Project no. 723678

ñThe next Generation of Carbon for the Process Industryò

Coordination and Support Action

Theme [SPIRE 5] ï Potential use of CO_2 and non-conventional fossil natural resources in Europe as feedstock for the process industry

Deliverable *1.1*:

Map of relevant CO_2/CO containing gases

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1. Executive Summary

Carbon monoxide (CO_2) and carbon dioxide (CO) are formed from the combustion of carbon containing materials. The carbon in the gases can be used as a feedstock for the process industry replacing carbon from fossil sources. As we move into a more carbon constrained environment, the ability to re-use carbon molecules multiple times could become a key component in the drive to reduce carbon emissions and ensure the sustainability of the process industry. The identification of the most promising sources of these carbon emissions enables new and existing industries to identify symbiotic opportunities which could enhance deployment. The processes where CO_2 or CO can be used in the process industry rely technologically and economically on several factors, including the volume and purity of the source and its proximity to suitable infrastructure

The European Pollutant Release and Transfer Register (E-PRTR) is a Europe-wide register that provides key environmental data from industrial facilities in European Union Member States and in Iceland, Liechtenstein, Norway, Serbia and Switzerland. The register contains data reported annually by more than 30,000 industrial facilities covering 65 economic activities across Europe.

The current E-PRTR (2014) lists facilities with CO_2 emissions above 0.1 Mt per year; total emissions of CO_2 in Europe from these facilities amounted to 1,779 Mt in 2014. There are many facilities with emissions below 0.1 Mt per annum, but it is unlikely that capturing the emissions from these facilities for use in the process industry will be economically viable. The E-PRTR database shows that there is a wide range of CO_2 sources across Europe producing more than sufficient CO_2 emissions to meet the demand that could be utilised as a feedstock for the chemical industry. The major inhibiting factor in CO_2 capture from point sources is the energy required for the capture and separation processes. The energy needed will both affect the cost and environmental implications of the process. Therefore, targeting the most pure streams of CO_2 will keep energy requirements to a minimum, as smaller volumes of emitted gas will need to be processed to result in the same volume of purified CO_2 when compared with a more dilute source. Primary targets for sourcing CO_2 should focus on those sources with the highest concentration of CO_2, (Hydrogen production, natural gas processing, ethylene oxide manufacture and ammonia production) as the higher concentration of CO_2 reduces the cost of capture. However, larger volumes of CO_2 are available from the iron and steel industry and cement industries, albeit at lower CO_2 concentration. As industries look to decarbonise (particularly the iron and steel and cement sectors) there is an observed market pull to deploy CO_2 utilisation technologies to provide an economically beneficial method of reducing CO_2 emissions. As next-generation carbon capture technologies reach the market, other sources of CO_2 may become increasingly economically viable.

Carbon monoxide (CO) is produced if the combustion of carbon containing sources to CO_2 proceeds under a lack of oxygen resulting in an incomplete combustion reaction. Diffuse industrial CO emissions originate from internal combustion engines in urban areas and point sources from various industrial sectors release CO. CO emissions higher than 0.005 Mt have to be reported in the E-PRTR.

The total CO emission for all European countries in 2014 was 3.38 Mt. Germany, followed by UK, France, Spain and Poland were the main emitting countries. The main contributor to CO emissions is the metal sector which contributes 71% (2.40 Mt), followed by the construction sector at 11% (0.37 Mt), the chemical sector at 10% (0.34 Mt), and the energy sector at 6% (0.20 Mt). The main emissions within the metal sector come from the manufacture of basic steel and ferro-alloys accounting for 92% of the metal sector emissions (2.2 Mt).

The amount of CO emitted is not equivalent to the amount produced in a steel mill, much more is produced than is emitted. Typically, CO and other gas-by-products from integrated steel mills are either re-used in the steel production process for on-site heating processes or for electricity production, only a minor fraction is emitted. This means a large proportion of the electricity and steam required in the steel production process is produced from steel mill gases. However, it is now being considered whether converting this CO into carbon-based products would be more beneficial than using it for electricity or steam production. The potential amount of CO available could be higher by a factor of 12-20, if the CO which is currently used for electricity and stream production was also taken into account.

2. Introduction

CarbonNext's objective is to evaluate the potential of new carbon sources in Europe. The project primarily focuses on new sources of carbon to be used as a feedstock and secondarily the impact this will have on energy availability, price and emissions. The evaluation will include multiple alternative carbon sources: carbon dioxide, carbon monoxide and other non-conventional fossil sources such as shale gas, tar sands and coal bed methane. CarbonNext will map and evaluate these alternative carbon sources and investigate symbiotic value chains between industrial sectors - where can the emission of one industry become the feedstock of another?

The CarbonNext project will inform, as a basis for decision-making, Europe's SME's, large industry and policymakers with an enhanced understanding of the impact and opportunities for new sources of carbon for the processing industry.

Carbon dioxide (CO_2) and carbon monoxide (CO) can be considered as carbon source for the process industries replacing carbon from fossil sources. The processes where CO_2 or CO can be used in the process industry rely technologically and economically on several factors. One factor is the characteristic of CO_2/CO containing sources. The characteristics of different sources differ strongly. For the process industry it is important to identify sources with the needed volume and purity. Furthermore, the given infrastructure around the sources must be taken into account in order to estimate the potential of each source. A hierarchy of sources to be used in relation to the most promising CO_2/CO valorisation routes is necessary in order to optimize the integration of CO_2/CO into the value chain.

The present report contains maps with assembled data of available and potential CO_2- and CO-containing gases in Europe. The used data were collected from the European Pollutant Release and Transfer Register (E-PRTR)[1] database by the European Environment Agency (EEA). CO and CO_2 emissions were classified into 9 industrial sectors: *Chemicals*, *Construction*, *Energy*, *Food/Agriculture*, *Metal*, *Mining*, *Paper*, *Waste and Others*. The maps with information about the location, volumes, local infrastructure will be used to evaluate the potential of the use of CO_2 and CO in the future.

The collection of the data was approved through desk research and interaction with relevant industrial associations and independent experts.

[1] European Pollutant Release and Transfer Register, available at: http://prtr.ec.europa.eu/#/home

2.1 Objective

The objective of the deliverable is to analyse the availability in respect to location, volume and purity of carbon from CO_2 and CO flue gases. This report gives an overview on CO_2 and CO point sources in Europe. The information will help to estimate which sources are most suitable for processes where CO_2 or CO can be used for further processing in the process industry

Carbon Dioxide is formed from one atom of carbon covalently bonded to two atoms of oxygen and is naturally occurring in our atmosphere. Carbon dioxide (CO_2) is produced when carbon containing materials are burnt to create energy and hence, as our energy requirements increase the amounts in the atmosphere are increasing. CO_2 comprises 80% of greenhouse gases occurring in our atmosphere and these greenhouse gases contribute to global warming. It is a necessary part of the carbon cycle where plants use CO_2, light and water to create carbohydrate energy and oxygen.

Carbon monoxide is a common industrial hazard resulting from the incomplete burning of natural gas and other material containing carbon such as gasoline, kerosene, oil, propane, coal, or wood. Carbon monoxide consists of a carbon atom and a oxygen atom joined by a triple bond. Forges, blast furnaces and coke ovens produce CO, however, internal combustion engines are one of the most common sources of exposure in the workplace. CO is toxic to animals which use haemoglobin (including humans) when encountered in concentrations above about 35 ppm. In the atmosphere, it is spatially variable and short lived, having a role in the formation of ground-level ozone.

Carbon monoxide and carbon dioxide are formed from the combustion of carbon containing materials. The carbon in the gases can be used as a feedstock for the process industry. As we move into a more carbon constrained environment, the ability to re-use carbon molecules multiple times could become a key component in the drive to reduce carbon emissions and ensure the sustainability of the process industry. The identification of the most promising sources of these carbon emissions enables new and existing industries to identify symbiotic opportunities which could enhance deployment.

2.2 Methodology

2.2.1 Emissions Data

The European Pollutant Release and Transfer Register (E-PRTR)[2] is a compulsory Europe-wide register that provides key environmental data regarding pollutants from industrial facilities in European Union Member States and in Iceland, Liechtenstein, Norway, Serbia and Switzerland. The register contains data reported annually by more than 30,000 industrial facilities within 9 industrial sectors, covering 65 economic activities across Europe. A facility must report data annually to the E-PRTR if it exceeds certain set criteria thresholds, these are 0.1Mt/yr for CO_2 and higher than 0.005 Mt/yr for CO.

[2] European Pollutant Release and Transfer Register, available at: http://prtr.ec.europa.eu/#/home

Data is reported by the individual facilities to authorities in their respective countries which is then checked for quality before being reported to the European Commission and European Environmental Agency for compiling into the E-PRTR.

As the E-PRTR is the most comprehensive dataset of emissions from the industrial sector, the most recent data from the 2014 register has been extensively used in compiling this report.

2.2.2 Mapping of Infrastructure

Carbon sources located close to current process industries are highly desirable as this reduces the costs of transport pipelines and associated infrastructure. The major European chemical parks have been identified as prime locations with existing infrastructure (Table 1) which could be utilised for new process industries using non-conventional carbon sources. For this reason, each map of industrial sector carbon sources is plotted alongside the chemical parks to identify synergies.

Table 1. Major European chemical parks included in the mapping. Adapted from E-PRTR

Name	City	Country
Chemiepark Linz	Linz	Austria
Schwechat	Schwechat	Austria
INEOS Antwerp site	Antwerp	Belgium
Port Of Antwerp	Antwerp	Belgium
Tessenderloo	Tessenderloo	Belgium
Kohtla-Järve	Kohtla-Järve	Estonia
Kokkola Industrial Park	Kokkola	Finland
Porvoo	Porvoo	Finland
Chemparc, Aquitaine	Pau	France
Fos-Lavera-Berre	Fos sur Mer	France
Port Jérôme	Lillebonne, Notre Dame de Gravenchon	France
Port of Le Havre	Le Have, Port-Jérôme	France
Port of Rouen	Rouen	France
Agro-Chemie Park Piesteritz	Piesteritz	Germany
BASF Schwarzheide GmbH	Schwarzheide	Germany
BASF SE, Ludwigshafen	Ludwigshafen	Germany
Castrop-Rauxel	Castrop-Rauxel	Germany
ChemCoast Park Brunsbüttel	Brunsbüttel	Germany
ChemiePark Bitterfeld Wolfen	Bitterfeld Wolfen	Germany

Chemiepark Knapsack	Huerth	Germany
Chemie- und Industriepark Zeitz	Zeitz	Germany
Chempark Dormagen	Dormagen	Germany
Chempark Krefeld-Uerdingen	Krefeld-Uerdingen	Germany
Chempark Leverkusen Currenta	Leverkusen	Germany
GENDORF Chemical Park	Burgkirchen a.d.Alz	Germany
Industrial Park Dorsten-Marl	Dorsten	Germany
Industriepark Höchst	Frankfurt-Höchst	Germany
IndustriePark Lingen	Lingen	Germany
Industriepark Premnitz	Potsdam	Germany
Industriepark Schwarze Pumpe	Spremberg	Germany
Industriepark Solvay Rheinberg	Rheinberg	Germany
industriepark walsrode	Walsrode	Germany
InfraLeuna GmbH	Leuna	Germany
Krefeld-Uerdingen Currenta	Krefeld-Uerdingen	Germany
Marl Chemical Park	Marl	Germany
NUON Industriepark Oberbruch	Oberbruch	Germany
Schkopau	Schkopau	Germany
Schwedt/Oder PCK Raffinerie GmbH	Schwedt	Germany
Stade	Stade	Germany
Wolfgang Industrial Park	Hanau	Germany
Pétfürdö	Pétfürdö	Hungary
Hellisheiði ON-Power	Hengill	Iceland
Monksland	Monksland	Ireland
Porto Marghera	Porto Marghera	Italy
ś roda ś lŃska	ś roda	Poland
Turek	Turek	Poland
ZILS - Sines Industrial and Logistics Zone	Sines	Portugal
Stráģske Chemko	Stráģske	Slovakia
AEQT - Tarragona Chemical Cluster	Tarragona	Spain

Huelva	Huelva	Spain
Stenungsund	Stenungsund	Sweden
Infrapark Baselland	Muttenz	Switzerland
Solvay Ind.park	Bad Zurzach	Switzerland
Chemelot	Geleen	The Netherlands
Chemical Cluster Delfzijl	Delfzijl	The Netherlands
EMMTEC Industry & Business Park	Emmen	The Netherlands
Port of Amsterdam	Amsterdam	The Netherlands
Port of Rotterdam	Rotterdam	The Netherlands
Valuepark Terneuzen	Terneuzen	The Netherlands
AkzoNobel R&D centre Felling UK	Felling	United Kingdom
Grangemouth	Grangemouth	United Kingdom
Saltend Chemicals Parks	Hull	United Kingdom
Wilton International	Middlesbrough	United Kingdom

3. Potential CO_2 sources

3.1 Definition and context

Carbon Dioxide is formed from one atom of carbon covalently bonded to two atoms of oxygen and is naturally occurring in our atmosphere. It is a necessary part of the carbon cycle where plants use CO_2, light and water to create carbohydrate energy and oxygen by photosynthesis. Carbon dioxide is produced when fossil fuels are burnt to create energy and hence, as our energy requirements increase the amounts of CO_2 emitted in the atmosphere are increasing. CO_2 comprises 80 % of greenhouse gases occurring in our atmosphere and these greenhouse gases contribute to global warming.

CO_2 acts as a greenhouse gas as it adsorbs and re-emits some of the infrared radiation which is created when visible light hits the Earth, trapping it in the atmosphere and causing a warming effect. CO_2 and other greenhouse gases (GHGs) in the atmosphere are necessary to keep the Earth at a temperature to sustain life, but increasing accumulations of GHGs lead to an increased global warming effect.

If current trends of greenhouse gas emissions continue, it is predicted that global temperatures will rise by between 3.7^{o}C and 4.8^{o}C above pre-industrial levels by 2100[3]. There is general agreement with IPPC views that we should be aiming to limit warming to a maximum of 2^{o}C. In order to give at least a 50 % chance of achieving this target, cumulative global CO_2 emissions need to be limited to 1100 GT between 2010 and 2050[2,4]. This will necessitate a reduction of CO_2 emissions of just below 40 GT by 2050. There are several mechanisms needed to achieve this goal. Scenario modelling by the International Energy Agency[2] gives a number of mitigation options which are combined to reach the necessary targets. These include increasing renewable energy capacity, efficiency measures, expansion of nuclear energy generation and fitting carbon capture and storage units to existing emitters. These must be deployed in increasing capacity to curb emissions and Figure 1 shows the IEAõs model to achieve this. Another approach is to dramatically curtail the use of fossil fuels, rapidly switching energy production to low-carbon sources. McGlade and Ekins[5] state that to give at least a 50 % chance of a lower than 2^{o}C rise, over 80 % of global current coal reserves, 50 % of gas reserves and 33 % of oil reserves must not be used. Either of these approaches to reduce greenhouse gas emissions necessitate a step-chance in technology and policy commitment to achieve them.

[3] IPCC (2014). Mitigation of Climate Change. Climate Change 2014. Cambridge University Press

[4] Meinshausen, M., Meinshausen, N., Hare, W., Sarah C. B. Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., & Allen, M.R., Greenhouse-gas emission targets for limiting global warming to 2¿°C (2009) Nature 458, 1158-1162

[5] McGlade, C.; Ekins, P. (2015). Nature, 517, 187.

