demands, e.g. for the supply of high-temperature heat in in the production chain for PVC, which is today delivered by natural gas. Electricity demand of the steel industry is due to the prospectively established DRI-Electric arc furnace (EAF) route, where iron ore is reduced to direct reduced iron (DRI) by the means of hydrogen and smelted afterwards in an EAF. Electricity is required to operate the electric arc furnaces and also for the supply of heat in the production of DRI (Material Economics, 2019). Depending on the decarbonisation strategy, the demand for industrial CCS within this region varies between 0.3 and 4 Mt CO_2/a as of 2050.

The storylines in Table 1 have been developed for the hot spot region of southern France.

Hot spot region southern Poland

The core of heavy industry in the region of southern Poland is around the Upper Silesian coal basin. This is the EU's only remaining region where coking coal is mined. Coking coal is the crucial resource for the production of primary steel in the conventional blast furnace/basic oxygen furnace route. For this reason the original hypothesis for the region was that the conversion process to hydrogen based DRI and processing in an electric arc furnace could take more time here.

In order to achieve climate neutrality CCS has to be used instead. Deviating from the methodology used for the other technologies and sectors where we assumed an equal technology mix at each site, we assumed for steel that CCS would be mainly used in Poland, the Czech Republic and Slovakia. This is due to the coking coal resources nearby and the scepticism towards natural gas imports in these countries, which would be required in a transition phase as reducing agent in the DRI plants.

Total electricity demand by new applications amounts to 6 TWh in the region. Steam and hydrogen use are much smaller and are limited to the two ammonia plants in the region. The CO_2 volume to be collected from five different sites is 5.8 Mt/a, with two big sources in the steel industry, one big cement plant and two smaller ones. One of the two smaller cement plants is very close to the bigger one (Cementownia Gorazdze), the other smaller one is located further north and quite remote from the other sources.

The "CCS-first assumption" was challenged during the stakeholder workshop. It has thus to be stated that hydrogen demands could be considerably higher in the region and CO_2 volumes to be stored could be lower respectively (1.6 Mt/a compared to 5.8 Mt/a).

The storylines in Table 2 have been developed for the hot spot region of southern Poland.

Conclusions & recommendations

Decarbonising the materials processing industries is directly linked to the conversion of the European energy system towards renewable sources. Both transformations are interlinked and interdependent. Industry decarbonisation will need huge amounts of green energy and feedstock, which requires a respective generation as well as an expansion of infrastructures.

Table 1. Infrastructure storylines for southern France.

Electricity	(1) Electricity generation in the region
	(2) Import electricity via an enhancement of the national transmission grid
	(3) Electricity import via DC-cable from North Africa
Hydrogen	(1) Generate hydrogen at site
	(2) Transport hydrogen via pipelines from north-western France
	(3) Import hydrogen from the MENA region
CCS	(1) Storage in the North Sea, particularly Norway
	(2) Storage in North Africa, particularly Algeria
	(3) Onshore storage in southwest France
	(4) Storage in the Mediterranean Sea

Table 2. Infrastructure storylines for southern Poland.

Electricity & Hydrogen	(1) Local generation of electricity and hydrogen
	(2) Import electricity and convert to hydrogen at site
	(3) Import electricity and hydrogen (a) from national sources, (b) from international sources
CCS	(1) International strategy – offshore storage in the North Sea, particularly Norway
	(2) National strategy – offshore storage in the Baltic Sea
	(3) National strategy – onshore storage in Poland

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.

ELECTRICITY INFRASTRUCTURE

Current European plans to expand the electricity grids (TYNDP) underestimate the need for expansion, because they do not reflect the necessary decarbonisation of heavy industry in a sufficiently differentiated and ambitious manner. This results in an underestimation of electricity consumption increase compared to what is actually needed when taking into account deep decarbonisation of heavy industries. That is why the scenario framework for European network planning (TYNDP) should already be expanded in the next version to include various industrial decarbonisation strategies with different levels of electricity intensity.

The challenges and potential solutions for the electricity grid vary greatly from region to region, with options tending to be sought first in the individual regional or geographical environment. However, the long-term challenges, especially the spatially concentrated increases in demand in a few core industrial regions, exceed the regional renewable solution potentials. Therefore, the design of electricity grids for comprehensive decarbonisation should be coordinated on a European-wide basis, with particular attention being paid to international energy partnerships with for example North Africa as well as the UK.

GAS AND HYDROGEN INFRASTRUCTURE

The future industrial hydrogen demand in the regions under consideration is generated in good spatial correlation to the existing gas networks. This neighbourhood of industry and gas grids is an excellent prerequisite for the adaptation and use of gas pipelines for the transport of hydrogen or hydrogen-rich gases to supply the decarbonised industry. This is especially true for multiple, parallel pipelines, which can then be successively adapted. That is why (similar to electricity) the scenario framework for the gas TYNDP should already be expanded soon to include various industrial decarbonisation strategies and the network planning should be reassessed under the premise of a switch to climate-neutral gases, especially hydrogen.

Coastal locations and especially ports are excellent starting points for decarbonisation of gas and industry, as they usually have differentiated infrastructures (or conditions) for the reception of offshore produced gases and gas imports as well as for the further transport of gases 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 gas grid. Industrial clusters and gas infrastructures near ports and coasts should therefore be given priority in the climate-neutral transformation.

CARBON CAPTURE AND STORAGE (CCS) INFRASTRUCTURE

With only a few exceptions, the results show a mismatch between CO_2 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. That is why successful demonstration projects are seen as particularly important and as needed drivers for implementation.

To some extent, 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 is particularly 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 exists 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

CO_2 on a large scale. That is why CCS should be planned and supported exclusively and as a priority for truly "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, substitution possibilities in other sectors and in order to prevent lock-in effects on other potential users and possible "keep coal alive" initiatives.

INDUSTRY TRANSFORMATION

The sooner industrial companies decide (backed by new politics) for a decarbonisation strategy (choice of technologies and energy sources) at their locations, the better and more foresightedly the necessary infrastructures can be adapted and expanded. Continued openness to changes in technology and energy sources increases the uncertainties and risks of inadequate solutions. Policymakers should therefore support strategic decisions in favour of robust climate-neutral developments, for example by introducing increasingly concrete guard rails and targets and, if necessary, supplement these by financial or regulatory support.

Strategies to improve resource efficiency and recycling management (like in the CE-scenario) should be demanded and promoted as a matter of priority, since these measurements are associated with a significantly lower increase in energy and resource demand than new electricity and gas-intensive or CCS strategies, which partly mitigates the challenges to ramp up green energy supply. In this way, they relieve the need to expand and reconstruct infrastructures.

Today's 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. Therefore it should be examined as a precautionary measure, whether and how new industrial sites, as well as those to be renewed, can be located better elsewhere (e.g. more in the vicinity of sweet spots) and, if necessary, which incentives should be created.

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