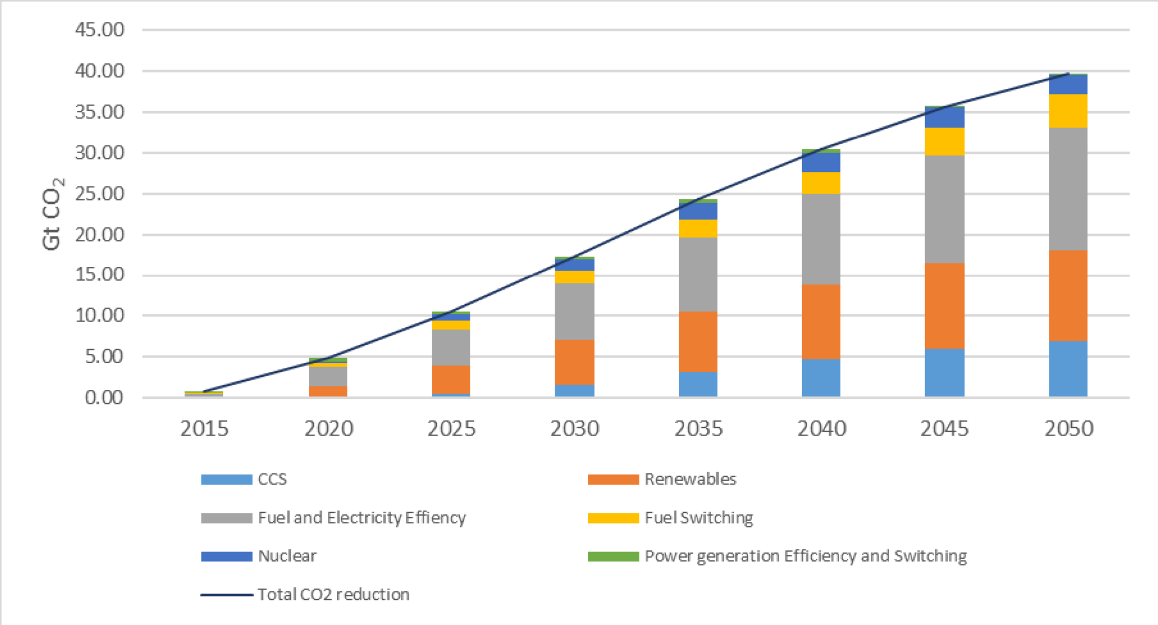

***Figure 1. World CO_2 reduction targets to meet the 2 °C Scenario (2DS) adapted from IEA*[2]**

EU emissions of CO_2 including aviation have been decreasing since 2006. Current annual emissions are in excess of 3500 million tonnes[6] (figure 2). European CO_2 emissions predominantly arise from the energy sector (figure 3), these emissions are related to point sources such as power plants and so are suitable for capture processes. The second largest emission category is the transport sector; these emissions from non-stationary sources can only be captured using technologies that take CO_2 from the air (called Direct Air Capture or DAC) once the CO_2 has entered the atmosphere. Industrial processes accounted for 8.5 % of the European CO_2 emissions in 2014. It is these emissions that are a key target for utilisation processes, as, although many industrial processes strive for emission reductions via efficiency measures, industrial processes can be complex to completely decarbonise. Therefore, pathways to reduced emissions via new technologies that also have an economic benefit are favourable.

[6] http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

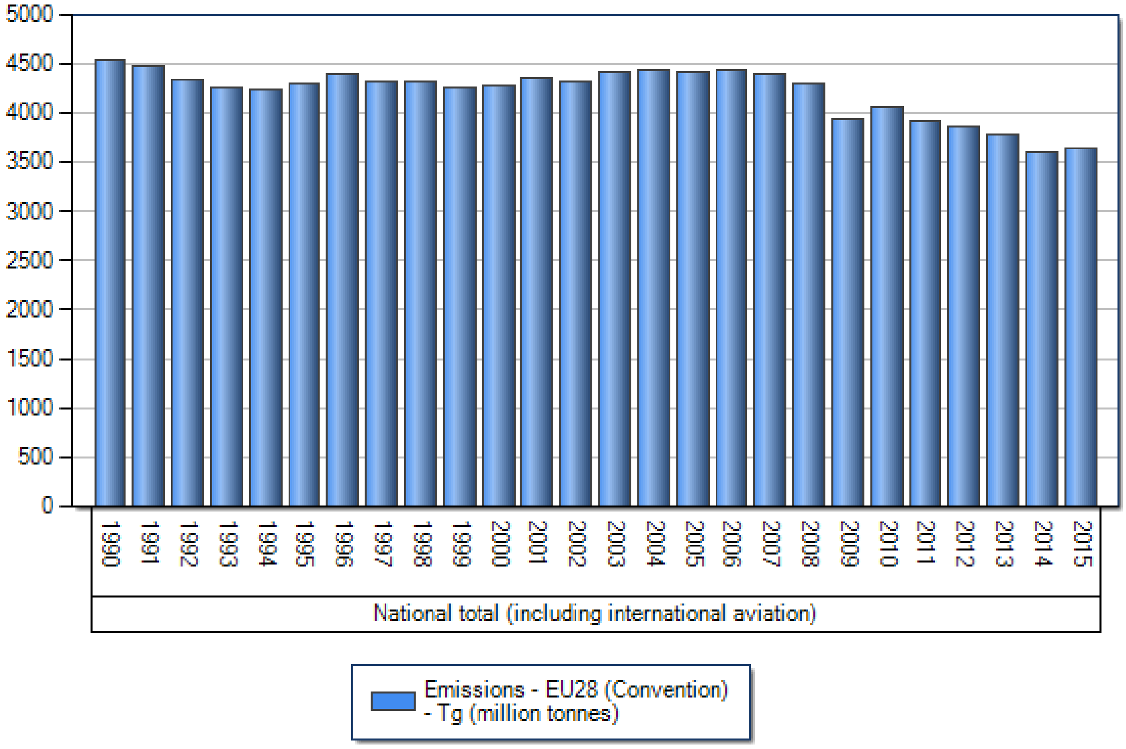

Figure 2. EU28 CO_2 emissions from 1990 to 2015. http://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

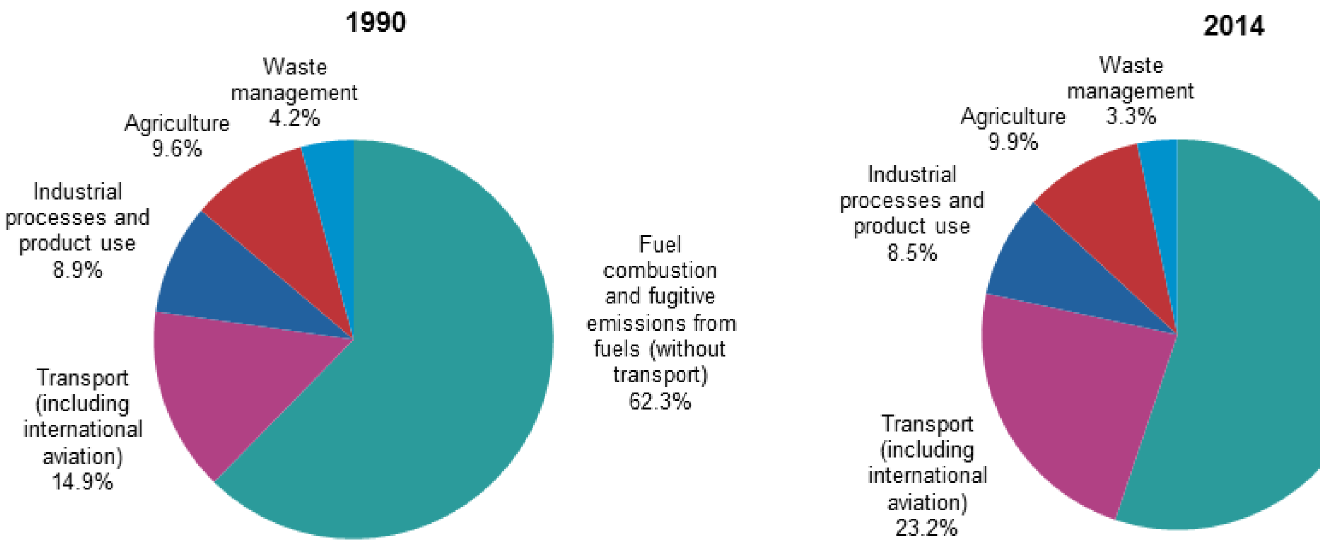

Figure 3. Greenhouse gas emissions, analysis by source sector, EU-28, 1990 and 2014 (percentage of total); Eurostat. www. http://ec.europa.eu/eurostat

If CO_2 emissions cannot be avoided via energy efficiency, process improvements and other techniques, other methods for reducing the amount of CO_2 entering the atmosphere are required such as carbon capture and storage or carbon dioxide utilisation (figure 4). Carbon Capture and Storage (CCS) is a process for capturing CO_2 from point sources and subsequently transporting it to a geological storage site where it is deposited for hundreds of years[7]. CCS is a key CO_2 mitigation technique with the IEA predicting that it will need to contribute to 1/6 of total CO_2 emission reductions by 2050 if we are to meet the Paris Accord. CCS is a distinct but linked technology to CO_2 utilisation. CCS is primarily a mitigation technique, whereas CO_2 utilisation uses CO_2 as source of carbon to produce new products. CO_2 utilisation can contribute to a circular economy, help facilitate the transition to renewable energy, provide new low-carbon routes in the process industry and contribute to decreasing emissions [8]; however in the short term CCS is expected to have a larger impact on emission targets than CCU.

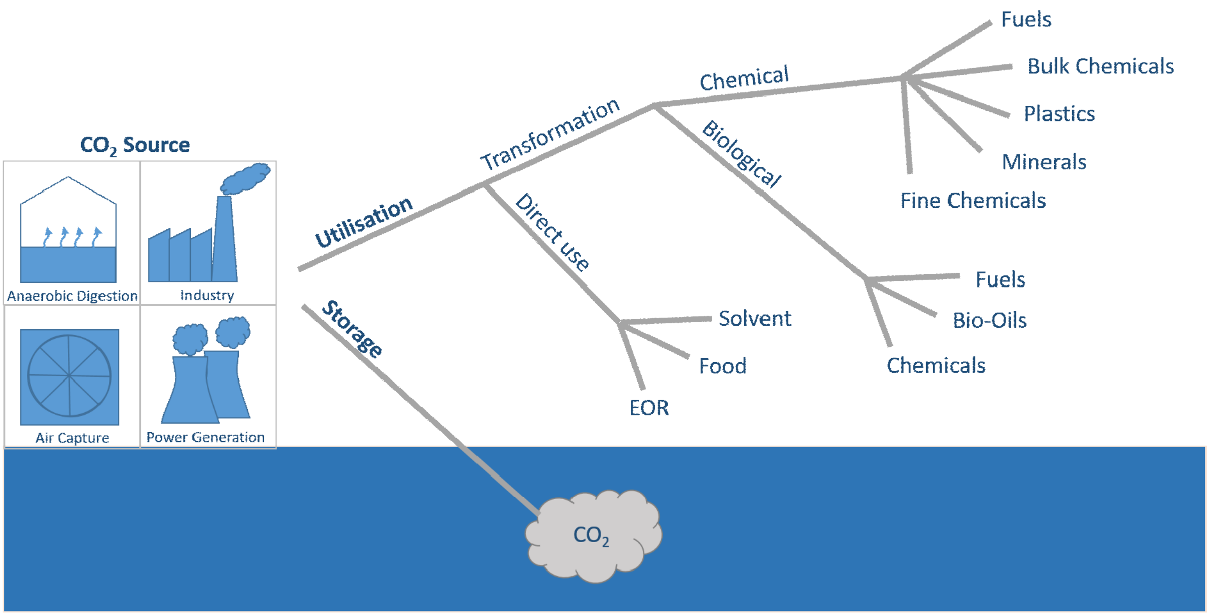

Figure 4. Possible routes for CO_2 emissions. CO2Chem, 2017

There has been an increased interest in the potential use of CO_2 as a carbon feedstock for the process industry in recent years. CO_2 utilisation technologies take CO_2 as a carbon source and

[7] Intergovernmental Panel on Climate Change (2005). IPCC Carbon dioxide capture and storage. Metz, B., Davidson, O., de Coninck, H.C., Loos, M., Meyer, L. A. (eds.), IPCC Special Report. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge and New York

[8] A Vision for Smart CO2 Transformation in Europe: Using CO2 as a resource. SCOT project (2015). Available at: http://www.scotproject.org/images/SCOT%20Vision.pdf

convert it via physical, chemical or biological processes into carbon-based products. CO_2 utilisation can be viewed as a new synthetic carbon cycle, which uses and releases CO_2 back to the atmosphere or sequesters it in products. CO_2 utilisation technologies are seen as a means of helping to mitigate climate change, while simultaneously creating useful, saleable products that can potentially offset the costs associated with the capture and/conversion processes[9]. Furthermore, re-use of CO_2 can help to broaden the raw material base for the process industry transitioning to a greater level of symbiosis between sectors and enabling a move away from reliance on fossil feedstocks. CO_2 utilisation is a demonstration of the principle of the circular economy where by one industryʼs waste becomes anotherʼs feedstock, returning emitted carbon (in the form of CO_2) into the process cycle to be used multiple times. CO_2 utilisation can help develop a sustainable process industry encompassing industrial innovation based on symbiotic, green practices.

The quantity of CO_2 that can be utilised varies between different uses. Therefore, a variety of sources can be used depending on the application. In general, processes to produce fuels require the most CO_2 but also have the largest energy demand, whereas processes to produce plastics and fine chemicals have a lower CO_2 demand. Matching supply and demand is key to ensure the economic viability of the process. Predicting the amount of CO_2 that can be utilized globally is difficult, several studies have been conducted that give a range of between 300 Mt/y in 2016[10] to 7 Gt/y by 2030[11], however the commonly accepted view is a range of 1.5 -2 Gt/yr for future consumption[12,13,14.] As Europe's share of GDP is about 23% and its share of chemical production is 29% it has been estimated that around 25% of global CO_2 utilisation could take place in Europe, i.e.up to 500 Mt/yr[15].

3.2 Mapping sources (current status)

The current E-PRTR lists facilities with CO_2 emissions above 0.1 Mt per year in 2014; total emissions of CO_2 in Europe from these facilities amounted to 1,779 Mtin 2014. There are many facilities with emissions below 0.1 Mt per annum, but it is unlikely that capturing the emissions from these facilities for use in the process industry will be economically viable and therefore these smaller emitters have

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[9] Styring, P.; Quadrelli, E.A.; Armstrong, A. (2015) *Carbon Dioxide Utilisation: Closing the Carbon Cycle*, Eds. Styring, P.; Quadrelli, E.A.; Armstrong, K., Elsevier, Amsterdam

[10] Aresta, M.; Dibenedetto, A.; Angelini, A.; (2013). The changing paradigm in CO2 utilization, Journal of CO2 Utilization, 3–4, 65–73

[11] Global CO2 Initative, 2016

[12] DECHEMA e.V., Verband der Chemischen Industrie(VCI), Position Paper. Utilisation and Storage of CO2. 2009; http://www.dechema. de/dechema_media/Positionspapier_co2_englisch-p-2965.pdf

[13] Centi, G.; Perathoner, S. CO2-based energy vectors for the storage of solar energy. Greenhouse Gases: Sci. Technol. 2011, 1, 21–35.

[14] Armstrong, K., & Styring, P. (2015). Assessing the Potential of Utilization and Storage Strategies for Post-Combustion CO2 Emissions Reduction. Frontiers in Energy Research, 3(March), 1–9. https://doi.org/10.3389/fenrg.2015.00008

[15] Assen, N. von der, Müller, L. J., Steingrube, A., Voll, P., & Bardow, A. (2016). Selecting CO2 Sources for CO2 Utilization by Environmental-Merit-Order Curves. Environmental Science and Technology. https://doi.org/10.1021/acs.est.5b03474

been discounted for this work. The E-PRTR data for CO_2 has been categorised based on industrial sector to identify emission sources and then mapped to show the locations of CO_2 emitters who emit more than 0.1 Mt of CO_2 annually (Table 2).

Table 2. Sources of CO_2 emission in the EU categorised by sector. Adapted from E-PRTR

Sector	CO_2 emissions in 2014[M tonnes]
Chemicals	245.1
Construction (including manufacture of cement)	144.1
Energy	1,065.5
Food and Agriculture	5.9
Metal (including iron and steel industry)	166.0
Mining	7.1
Paper	77.1
Waste	55.5
Other	13.1

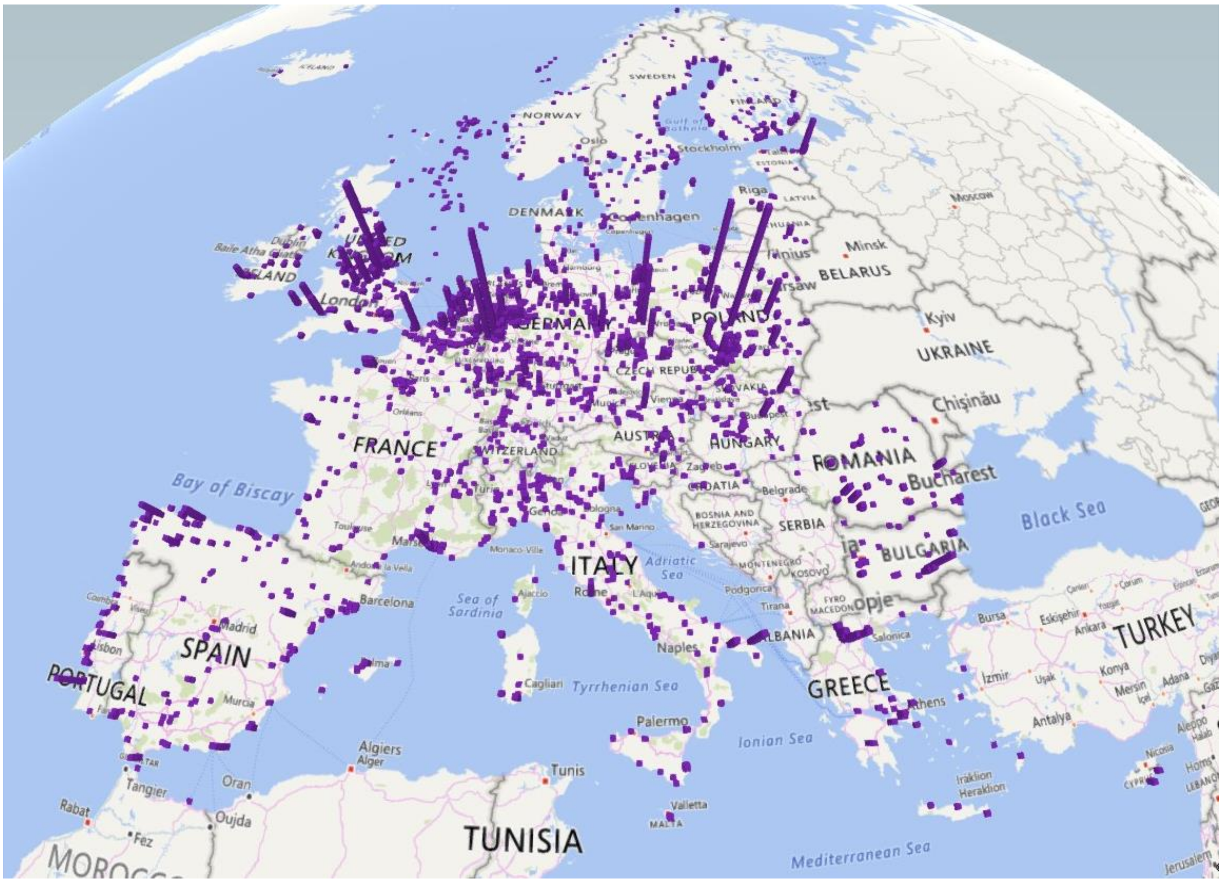

Figure 5. Map of location of sources of CO_2 emission in the EU. Adapted from E-PRTR.

The E-PRTR database shows that there is a wide range of CO_2 sources across Europe (figure 5) producing more than sufficient CO_2 emissions to meet the demand that could be utilised as a feedstock for the chemical industry. The most prevalent emitter of CO_2 are power plants as is shown by Table 3 - the top 20 emitters of CO_2 in the EU. It should be noted that the current available E-PRTR data is from 2014 and whilst this is the most up-to-date available, some coal-fired power plants have closed since then.

Table 3. Top 20 emitters of CO_2 in EU. Adapted from E-PRTR.

CO_2 Emission [Mt/yr]	Name of facility	Location	Country	Main Activity
8.96	U.S.Steel s.r.o.	Koġice	Slovakia	Manufacture of basic iron and steel and of ferro-alloys
9.19	Longannet Power Station	Kincardine	United Kingdom	Production of electricity
9.21	West Burton Power Station	Retford	United Kingdom	Production of electricity
9.22	E.On Uk Plc, Ratcliffe-On-Soar Power Station	Nottingham	United Kingdom	Production of electricity
9.68	Eesti Energia Narva Elektrijaamad AS, Eesti elektrijaam	Auvere küla, Vaivara vald	Estonia	Production of electricity
10.3	"TETs Maritsa iztok 2" EAD	Kovachevo	Bulgaria	Production of electricity
10.9	Enel Produzione SpA - Centrale di Torrevaldaliga Nord	CIVITAVECCHIA	Italy	Production of electricity
11.4	Elektrownia "KOZIENICE" S.A.	świerŨe Górne	Poland	Production of electricity
11.7	Kraftwerk Schwarze Pumpe	Spremberg	Germany	Production of electricity
11.8	PPC S.A. SES AGIOY DHMHTRIOY	AGIOS DIMITRIOS, ELLISPONTOS	Greece	Production of electricity
11.9	Vattenfall Europe Generation AG Kraftwerk Lippendorf	Böhlen	Germany	Production of electricity
12	CENTRALE TERMOELETTRICA Federico II (BR SUD)	BRINDISI	Italy	Production of electricity
18.7	Kraftwerk Boxberg	Boxberg/O.L.	Germany	Production of electricity

18.8	RWE Power AG	Eschweiler	Germany	Production of electricity
23.7	Drax Power Station	Selby	United Kingdom	Production of electricity
24.5	Vattenfall Europe Generation AG Kraftwerk Jänschwalde	Peitz	Germany	Production of electricity
24.9	Elektrownia PŃtnów II Sp.z o.o.	Konin	Poland	Production of electricity
27.2	RWE Power AG Kraftwerk Niederaußem	Bergheim	Germany	Production of electricity
32.4	RWE Power AG Kraftwerk Neurath	Grevenbroich	Germany	Production of electricity
36.8	PGE Górnictwo i Energetyka Konwencjonalna S.A., Oddziağ Elektrownia Beğchatów	Rogowiec	Poland	Production of electricity

There are in excess of 2000 point source emitters of CO_2 in Europe. Thus, it is necessary to identify the most promising sources of CO_2 that could serve the process industry in the near term. Two recent research papers have assessed sources of CO_2 for CO_2 utilisation to ascertain the best sources for CO_2 utilisation. The two works use different methodology to select the most promising sources. Naims, 2016[16] assessment is based on economics whilst Von der Assen *et al*, 2016[17] is based on an environmental merit order. Both studies used extensive literature searches to ascertain benchmarked data for best practice scenarios for CO_2 emitters. Naims compared the cost of CO_2 captured and CO_2 avoided to create a merit order, whilst, Von der Assen *et al.* created environmental order of merit curves based on environmental impacts as defined by comparative life cycle analysis (LCA) studies. The two assessments do overlap although both do not cover exactly the same CO_2 sources; for example, Naims, 2016 does not analyse retrofit post-combustion onto power generation, only pre-combustion and neither does it consider fermentation processes within Europe.

Both papers conclude that the purest CO_2 sources should be targeted first:

Å Hydrogen production
Å Gas processing
Å Ethylene oxide manufacture
Å Ammonia production

[16] Naims, H. (2016). Economics of carbon dioxide capture and utilizationð a supply and demand perspective. Environmental Science and Pollution Research, 23(22), 22226ï 22241. https://doi.org/10.1007/s11356-016-6810-2

[17] Assen, N. von der, Müller, L. J., Steingrube, A., Voll, P., & Bardow, A. (2016). Selecting CO2 Sources for CO2 Utilization by Environmental-Merit-Order Curves. Environmental Science and Technology. https://doi.org/10.1021/acs.est.5b03474

Å Bio-ethanol fermentation (assessed by Naims only and based on North America and Brazil not EU)

Followed by subsequent targets of lower purity:

Å Paper and pulp industry

Å Integrated Gasification Combined Cycle (IGCC)

Å Iron and Steel

Å Cement

These conclusions are unsurprising since the major inhibiting factor in CO_2 capture is the energy required for the capture and separation processes. The energy needed will both affect the cost and environmental implications of the process. Therefore, targeting the most pure streams of CO_2 will keep energy requirements to a minimum as smaller volumes of emitted gas will need to be processed to result in the same volume of purified CO_2 when compared with a more dilute source. Naims, 2016 concludes that for near term scenarios high purity CO_2 which can be captured for low cost of approximately ú33/tonne should be sufficient. Von der Assen notes increases in ethanol plants and biogas fermentation will lead to new relatively pure CO_2 sources which will be environmental beneficial from a capture perspective. Due to the lower CO_2 concentration in the emissions from the power sector most of the largest emitters are not included in the primary target sources. The CO_2 concentrations in each stream, emissions per year and the estimated cost per tonne of capturing the CO_2 are identified in Table 4 below.

Table 4. Key sources of CO_2 in Europe. Adapted from E-PRTR and Naims, 2016.

CO_2 Source	CO_2 concentration [%]	Emission per year [Mt CO2/year]	Cost [€/t CO_2]	Number of point sources emissions over 0.1 Mt/yr
Hydrogen Production	70-100	5.3	30	15
Natural Gas Production	5-70	5.0	30	10
Ethylene oxide Production	100	17.7	30	6
Ammonia Production	100	22.6	33	27
Paper Pulp Industry	7-20	31.4	58	35
Coal to Power (IGCC)	3-15	3.7	34	3
Iron and steel	17-35	151.3	40	93
Cement	14-33	119.4	68	212
Total		**356.4**		

Using the analysis of the best sources of CO_2 for CO_2 utilisation (Table 4), the latest E-PRTR data has been used to construct maps of the key sources of CO_2 across Europe. In addition to mapping the point sources of the CO_2, the major European chemical parks (see section 2.2) have also been mapped to identify potential utilisers of this new carbon source. CO_2 sources located close to current process industries are highly desirable as this reduces the costs of transport pipelines and associated infrastructure. For this reason, each map of industrial sector CO_2 sources is plotted alongside the chemical parks. Figure 6 presents an overview of all of the carbon sources. It can be observed from the mapping that the most prevalent source of CO_2 is the cement industry, as although the steel industry is a greater contributor to emissions there are fewer point sources.

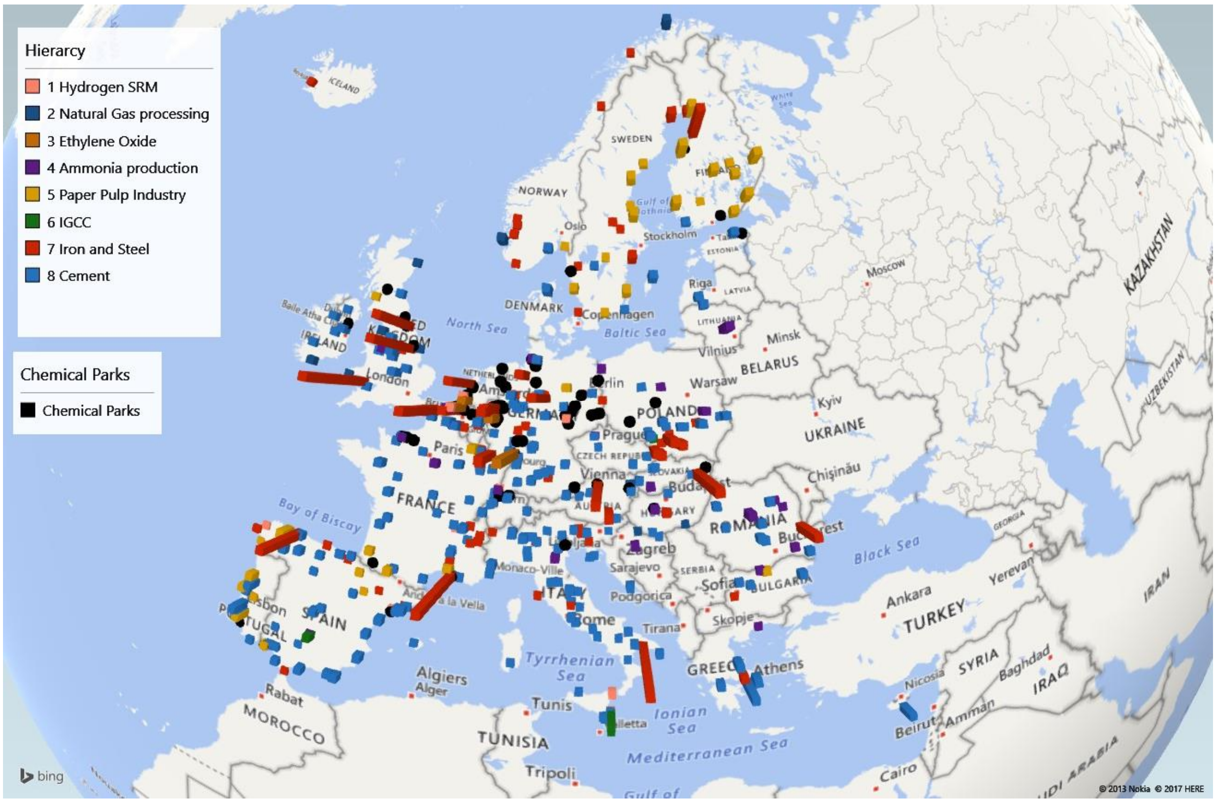

Figure 6. Map of key sources of CO_2 in Europe. Adapted from E-PRTR.

Steam Reforming of Methane (SRM) to produce Hydrogen

Steam reforming of methane is used to produce most of the current hydrogen supply. Methane (CH_4) is reacted with high temperature steam at 700-1000 ºC under pressure using a catalyst to promote the reaction, hydrogen, cabon monoxide and carbon dioxide are produced. Subsequently, the water-gas shift reaction takes place to convert the produced carbon monoxide and water to hydrogen and carbon dioxide. The process results in high purity hydrogen and carbon dioxide streams.

There are 16 SRM facilities listed in the E-PRTR, emitting between 0.136-0.805 Mtonnes of CO_2 per annum (Table 5 and Figure 7)

Table 5. Emissions of CO_2 from Steam Reforming of Methane facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.136	Linde France Usine de Chalampé	CHALAMPE	France
0.152	AIR LIQUIDE FRANCE INDUSTRIE - BELLE ETOILE	SAINT-FONS	France
0.168	Air Liquide Italia Produzione - Impianto Produzione Idrogeno Melilli	MELILLI	Italy
0.191	AIR LIQUIDE IBERICA DE GASES	ARTEIXO	Spain
0.196	AIR LIQUIDE HYDROGENE SMR Lavéra	MARTIGUES	France
0.246	Linde Gas Produktionsgesellschaft mbH & Co. KG / TOTAL	Spergau	Germany
0.261	AIR LIQUIDE HYDROGENE	NOTRE-DAME-DE-GRAVENCHON	France
0.262	Boc Limited, Seal Sands Boc Hydrogen Plant	Middlesbrough	United Kingdom
0.278	Air Products Nederland BV (Botlek)	Botlek Rotterdam	Netherlands
0.313	Linde Gas Italia Srl - Sito di Milazzo	MILAZZO	Italy
0.343	HYCO (LA POBLA DE MAFUMENT)	Pobla de Mafumet, La	Spain
0.393	Servizi Milazzo Srl	MILAZZO	Italy
0.417	Linde Gas Produktionsgesellschaft mbH & Co. KG	Leuna	Germany
0.477	AIR LIQUIDE LARGE INDUSTRY	Antwerpen	Belgium
0.616	Air Products HyCo 4 (Botlekweg)	Botlek Rotterdam	Netherlands
0.805	Air Liquide Industrie BV	Botlek Rotterdam	Netherlands

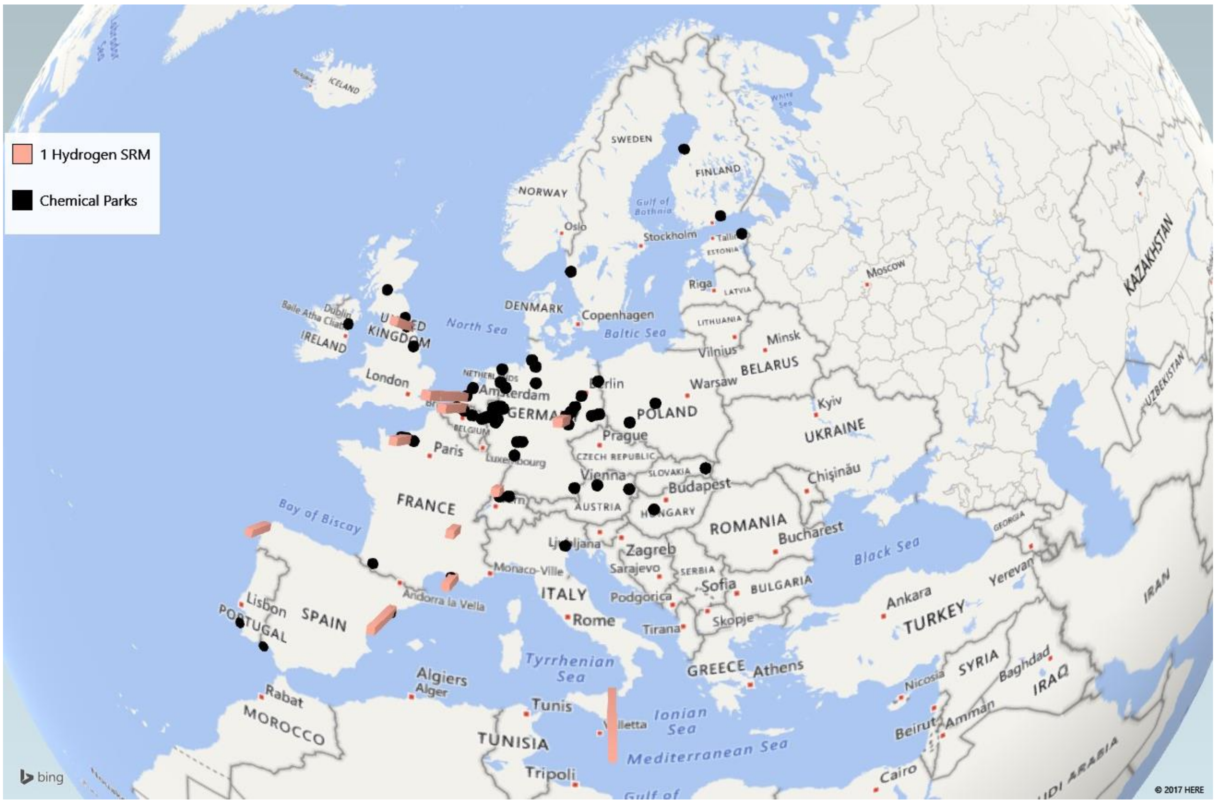

Figure 7. Locations of emissions of CO_2 from Steam Reforming of Methane facilities in Europe. Adapted from E-PRTR.

Natural Gas Processing

Natural gas has not the purity needed for futher processing when it is extracted, CO_2 and other acid gases such as H_2S must be removed from natural gas before it can be r use. Typically amine adsorption processes are used to remove the CO_2 leading to a high purity stream. Emissions of CO_2 from natural gas processing range from 0.1 -1 Mt/yr from 10 listed facilities in the E-PRTR (Table 6 and Figure 8).

Table 6. Emissions of CO_2 from Natural Gas Processing facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.115	MOL Magyar Olaj- és Gázipari Nyrt.	AlgyŖ	Hungary
0.211	OMV Austria Exploration u. Production	Aderklaa	Austria
0.217	Perenco UK Limited, Dimlington Gas Terminal	Hull	United Kingdom
0.247	South Hook Lng Terminal	Milford Haven	United Kingdom
0.324	Golden Eye Module	Peterhead	United Kingdom
0.427	CPS I, II, III	Virje	Croatia

0.563	Barrow Gas Terminals - North And South	Barrow-In-Furness	United Kingdom
0.652	Bord Gais Energy Ltd	Cork	Ireland
1.04	Hammerfest LNG	Ukjent Kode Benyttet (9601)	Norway
1.19	Gassco Kårstø	Tysværvåg	Norway

Figure 8. Locations of emissions of CO_2 from natural gas processing facilities in Europe. Adapted from E-PRTR.

Ethylene Oxide Production

Ethylene oxide is produced by the oxidation of ethylene and requires a silver catalsyt to promote the reaction. Ethylene oxide is a used as a intermediate to produce many industrial chemicals including polymers and ethylene glycols. High purity CO_2 is produced in the production of ethylene oxide which must be removed. Six ethylene oxide facilities producing more than 0.1 Mt CO_2/yr are listed in the E-PRTR producing a combined emission of 17.7 Mtonnes/yr of CO_2 (Table 7 and Figure 9); although ICIS[18] lists 12 plants in Europe, it is presumed that the other six facilites have emissions of less that 0.1 MT/yr; however these may be of interest to end users who require smaller volumes of CO_2.

[18] https://www.icis.com/resources/news/2013/04/13/9658385/chemical-profile-europe-ethylene-oxide/

Table 7. Emissions of CO_2 from ethylene oxide production facilities in Europe. Adapted from E-PRTR

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.19	INEOS	Zwijndrecht	Belgium
1.92	Shell Nederland Chemie BV (Moerdijk)	Moerdijk	Netherlands
2.76	Dow Benelux BV (Hoek)	Hoek	Netherlands
2.84	INEOS Köln GmbH	Köln	Germany
3.08	BASF ANTWERPEN	Antwerpen	Belgium
6.91	BASF SE	Ludwigshafen am Rhein	Germany

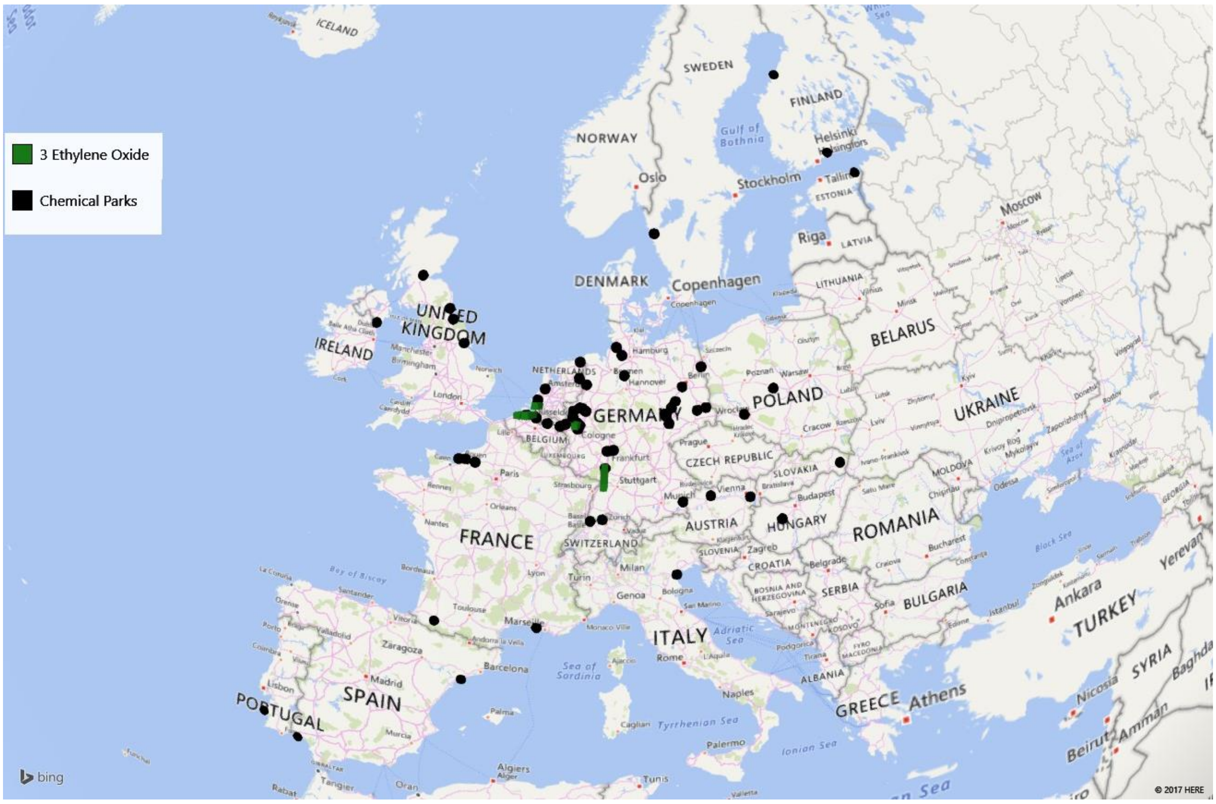

Figure 9. Locations of emissions of CO_2 from ethylene oxide production facilities in Europe. Adapted from E-PRTR.

Ammonia Production

CO_2 emissions from ammonia production amounted to 22.6 Mtonnes in 2014. Ammonia is predominantly used as a fertilizer and is produced via the Haber process. CO_2 is produced during the production of hydrogen which is combined with nitrogen to produce ammonia. There are 27 facilities producing ammonia with emissions ranging from 0.1-3.2 Mtonnes per year listed in the E-PRTR, the 10 largest emitters are listed in Table 8, whilst Figure 10 shows the location of all 27 facilities.

Table 8. Emissions of CO_2 from ammonia production facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.807	YARA ITALIA SpA - STAB. FERRARA	FERRARA	Italy
0.862	Duslo a.s.	ĠaĞa	Slovakia
0.896	NitrogénmŤvek Zrt.	PétfürdŖ	Hungary
0.913	ANWIL S.A.	Wğocğawek	Poland
0.943	YARA Brunsbüttel GmbH	Büttel	Germany
1.44	Zakğady Chemiczne "POLICE" S.A.	Police	Poland
1.57	SC AZOMURES SA	TARGU MURES	Romania
1.89	Zakğady Azotowe "Puğawy" S.A.	Puğawy	Poland
2.38	AB "Achema"	Jonalaukis	Lithuania
3.18	YARA Sluiskil BV	Sluiskil	Netherlands

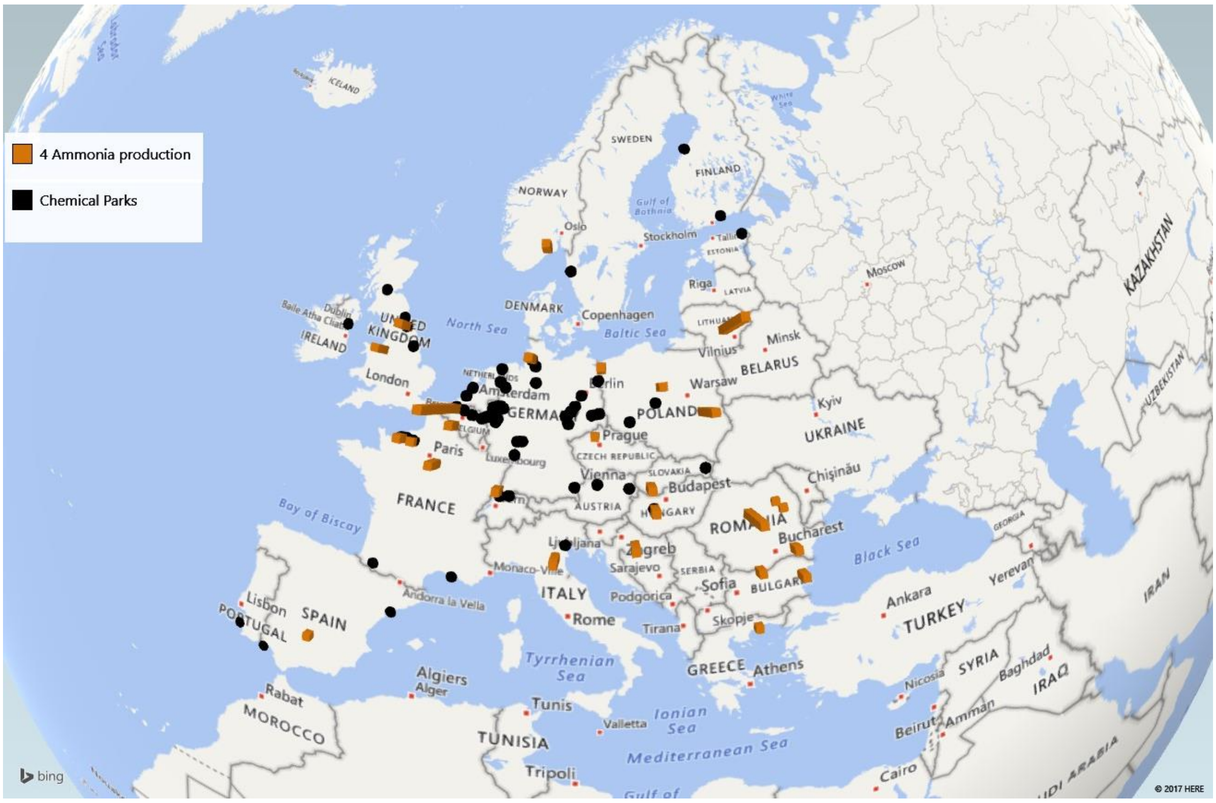

Figure 10. Locations of emissions of CO_2 from ammonia production facilities in Europe. Adapted from E-PRTR.

Paper Pulp Industry

The paper pulping industry is highly energy intensive and hence has high CO_2 emissions. There are 35 facilities in Europe with emissions ranging from 0.1 ï 2 Mtonnes per year. Facilities are predominently clustered in Finland, Sweden, Spain and Portugal. The locations of the paper pulp facilites may inhibit the use of the CO_2 in the process sector. As can be observed in Figure 11, the majority of the facilities are not in close proximity to exisiting chemical parks, and are often located in rural areas (close to sources of wood). Therefore cost of building the necessary infrastructure or transporting the CO_2 to the required location for use may be prohibitive.

Table 9. Emissions of CO_2 from the 10 largest emitting paper pulp production facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
1.26	Complexo Industrial de Setúbal da Portucel	SETÚBAL	Portugal
1.36	CEASA ENCE- FÁBRICA DE NAVIA	NAVIA	Spain
1.37	Metsä Fibre Oy, Joutsenon tehdas	PULP	Finland
1.49	Metsä Fibre Oy Kemin tehdas	KEMI	Finland
1.54	Metsä Fibre Oy, Rauman tehdas	RAUMA	Finland
1.59	STORA ENSO OYJ, ENOCELLIN TEHDAS	UIMAHARJU	Finland
1.59	Skutskärs Bruk	SKUTSKÄR	Sweden
1.83	Södra Cell Mönsterås	MÖNSTERÅS	Sweden
1.89	UPM KYMMENE OYJ, UPM, Pietarsaari	PIETARSAARI	Finland
1.97	Zellstoff Stendal GmbH	Arneburg	Germany

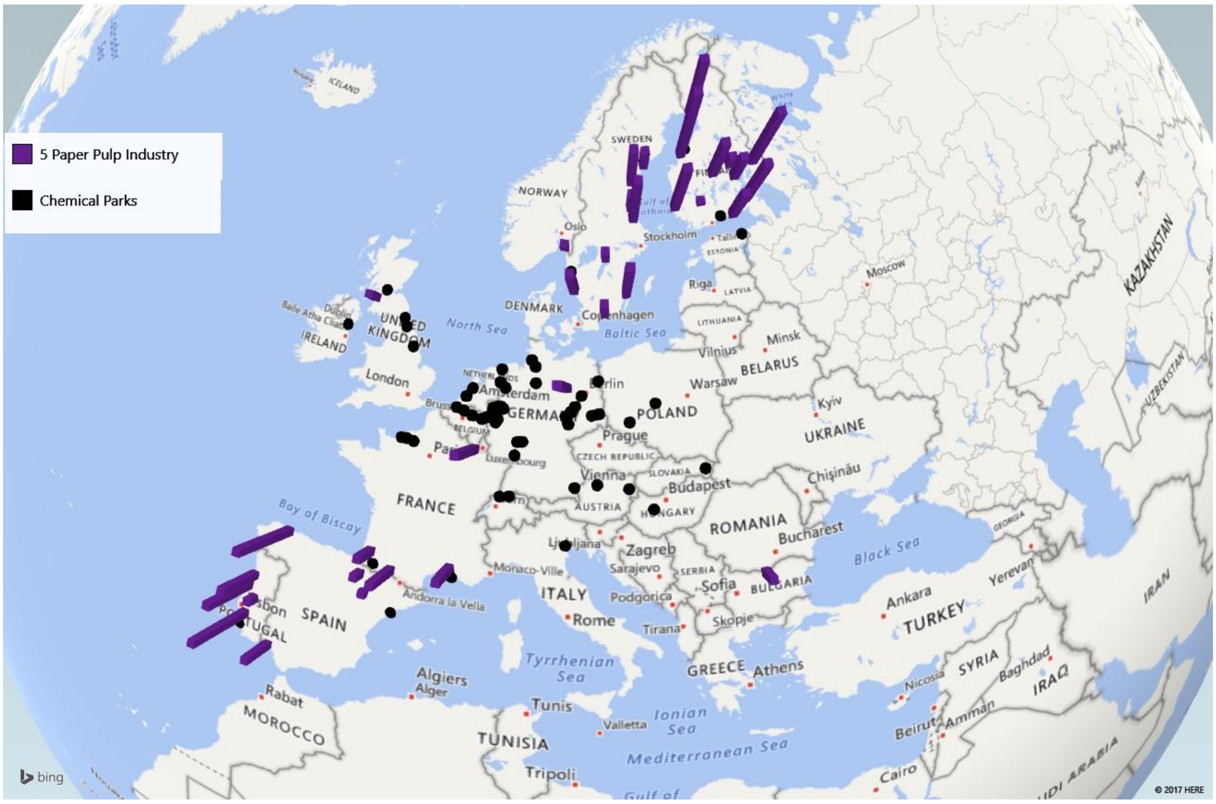

Figure 11. Locations of Emissions of CO_2 from paper pulp facilities in Europe. Adapted from E-PRTR.

IGCC

Integrated gasification combined cycle (IGCC) power plants use a gasifier to turn a carbon feedstock (usually coal) into synthesis gas (CO and H_2) which is then used in gas and steam turbines to produce electricity. Three facilities are listed in Europe (Table 10, Figure 12), although there are predictions that the sector could grow. IGCC can be combined with carbon capture technologies as the higher concentrations of CO_2 in the exhaust streams make capture easier than in traditional power plants where the CO_2 is more dilute.

Table 10. Emissions of CO_2 from IGCC facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
0.281	TAURON Wytwarzanie Spóǩa Akcyjna -Oddziağ Elektrownia Blachownia w Kňdzierzynie-Koŧlu	Kňdzierzyn Koŧle	Poland
0.821	ELCOGAS S.A. - CENTRAL TÉRMICA GICC	PUERTOLLANO	Spain
2.68	ISAB SUD IMPIANTO IGCC	PRIOLO GARGALLO	Italy

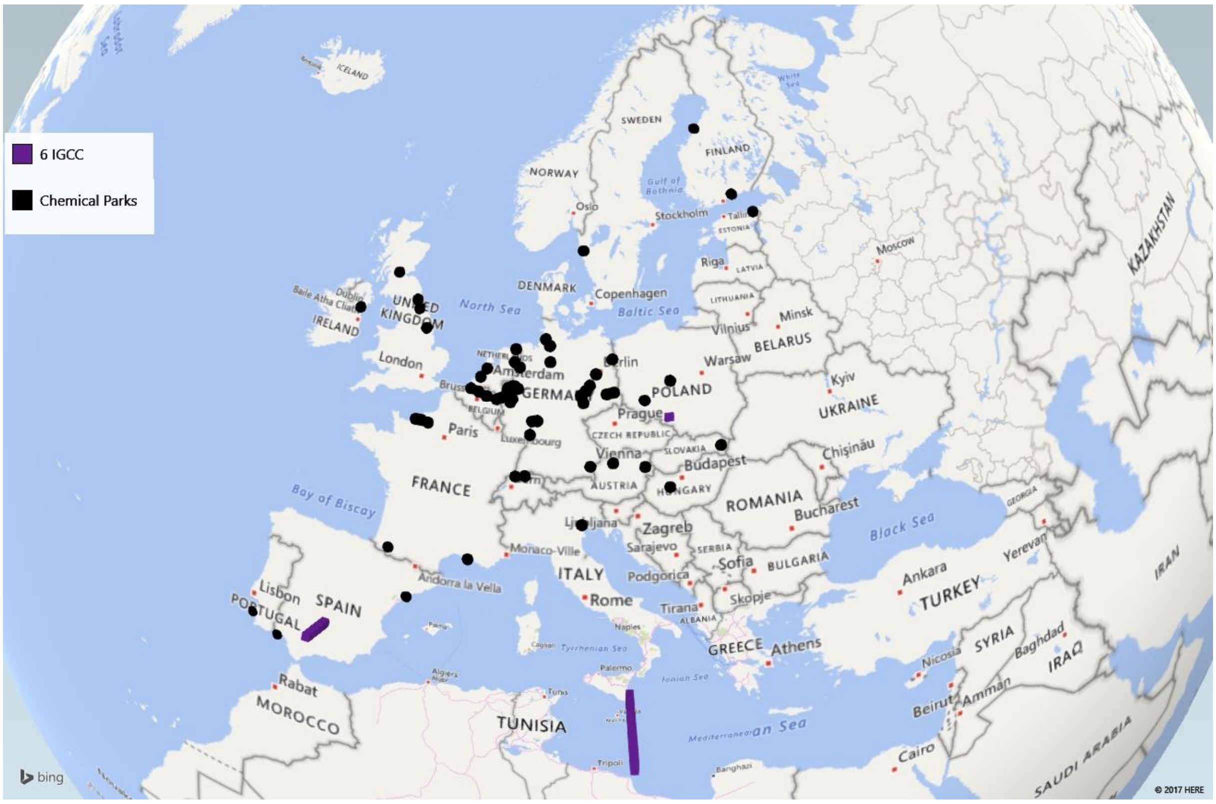

Figure 12. Locations of emissions of CO_2 from IGCC facilities in Europe. Adapted from E-PRTR.

Iron and Steel production

The production of Iron and Steel is highly energy intensive and hence emission levels are high. Steel production occurs in two stages, firstly iron production then steel making. The iron production process produces the most emissions (70-80% of the total emissions), as iron ore is reduced to iron usually with coke. The sector is continuously looking to reduce emissions and therefore the utilisation of CO_2 is seen as a promising pathway. Many facilities are located near to chemical parks and hence the required infracstruture and experitise for utilising the CO_2 in the process industry is available.

Table 11. Top 10 emitters of CO_2 from iron and steel production facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
5.93	Sahaviriya Steel Industries Uk Limited, Teesside Integrated Iron And Steelworks	Redcar	United Kingdom
5.93	Tata Steel IJmuiden BV	Velsen-Noord	Netherlands
7.17	Scunthorpe Intergrated Iron And Steel Works	Scunthorpe	United Kingdom
7.42	ILVA S.P.A. Stabilimento di Taranto	TARANTO	Italy
7.73	ARCELORMITTAL ATLANTIQUE et LORRAINE SITE DE DUNKERQUE	DUNKERQUE	France
7.92	ArcelorMittal FOS	FOS-SUR-MER	France

8.03	Salzgitter Flachstahl GmbH Werk Salzgitter	Salzgitter	Germany
8.54	Port Talbot Steel Works	Port Talbot	United Kingdom
8.66	voestalpine Stahl GmbH	Linz	Austria
8.96	U.S.Steel s.r.o.	Koġice	Slovakia

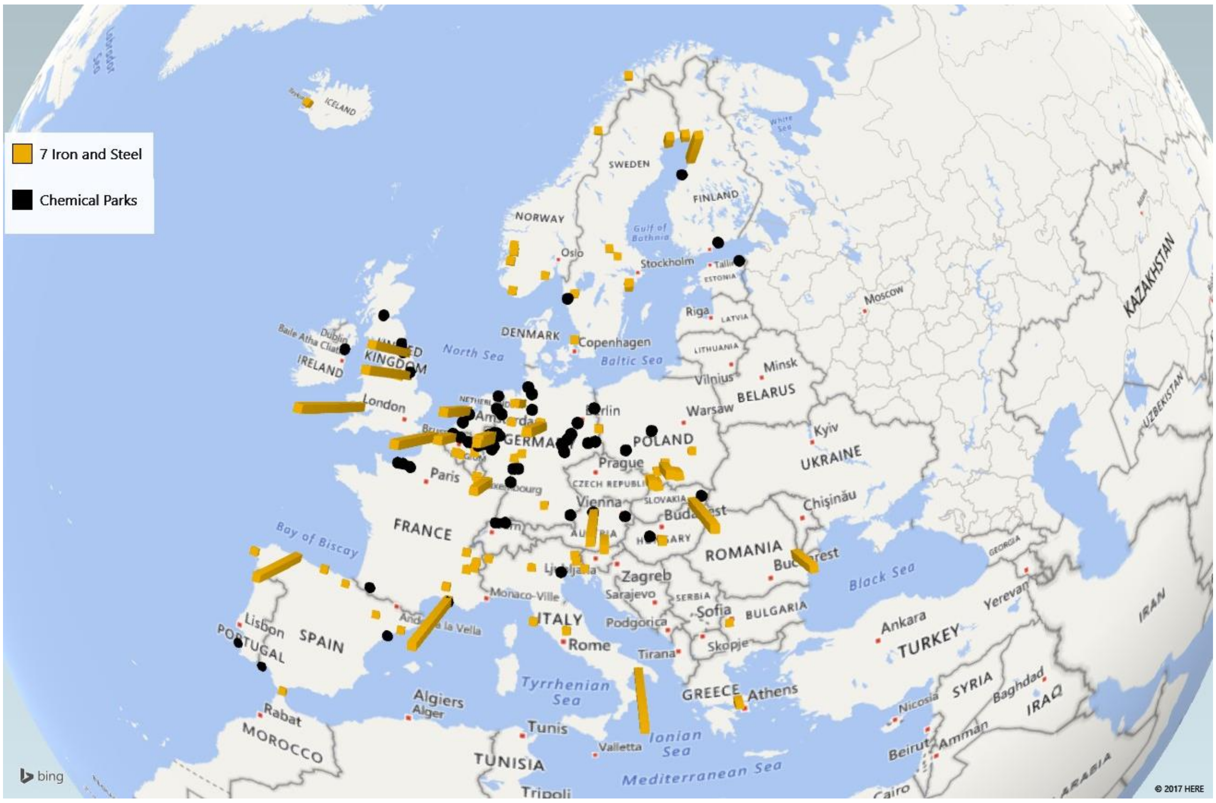

Figure 13. Locations of Emissions of CO_2 from iron and steel production facilities in Europe. Adapted from E-PRTR.

Cement industry

The cement industry has the most entries in the E-PRTR with over 200 facilities emitting more than 0.1 Mt CO_2 per year (Figure 14). Emissions range from 0.1-2.2 Mt CO_2/yr, with the top 10 emitters identified in Table 12. The production of cement is highly energy intensive and CO_2 emissions occur in predominantly in two areas of the cement making process; limestone (calcium carbonate) is calicated to produce calcium oxide whilst releasing CO_2 and the kilns require heating necessitating the burning of fossil fuels. The cement industry is deploying efficiency measures to reduce emissions, but will need carbon capture and utilisation/storage to decarbonised completely.

Table 12. Ten largest emitters of CO_2 from cement production facilities in Europe. Adapted from E-PRTR.

CO_2 emission MTonnes/yr	Facility Name	City	Country
1.36	CCB sa - Site de Gaurain-Ramecroix	GAURAIN-RAMECROIX	Belgium
1.46	CEMEX Zement GmbH	Rüdersdorf bei Berlin	Germany
1.5	Cementownia Warta S.A.	Trňbaczew	Poland
1.51	Centro de Produção de Alhandra	VILA FRANCA DE XIRA	Portugal
1.53	VASSILIKO CEMENT WORKS PUBLIC COMPANY LTD, Vassilikos Plant	ZYGI	Cyprus
1.7	Cementa AB, Slitefabriken	Slite	Sweden
1.72	AALBORG PORTLAND A/S	Aalborg Øst	Denmark
1.73	TITAN CEMENT S.A. - KAMARI PLANT	KAMARI, DERVENOCHORIA	Greece
1.84	Grupa OŰarów S.A.	Karsy	Poland
2.2	GóraŰdŰe Cement S.A., Cementownia GóraŰdŰe	Chorula	Poland

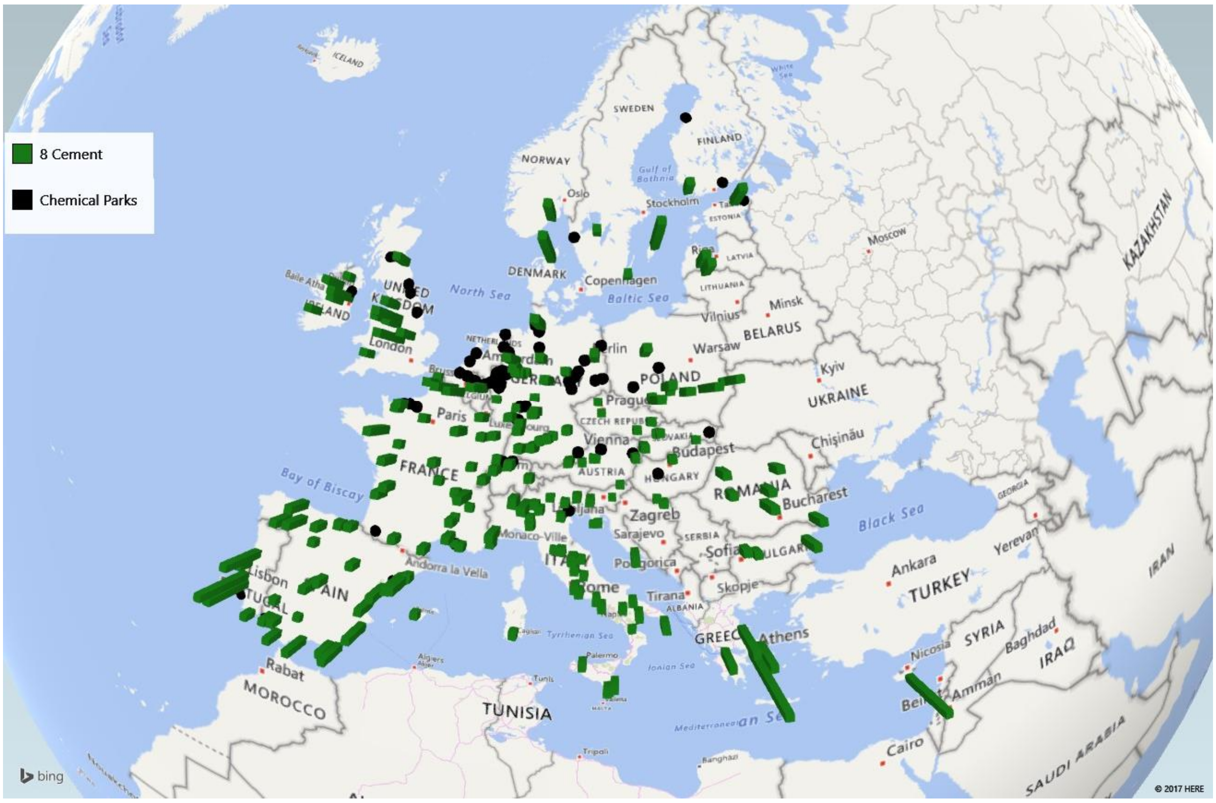

Figure 14. Locations of emissions of CO_2 from cement production facilities in Europe. Adapted from E-PRTR.

3.2.1 Predict future sources in respect of EU Climate goals: Which sources will be available in the long term

It is expected that the main change in CO_2 availability will arise from reductions in emissions arising from coal power generation, which is expected to decrease significantly by 2100. Over the medium term, "clean coal" technologies such as integrated gasification combined cycle or pressurized fluidized bed will improve combustion efficiencies and in the longer term there is expected to be a move away from coal altogether. The relatively ambitious IEA 2°C scenario of the ETP2015 model foresees a reduction of coal as fuel input for electricity and heat generation from 33.8 EJ (10^{18} J) in 2012 to 5.1 EJ in 2050, corresponding to a 85% reduction.[19] With around 46 % of the global emissions arising from fossil fuel combustion currently coming from coal[20] reductions in coal use will impact CO_2 availability. However, the impact upon CO_2 utilisation may be limited, as CO_2 from this source is generally of low concentration at 12-14%[21] and can be contaminated with sulphur and heavy metals such as mercury, making capture and purification (clean-up) more expensive. Consequently, it is expected that CO_2 arising from purer sources will be preferentially utilised as described previously.

The report Energy Technology Transitions for Industry: Strategies for the next industrial revolution, IEA 2009[22], looks at five industrial sectors: iron & steel, cement, chemicals & petrochemicals, pulp & paper and aluminium. It concludes that in order to reach a global emissions reduction of 50% by 2050, industry would need to reduce emissions by 21% (this assumes a near complete decarbonisation of the power sector). However, due to strong growth in demand, such reductions are not expected to be achieved by efficiencies and technology improvements alone. It is projected to be achieved only by including CO_2 capture within the adopted strategies giving rise to possible opportunities for use of the CO_2 as a feedstock.

Technology changes will determine future industrial emissions and some industrial sectors will be able to reduce emissions more significantly than others. Around 96% of global H_2 production is currently from steam reforming of methane, oil-based or coal gasification[23] which result in CO_2 emissions which will only increase if projected increases in H_2 usage transpire. However, a switch to electrolysis of water using renewable energy will mean that CO_2 availability from this source will decrease significantly (other low-carbon technologies such as photocatalytic water-splitting or biohydrogen/fermentative production are further from commercial reality). Currently H_2 usage is split roughly 50:50 between hydro-treating/hydro-cracking by refineries and ammonia/nitrogen-based fertilizer production by the chemical industries[16]

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[19] Energy Technology Perspectives 2015, IEA

[20] Trends in global CO2 emissions: (2016) PBL Netherlands Environmental Assessment Agency and EC Joint Research Centre.

[21] Chapter 2 Sources of CO2. IPPC Special Report on Carbon Capture and Storage. https://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf

[22] Energy Technology Transitions for Industry: Strategies for the next industrial revolution, IEA 2009.

[23] Energy Technology Perspectives 2012, IEA.

One major CO_2 source, natural gas processing, is expected to increase in the medium term as power generation shifts away from coal and natural gas is used to balance intermittent renewable generation. Projections suggest that natural gas use will increase by 85% between 2007 and 2050[24] so CO_2 emissions arising from processing/cleaning the gas prior to its eventual combustion will rise.

3.3 Overview CO_2 Capture technologies

Carbon dioxide for utilisation processes can be obtained from a range of sources; industrial emitters, power generation, fermentation, anaerobic digesters or from the air. Each source will give CO_2 at differing content, purity and humidity presenting challenges in catalyst design or necessitating costly purification and concentration before use.

There are three main types of carbon capture related to power plant emissions; post-combustion, pre-combustion and oxy-fuel combustion. When looking to capture emissions from industrial sources post-combustion is the most applicable technology (Figure 15).

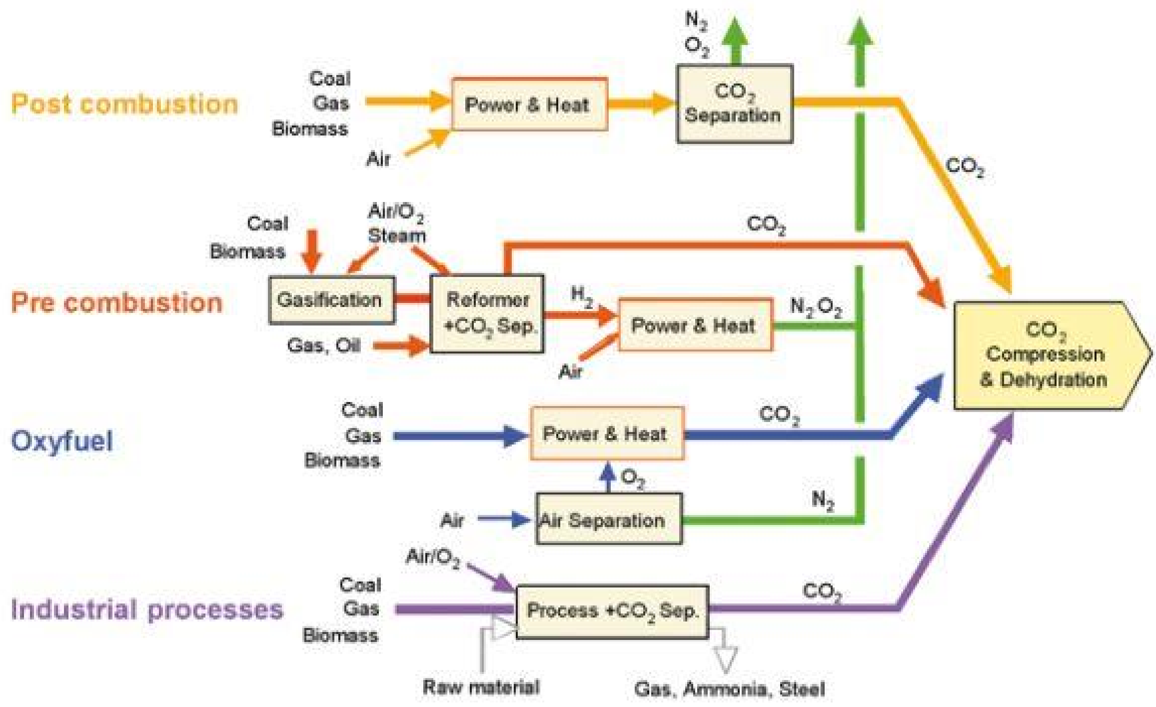

Figure 15. CO_2 capture technologies[25].

[24] Energy Technology Perspectives 2010, IEA.

[25] Chapter 11 A Review on Technologies for Reducing CO2 Emission from Coal Fired Power Plants By S. Moazzem, M.G. Rasul and M.M.K. Khan DOI: 10.5772/31876

For post-combustion capture the current industrial standard uses aqueous solutions of monoethanolamine (MEA) at concentrations of 15-30% (w/w). MEA has problems of toxicity, corrosion, reactive chemistry and evaporative loss and therefore is not an ideal capture agent. It works by a mixture of physi- and chemi-sorption in the strong interaction between CO_2 and basic NH_2 group. The energy requirement for desorption makes the process energy intensive. A 25%-40% increase in the energy required to run a power plant is needed for the carbon capture process. In an MEA absorber over 70% of its volume is occupied by water which has implication on capital expenditure.

New materials that show selective physisorption are being developed which are more economic, have a smaller energy penalty and are more environmentally friendly (Table 13).

Table 13. Comparison of average reported energy costs for several post-combustion CO_2 capture processes including maximum and minimum reported values[26].

Method	MEA	Advanced Amine	Membrane	Vacuum Swing	High Pressure	Thermodynamic Minimum
Type	TSA	TSA	PSA	VPSA	PSA	--
Av. Capture Cost (MJ/t)	3840	2690	2500	1660	1170	210
Range (min/max)	2570 4600	1800 3220	1900 3250	1220 2100	860 1580	170 250

New carbon capture technologies such as those shown in Table 13 are demonstrating energy cost benefits over traditional amine processes. This is particularly significant for the use of CO_2 as a feedstock for the chemicals industry as having reduced feedstock costs will have an impact on the economic viability of the process. Currently it is observed that the most attractive sources of CO_2 are those that require little or no separation i.e. fermentation or ammonia production. However, if the use of CO_2 as feedstock for the process industry reaches its predicted potential, these sources will not be sufficient and cheap capture and separation technologies will become key to successful implementation.

[26] Styring P, Reed D. G. and Dowson G.R..(2017) Cellulose-Supported Ionic Liquids for Low Cost Pressure Swing CO2 Capture. Front. Energy Res doi: 10.3389/fenrg.2017.00013.

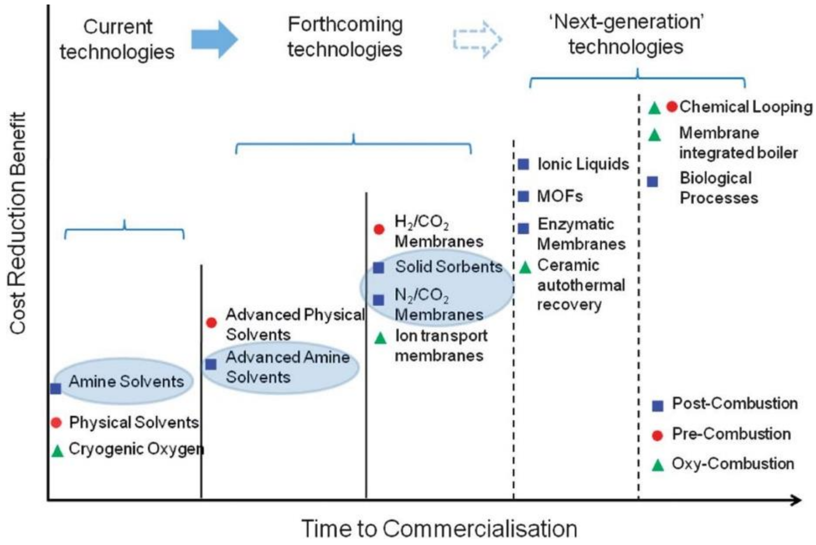

Fig 16. Development of new Carbon Capture technologies[27].

A key target for future CO_2 utilisation is sourcing CO_2 from the atmosphere, this is known as direct air capture (DAC). DAC would provide a closed loop cycle, whereby CO_2 would be used, then either sequestered in a long term product or re-emitted after a product such as urea or methanol are used. This re-emitted CO_2 could then be captured again providing a closed loop. The significant advantage of DAC is that the capture unit can be sited with the utilisation facility, negating the need for transport of the CO_2 feedstock. DAC technologies are currently in low to mid-level technologies readiness. One notable exception to this is Climeworks[28] Climeworks have constructed a commercial DAC facility which will capture 900 tonnes of CO_2 annually to be supplied to a greenhouse. However, costs will need to be significantly reduced before widespread deployment.

3.4 Key challenges in respect to CO_2 utilisation

There are a number of key challenges regarding the use of CO_2 as a feedstock for the process industry. The largest being creating economically viable processes that simultaneously have a positive environmental impact when compared to traditional production methods. Theoretically, CO_2 can be used as a carbon source in many process, however whether the theory can be industrially deployed is complex. Comprehensive techno-economic analysis is required combined with robust life-cycle analysis to ensure process viability. A key cost is the capture of the CO_2. As described above there

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[27] Zhao, M., Minett, A. I., & Harris, A. T. (2013). A review of techno-economic models for the retrofitting of conventional pulverised-coal power plants for post-combustion capture (PCC) of CO $_2$. *Energy Environ. Sci.*, *6*(1), 25ï 40. https://doi.org/10.1039/C2EE22890D

[28] www.climeworks.com

are plentiful sources of CO_2 throughout Europe, but the capture of CO_2 from these sources may not be economically viable using currently available technologies. Other key challenges include:

- Matching volumes of CO_2 from emitters to technology solutions
- Reducing transportation distance
- Decreasing costs of air-capture so CO_2 utilisation technology locations can be decoupled from CO_2 sources
- Decreasing the energy penalty of capture technologies
- CO_2 storage for utilisation
- Standardisation of Life Cycle Analysis to allow comparison between technologies for environmental impacts and CO_2 reduction
- Integration with mechanisms such as ETS
- If CCS deployment to the power industry takes place, putting mechanisms in place to utilise a proportion of the captured CO_2
- Emitters with no significant process industry in close proximity, should CO_2 be transported or new industry be encouraged to locate
- Need to decarbonise carbon intensive industry may provide a push for deployment of CO_2 utilisation technologies.

3.5 Conclusion (Future outlook and potential impact)

There are plentiful sources of CO_2 which could be used as a carbon feedstock for the process industry in Europe. Primary targets for sourcing CO_2 should focus on those sources with the highest concentration of CO_2, (Hydrogen production, natural gas processing, ethylene oxide manufacture and ammonia production) as the higher concentration of CO_2 reduces the cost of capture. However, larger volumes of CO_2 are available from the iron and steel industry and cement industries, albeit at lower CO_2 concentration. As industries look to decarbonise (particularly the iron and steel and cement sectors) there is an observed market pull to deploy CO_2 utilisation technologies to provide an economically beneficial method of reducing CO_2 emissions. As next-generation carbon capture technologies reach the market, other sources of CO_2 may become increasingly economically viable.

4. Potential CO sources

4.1 Definition and context

Carbon monoxide (CO) is produced if the combustion of carbon containing sources to CO_2 proceeds under a lack of oxygen in an incomplete combustion reaction. CO is toxic to humans and animals due to the strong binding of CO to haemoglobin compared to oxygen- resulting in suffocation if encountered in concentrations higher than 30 ppm[29]]. On the other hand, CO is a strong reducing agent and an essential starting material for the production of many chemical products.

The main source of CO is of natural origin due to photochemical reactions in the troposphere, volcano eruptions and forest fires[30],[31],[32] In the atmosphere, CO is a short-lived greenhouse gas and spatially variable in its concentration. Diffuse industrial CO emissions originate from internal combustion engines in urban areas. Furthermore, point sources from various industrial sectors release CO. These industrial point sources are listed in the European Pollutant Release and Transfer Register (E-PRTR) by the European Environment Agency. CO emissions higher than 0.005 Mt have to be reported to this database beginning from 2007[33]. Hence, key information on industrial facilities can be extracted from this reference. The report year 2014 was chosen, as this was the most recent and complete year in the database during our study. Reported CO point sources are given in Figure 17: The total CO emission for all European countries in 2014 was 3.38 Mt. Germany, followed by UK, France, Spain and Poland were the main emitting countries.

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[29] Safety data sheet CO, BOC, 15.03.2106, https://www.boconline.co.uk/internet.lg.lg.gbr/en/images/sg-019-carbon-monoxide-v1.2410_39621.pdf?v=4.

[30] A. Guenter et al., Atmospheric Environment, 34, 12-14, (2000), pp. 2205-2230, http://doi.org/10.1016/S1352-2310(99)00465-3

[31] M. A. K. Khalil, and R. A. Rasmussen, Nature, 332, (1988), pp. 242-245, doi:10.1038/332242a0

[32] B. Weinstock, and H. Niki, Science, 176, 4032, (1972), pp. 290-292, DOI: 10.1126/science.176.4032.290

[33] E-PRTR database, CO emission data from 2014, http://prtr.ec.europa.eu/#/home

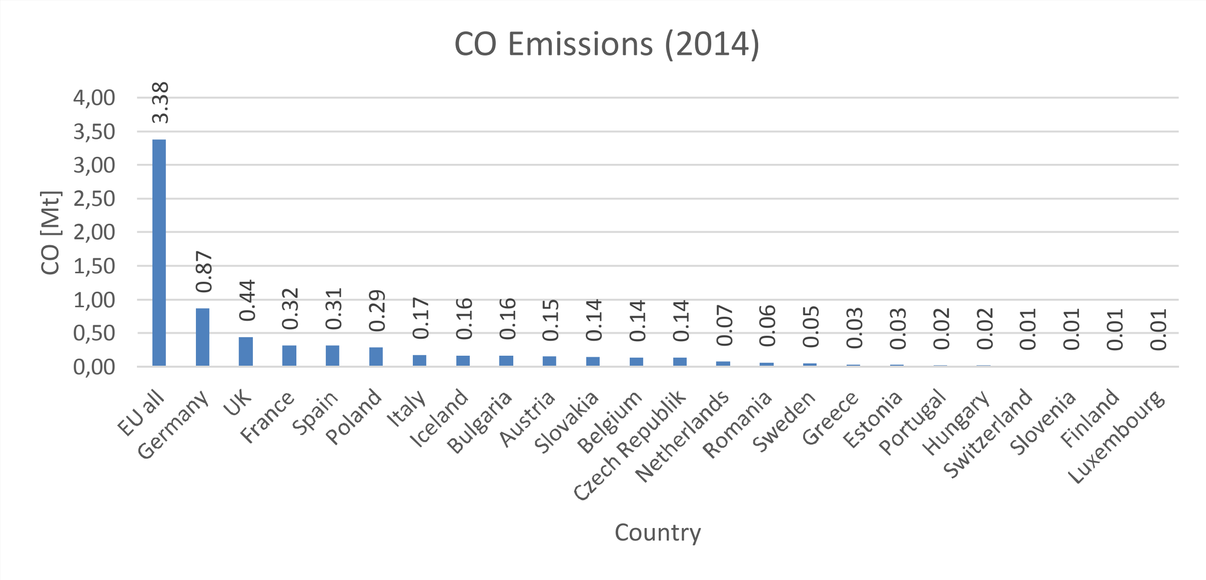

Figure 17: European countries with CO emissions higher than 0.005 Mt, from E-PRTR database

Current use of CO

CO is directly consumed as a feedstock in the chemical industry for the production of basic inorganic and organic chemicals, polymers, hydrocarbons and synthetic fuels. It can either be used directly or as syngas (mixture of CO and hydrogen (H_2)). In Europe, syngas is mainly produced via steam methane reforming, or alternatively autothermal reforming using oxygen rather than steam. Other world regions such as China also produce syngas from heavier feedstocks, predominately coal via partial oxidation. CO and CO_2 are furthermore connected by the watergas shift reaction, which is used to adjust the ratio of hydrogen and carbon monoxide to the needs of the subsequent chemical reaction.

The required amount and the purity of CO highly depend on the reaction and the process route. Furthermore, CO as a by-product is often either re-used in the production process or burned. The high calorimetric valorization (556 kJ/mol)[34] is used for heating or electrification; additionally toxic CO emissions are reduced.

Potential for the chemical industry

The CO value chain could be expanded beyond the current syngas production schemes used in the chemical industry, if side stream CO can be transferred from point sources to the consuming chemical industry by industrial symbiosis. However, this requires a spatially nearby producer-consumer relation which is closely linked to the chemical and industrial parks. As indicated, the amount of CO could be higher if CO would not be re-used on-site. For the steel industry, which is the major CO emitter, the amount could be increased by a factor of 10-20 (see section 4.3 for more details). But, CO is often emitted as one component of a mixed gas fraction and needs to be separated and purified for further

[34] Binnewies, M. Jäckel, H. Willner, G. Rayner-Canham, Allgemeine und Anorganische Chemie, Spektrum Akademischer Verlag Heidelberg, 1. Auflage, 2004, ISBN3-8274-0208-5

processes in the chemical industry. The technical aspects and the industrial feasibility of the required technologies are currently investigated in big national research projects like the German *Carbon2Chem*, the Dutch *steel2chemicals* and the German *Kopernikus Power-to-X* project.[35, 36 ,37]

4.2 Mapping sources

4.1 Definition and context

Information on the amount and the location of industrial point sources have been extracted from the E-PRTR database for the reporting year 2014. CO and CO_2 emissions were classified into 9 industrial sectors: *Chemicals*, *Construction*, *Energy*, *Food/Agriculture*, *Metal*, *Mining*, *Paper*, *Waste and Others*. The total CO Emission is 3.38 Mt of which the metal sector contributes to 71% (2.40 Mt), the construction sector to 11% (0.37 Mt), the chemical sector to 10% (0.34 Mt), and the energy sector by 6% (0.20 Mt). The main contribution within the metal sector comes from the manufacture of basic steel and ferro-alloys with 92% of the metal sector emissions (2.2 Mt), which results in 65% of the total emission (Figure 18).

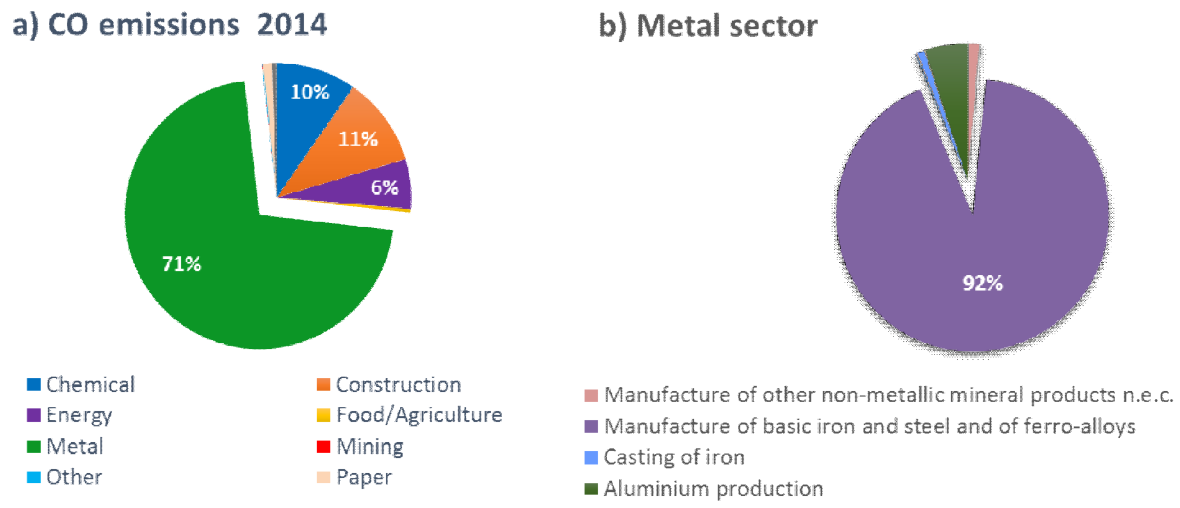

Figure 18: CO Emissions for 2014 from E-PRTR database. a) Plotted sector vise and b) detailed plot for the metal sector.

The second highest emission is produced in the construction sector by manufacturing of cement with 70% of the construction sector emission (0.26 Mt). This value is low compared to the emissions from the iron and steel industry. Hence, in this stage of the CarbonNext project we mainly focus on iron and

35 Carbon2Chem, BMBF funded project, https://www.fona.de/de/carbon2chem-21137.html
36 Steels2Chemicals, Dutch project in planning
37 BMBF funded project, https://www.kopernikus-projekte.de/projekte/power-to-x

steel production as CO source, bearing in mind that the possible CO emissions in total are much higher.

4.2 Mapping Sources in Europe

To give a more detailed overview of the point sources than the country vise listing (18), all CO emissions in Europe from 2014 were mapped in Figure based on the amount of CO and their location.

Figure 19: Mapping of the total CO emissions based on E-PRTR database for 2014.

A more detailed analysis was performed by mapping CO emissions by the nine classified sectors (Figure 20). This was correlated with the locations of the industrial sites which are marked as light blue circles. In accordance with Figure , the metal sector shows the highest and localized emissions. In many cases, they are located near a chemical park which could be relevant for best practice examples later on. Furthermore, one facility in Spain, located in Mansilla da las Mulas, also shows a very high CO emission (0.119 Mt per year). This is due to the production of inorganic SiC, which could be a source of relatively pure CO if the production takes the following reaction: $SiO_2 + 3\,C \rightarrow SiC + 2CO$. This source will be taken into account for the further investigation of the project.

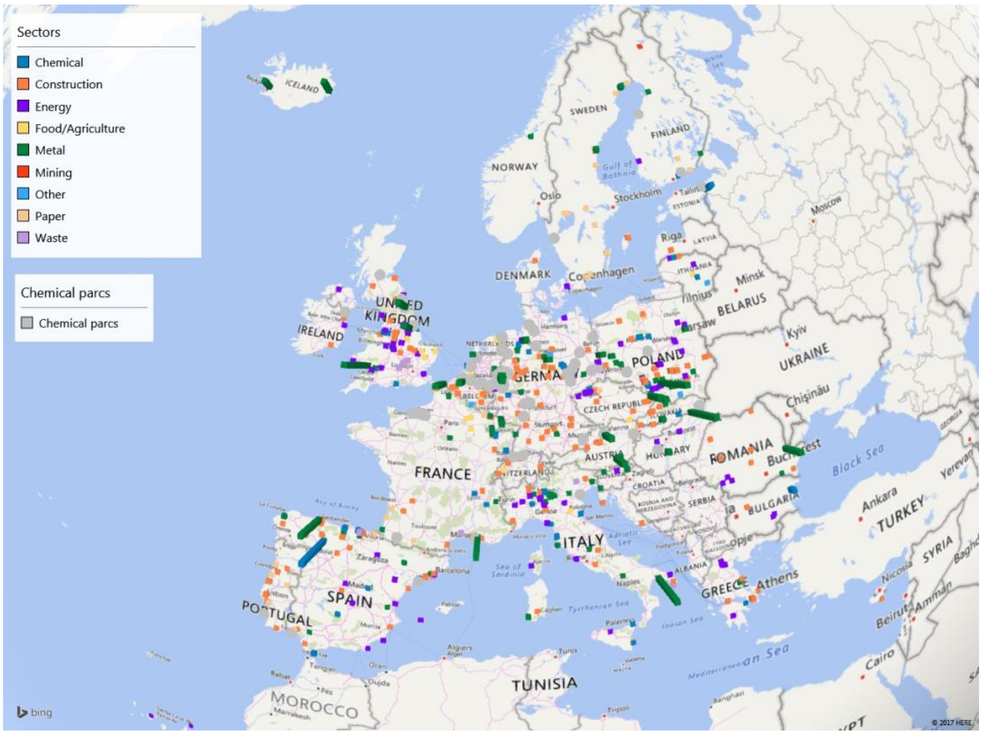

Figure 20: Mapping of CO emissions for all nine sectors. The locations of the chemical parks are indicated.

As deduced from the previous section, CarbonNext focuses at the iron and steel industry as the identified main CO emitter. The relevant point sources are shown in Figure 21. The corresponding CO emission values are given in Table 14.

Figure 21: Mapping of the CO emissions from steel production based on E-PRTR data, 2014 and the location of chemical parks in Europe.

Table 14: Location of CO point sources with emissions higher than 0.005 Mt.

City	Country	CO Emissions (Mt)	Main Economic Activity
Duisburg	Germany	0.220	Manufacture of basic iron and steel
Port Talbot	United Kingdom	0.159	Manufacture of basic iron and steel
Dunkerque	France	0.151	Manufacture of basic iron and steel
DŃbrowa Górnicza	Poland	0.133	Manufacture of basic iron and steel
Duisburg	Germany	0.132	Manufacture of basic iron and steel
Gent	Belgium	0.122	Manufacture of basic iron and steel
Koġice	Slovakia	0.114	Manufacture of basic iron and steel
Fos-Sur-Mer	France	0.104	Manufacture of basic iron and steel
Taranto	Italy	0.104	Manufacture of basic iron and steel
Availe	Spain	0.100	Manufacture of basic iron and steel
Dillingen/Saar	Germany	0.094	Manufacture of basic iron and steel
Redcar	United Kingdom	0.087	Manufacture of basic iron and steel
Scunthorpe	United Kingdom	0.074	Manufacture of basic iron and steel
Bremen	Germany	0.068	Manufacture of basic iron and steel
Linz	Austria	0.068	Manufacture of basic iron and steel
Donawitz	Austria	0.066	Manufacture of basic iron and steel
TŚnec	Czech Republic	0.063	Manufacture of basic iron and steel
Salzgitter	Germany	0.061	Manufacture of basic iron and steel
Velsen-Noord	Netherlands	0.058	Manufacture of basic iron and steel
Slezská Ostrava	Czech Republic	0.056	Manufacture of basic iron and steel
Galati	Romania	0.054	Manufacture of basic iron and steel
Eisenhüttenstadt	Germany	0.042	Manufacture of basic iron and steel
Dunaújváros	Hungary	0.014	Manufacture of basic iron and steel
Luleå	Sweden	0.010	Manufacture of basic iron and steel
Belleville	France	0.010	Casting of iron
Kraków	Poland	0.008	Manufacture of basic iron and steel
Duisburg	Germany	0.006	Manufacture of basic iron and steel

4.3 Current usage of CO [environmental, economic, technological]

As the iron and steel industry is the main emitter, the current usage of CO is illustrated only for those cases. However, the usage is also generally true for other industrial processes.

Typically, CO and other gas-by-products from integrated steel mills are either re-used in the steel production process or used for caloric valorization for on-site heating processes or electrification[38,39,40,41,] Only a minor fraction is emitted[42]. A large proportion of the electricity and steam required in the steel production process is produced from steel mill gases[43] . Importantly, the plant systems were designed in order to use the gases optimally and to minimize the amount of external energy supply. Hence, only a minor part of the CO is emitted into the atmosphere. Additionally, air pollution filters are used as an extra cleaning step. This is a must-do situation in order to minimize emissions of toxic CO. It is now being considered whether converting this CO into carbon-based products would be more beneficial than using it for electricity or steam production. Therefore, calculations are presented below to establish the total amount of CO produced in comparison to the small percentage emitted.

Estimated CO production in Iron and Steel Sites

CO emissions and their usage highly depend on the facility and the production route of the individual iron and steel production sites. Steel production can be classified in the following routes and including several process steps (Figure 22, adapted from reference [44]):

- Route 1a from iron ore) coke plant, **blast furnace**, oxygen blown converter
- Route 1b from iron ore) **smelting reduction** oven, oxygen blown converter
- Route 1c from iron ore) **direct reduction**, electric arc furnace
- Route 2 from scrap) conversion of **scrap to steel**

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[38] M. Sprecher, M. Baldermann, H.P. Domels, M. Hensmann, B. Stranzinger, and M. Marion, ñEnergy network in integrated mills - Reasonable use of by-product gases in the energy networkò, in METEC, 2015, European Steel Technology & Application Days, 2; 1-4

[39] M. Marion, M. Baldermann, H.P. Domels, M. Hensmann, B. Stranzinger, and M. Sprecher, ĂRationelle Nutzung der Kuppelgase im Energieverbund in integrierten Hüttenwerkenñ, stahl und Eisen, 125, (2015), Nr. 4

[40] J. Reichel, M. Baldermann, H.P. Domels, and M. Sprecher, ĂEnergiebilanz der integrierten Stahlerzeugungsrouteñ, stahl und eisen, 136, (2016), Nr. 8

[41] J. Reichel, M. Baldermann, H.P. Domels, and M. Sprecher, ĂEnergy balance of the integrated routeñ, englisch manuscript of [#Sprecher3a], private communication

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[43] Die Anlagenwelt von Thyssenkrupp Steel- Werke und Produktionsanlagen, Thyssenkrupp Steel Europe AG, Ausgabe 07/2011, https://www.thyssenkrupp-steel.com/media/content_1/publikationen/werke_und_produktionsanlagen_de.pdf

[44] Scheme Steel production routes, VDEH, http://en.stahl-online.de/wp-content/uploads/2013/10/Bild-24_eng.jpg

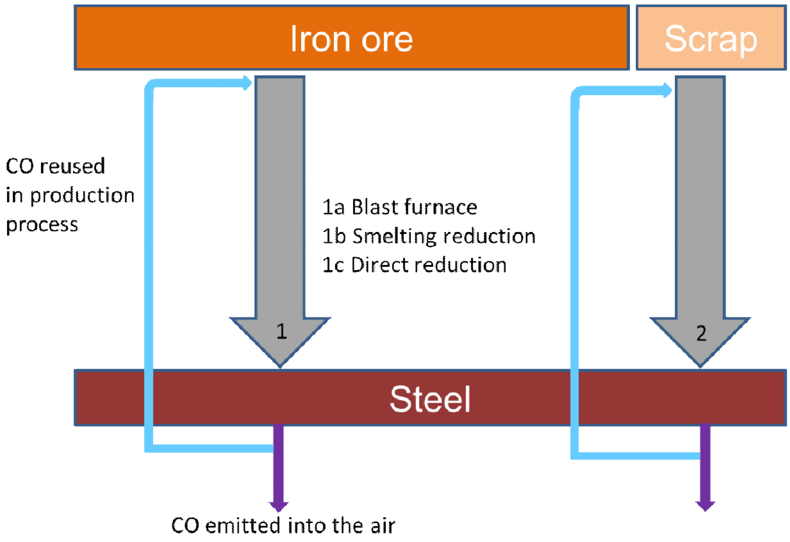

Figure 22: Steel is produced via two main production routes. 1: from iron ore to steel, 2: from scrap to steel. Route 1 can be taken via 1a) blast furnace, 1b) smelting reduction, and 1c) direct reduction. For each process route, CO is partly emitted into the air and mainly re-used in the steel production process, indicated by a blue arrow. Only a minor fraction is emitted into the atmosphere (purple arrow). Adapted from reference [37].

For the integrated blast furnace route (route 1a), gas-by-products and their components are presented in for the individual process steps . Converter gas has the highest CO content (70%) compared to the blast furnace (22%) and the coke plant (7%). Consequently, converter gas would be first choice for CO as an alternative carbon source. Other references do not vary significantly[45] and are included in the error calculation.

Table 15: By-product gases from steel production via blast furnace route; analysis before combustion [32,33,34]

Gas fraction	Unit	Coke plant	Blast furnace	Converter gas
CO	vol%	7%	22%	70%
H_2	vol%	61%	2%	2%
CH_4	vol%	22%	0%	0%
Hydrocarbons	vol%	3%	0%	0%
CO_2	vol%	2%	22%	14%
N_2	vol%	6%	54%	16%

However, the volume fraction of route 1a is dominated by the blast furnace and usually all gas-by-products are combined and currently re-used in the production process (Figure 23).

[45] G. Harp, C. Bergins, T. Buddenberg, presentation Jahrestreffen Frankfurt II- Jahrestreffen der ProcessNet Fachgruppe Energieverfahrenstechnik, 21.-23.3.2017, Frankfurt

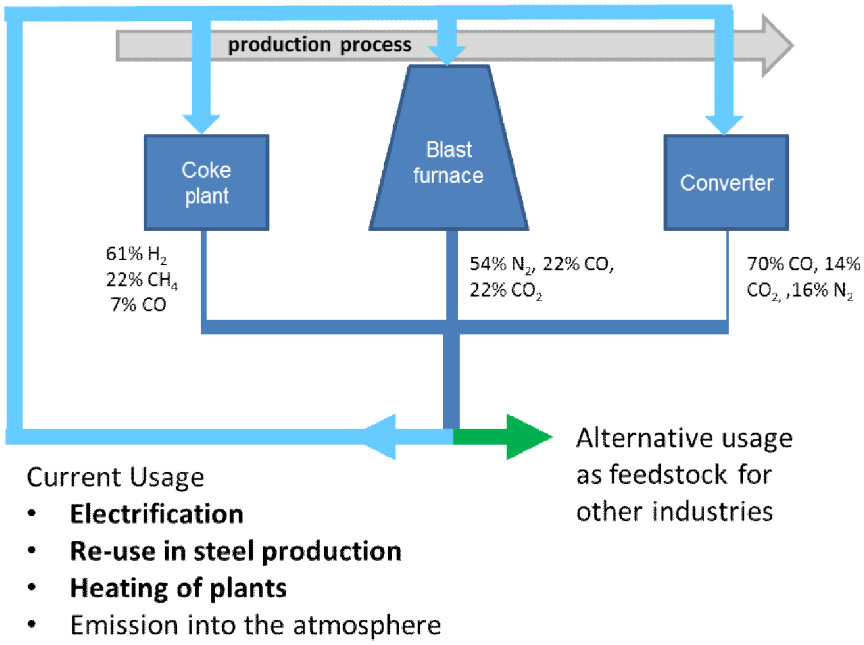

Figure 23: Emissions in the steel production process via blast furnace route. Composition of by-product gases from reference[32,33,34].

For the evaluation of the potential of CO as feedstock for the chemical industry, data from the E-PRTR database can be used to estimate the CO that is actually produced from the steel production if the following facts for the individual facilities were known:

- Plant facts
- Process routes
- Crude steel production
    - Gas composition and volume flow (see Table for the integrated blast furnace route 1a)
    - Fraction and recycle path for current re-use of CO

In many cases, these facts are often confidential and not freely accessible, often only a qualitative but not quantitative analysis is published. Also, data from different sources are difficult to compare since they use different classifications of routes or do not specify the amount and the exact experimental methods how the emissions were determined. [46,47,48]

[46] Steel Statistical Yearbook 2016, data from 2014, https://www.worldsteel.org/
[47] Scheme Steel production routes, VDEH, http://en.stahl-online.de/wp-content/uploads/2013/10/Bild-24_eng.jpg

The CO estimation shall be exemplified for the steel production in Duisburg and compared to point sources listed in the E-PRTR database. The calculations have been performed using data for gas composition, steel production and volume flow for the blast furnace route, but the exact location and number of facilities is not given within these references. Therefore, the calculation is compared to two different scenarios: a) Hüttenwerk Krupp Mannesmann GmbH only, and b) all Duisburg facilities including the aforementioned facility (16).

Table 16: Facilities of the iron and steel industry located in Duisburg, Germany, EPRTR.

Facility Name	CO Emissions (Mt)
Hüttenwerke Krupp Mannesmann GmbH	0.220
ThyssenKrupp Steel Europe AG Werk Schwelgern	0.132
ThyssenKrupp Steel Europe AG Werk Beeckerwerth	0.006
ThyssenKrupp Steel Europe AG Werk Hamborn	0.004
ThyssenKrupp Steel Europe AG Werk Bruckhausen	0.004

With 8000 to 8760 hours of operation per year this results in 4.3 to 4.8 Mt CO, if no CO would be re-used.

Compared to scenario a) the listed CO emission 0.22 Mt CO could be increased by a factor of 20±2. Compared to scenario b) this could increase the listed emission of 0.37 Mt CO by a factor of 12±1 (Figure 24).

[48] Emissionsfaktoren zur Eisen- und Stahlindustrie für die Emissionsberichterstattung, Umweltbundesamt, 2012

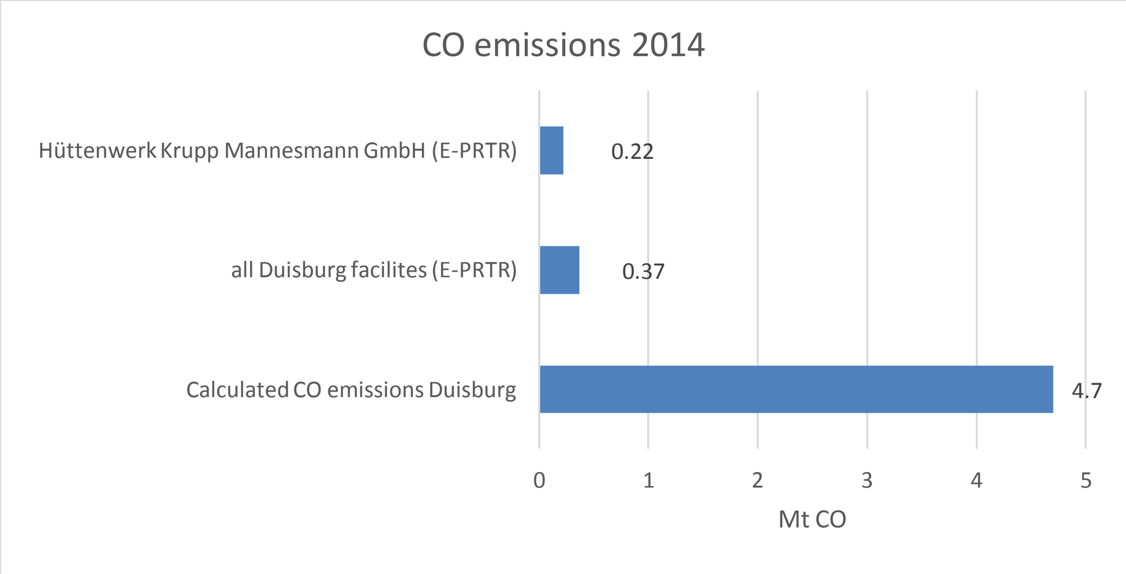

Figure 24: Example of calculated CO emissions for Duisburg from steel manufacturing if no CO would be consumed within the process and comparison to E-PRTR database which gives the real emissions of point sources and includes re-use of CO at the steel production facilities.

However, for a detailed mapping of the potential CO amount for the other facilities, specific input from the steel industry is required as CO emissions are facility-dependent (process route, plant configuration, amount and composition of raw materials, recycling of CO). It is known that the gas composition of gas-by-products is relatively similar for equivalent routes, but volume flow and the crude steel production can vary significantly.

However, using the data for the Duisburg facility above an estimation of the European steel emissions can be made for plants using oxygen-blown converters (blast furnace route 1a and the smelting reduction route 1b). Crude steel production for 2014, for both routes together, is listed in reference[39], table 17] for Europe (EU 28 & other). Crude steel production via route 1a and 1b is 115 Mt, which is 55% of the total steel produced via all four routes in Europe and thus comparable to the E-PRTR database.

Table 17: Crude steel production for 2014 by process [adapted from SSYB].

Region	Oxygen blown converter [Mt] (route 1a, 1b)	Direct reduction [Mt] (route 1c)	Electric furnace [Mt] (route 2)	Open heat furnace [Mt]	Total [Mt] (all routes)
EU 28	103,27	0,67	66,04	0,00	169,98
EU other	11,66	0,00	26,72	0,00	38,37
World	1229,80	77,12	430,04	7,58	1736,96

Using the same calculation as above and recalculated it with a crude steel production of 115 Mt, the potential CO amount is 43±3 Mt for the integrated route taking all process steps together (route 1a coke plant, blast furnace, oxygen blown converter and route 1b smelting reduction oven, oxygen blown converter). The value derived from E-PRTR database for the steel industry is just 1.2 Mt (55% of 2.2 Mt CO). If the converter gas could be separated from the 45 Mt and the CO extracted this would be 6 Mt CO.

In general emissions would be lower due to a systematic error, as for this estimation the volume flow for route 1b was set equal to route 1a-which is different in the real production process. Nevertheless, it is obvious that a much higher CO amount, with an increase of 12-20 times, could be available and used as an alternative carbon source.

4.3 Key challenges

CO can be used directly or as syngas to produce chemical raw materials, fuels or polymers by the chemical industry. In an industrial symbiosis, this increase in the CO value chain and the reduction of toxic CO emissions is the key motivation for alternative use of CO from the steel industry point of view.

However, alternative use of CO automatically implements that CO would be lost for the conversion to electricity/energy- which is not economically feasible at present[49,50] Furthermore, separation and purification techniques are needed to match the requirements for CO for the use in the chemical industry. Fluctuation of by-product gases in the steel production process would also require storage solutions.

To encourage investments and secure long term and high capital expenditures political framework conditions and taxes (e.g. the German Renewable Energy Act (EEG-Umlage) and Emissions Trading systems have to be stable over a long-term perspective to enable a cross-sectional use of by-product gases[51]. This has also been identified in the revised Renewable-Energy-Directive (RED II) by the European Commission. Industrial symbiosis has also to be consistent with European and national cartel laws.

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[49]] M. Marion, M. Baldermann, H.P. Domels, M. Hensmann, B. Stranzinger, and M. Sprecher, ĂRationelle Nutzung der Kuppelgase im Energieverbund in integrierten Hüttenwerkenñ, stahl und Eisen, 125, (2015), Nr. 4

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4.4 Future outlook and potential impact

CO emissions from point sources can be used as alternative carbon source if the amount of CO and the purity match the requirements of the consumers. Currently, emissions from the steel industry are the primary point sources of CO in Europe.

Therefore, future processes to increase the potential impact of CO as alternative carbon source require technical changes as well as economic and if necessary political support. From the technological point of view, separation technique to split the mixed gas fraction into its individual components and the consecutive cleaning and purification steps are known in their physicochemical principles. The corresponding technologies are already tested on a lab scale but their feasibility on an industrial scale has not been shown yet. This is part of the Carbon2Chem project (funded by the German Federal Ministry of Education and Research) and steel2chemicals (NL project). *Both projects have aim to developed novel technologies based on syngas as alternative carbon source, but demonstration of the technical feasibility in an industrial environment and industrial scale is still in progress.*

Reuse-of CO within the production process is currently essential for the energetic efficiency and independence of the production sites from external supplies. For cross-sectional symbiosis changes of the political and also economic framework conditions are needed including building of transportation infrastructure to get CO from the producer to the consumer.

We could show that the potential amount of CO could be higher by a factor of 12-20, compared to the currently reported values just by the European steel industry. Together with other single sources, e.g. the appointed SiC factory in Spain, facilities from the cement industry (construction sector), and electrolysis plants in the aluminum production best practice examples for an alternative use of CO will be identified in the progress of CarbonNext.

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