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Abstract

Purpose – The aim of this study is to assess the role of CO_2 capture and storage (CCS) technologies in reduction of CO_2 emissions from European industries.
Design/methodology/approach – A database covering all industrial installations included in the EU ETS has been created. Potential capture sources have been identified and the potential for CO_2 capture has been estimated based on branch and plant specific conditions. Emphasis is placed here on three branches of industry with promising prospects for CCS: mineral oil refineries, iron and steel, and cement manufacturers.
Findings – A relatively small number (~270) of large installations (>500 000 tCO_2/year) dominates emissions from the three branches investigated in this study. Together these installations emit 432 $MtCO_2$/year, 8% of EU's total greenhouse gas emissions. If the full potential of emerging CO_2 capture technologies was realized some 270-330 Mt CO_2 emissions could be avoided annually. Further, several regions have been singled out as particularly suitable to facilitate integrated CO_2 transport networks. The most promising prospects for an early deployment of CCS are found in the regions bordering the North Sea.
Research implications/limitations – Replacement/retrofitting of the existing plant stock will involve large investments and deployment will take time. It is thus important to consider how the current industry structure influences the potential to reduce CO_2 in the short-, medium- and long term. It is concluded that the age structure of the existing industry plant stock and its implications for the timing and deployment rate of CO_2 capture and other mitigation measures is important and should therefore be further investigated.
Practical implications – CCS has been recognized as a key option for reducing CO_2 emissions within the EU. This assessment shows that considerable emission reductions could be achieved if targeting large point sources in some of the most emission intensive industries. Yet, a number of challenges need to be resolved in all parts of the CCS chain. Efforts need to be intensified from all stakeholders to gain more experience with the technological, economical and social aspects of CCS.
Originality/Value – This study provide a first estimate of the potential role for CO_2 capture technologies in lowering CO_2 emissions from European heavy industry. By considering wider system aspects as well as plant specific conditions the assessment made in this study gives a realistic overview of the prospects and practical limitations of CCS in EU industry.
Keywords CCS, Industry, European Union, Refineries, Iron- and Steel, Cement
Paper type Research paper

1. Introduction

Over the last decade the EU has implemented a range of policies aimed at combating climate change. Even though the trend varies across member states and between sectors the EU has managed to decrease overall greenhouse gas (GHG) emissions by 9.3% between 1990 and 2007 (EEA, 2009a). However, to meet the targets of a 20-30% emission reduction by 2020 and a further reduction of 50-80% by 2050 compared to the 1990 levels, extensive additional efforts obviously need to me made. In the European Commission's climate change and energy package (European Commission, 2008a) which was introduced in January 2008 and adopted by the European Parliament and Council in April 2009, a number of legislative proposals are put forward aimed at facilitating further emission reductions beyond the commitment period under the Kyoto protocol (2008-2012). Two central components of this package are a strengthening and expansion of the EU Emission Trading System (EU ETS) and a regulatory framework for the promotion and development of CO_2 Capture and Storage (CCS) technologies.

The EU ETS was introduced as a means to allow EU member states to achieve compliance with their commitments under the Kyoto Protocol as cost effectively as possible. In its present form the system covers CO_2 emissions from large stationary sources in the energy and industrial sectors; combustion installations, oil refineries, coke ovens, iron and steel plants, and industries manufacturing cement, lime, glass, ceramics, and pulp and paper (EU, 2003). Together, these installations account for more than 40% of the EU's total GHG emissions.

To realise the goals of further, extensive, emission cuts beyond 2020 the European Community has agreed to increase efforts to deploy CCS technologies (EU, 2009). To support this development the EU has set out to provide economic incentives and to develop a legal framework for CCS (e.g. In December 2009 the European Commission granted a total of €1 billion to six CCS projects in the power sector (European Commission, 2009a)). From 2013, CO_2 capture, transport and storage installations will be incorporated in the EU ETS. To help stimulate the construction and operation of commercial demonstration projects, 300 million emission allowances will be set aside for them in the new entrants reserve. Between 2013 and 2016 Member States will also be allowed to use revenues from the EU ETS to support the construction of highly efficient power plants, including power plants that are capture ready.

In a number of reports (e.g. (IEA, 2004; IPCC, 2005)) CCS has been recognized as one of a number of key mitigation options for combating global climate change. There are also numerous examples of studies in the literature exploring the potential for CCS and matching CO_2 sources and sinks on national, regional and global level (e.g. (Farla *et al.*, 1995; IEA GHG, 2005; Stangeland, 2007; Damen *et al.*, 2009; Vangkilde-Pedersen *et al.*, 2009)). It has been shown that through application of CCS technologies CO_2 emissions from large stationary sources can be lowered considerably. To date most attention has been focused on the application of CCS technologies in fossil fuelled power plants. The aim of the assessment presented in this paper is to provide a first estimate of the potential for CO_2 capture in European industry and to identify regions that could facilitate deployment of integrated CO_2 transportation networks. This study builds on an earlier investigation of the potential for CCS in the European electricity generation system (Kjärstad and Johnsson, 2009).

2. Methodology

This assessment is based on the current structure of the European industry. A database covering all industrial installations included in the EU ETS has been created (the main features of this database are presented below).

The analysis has been limited to three branches, mineral oil refineries, iron and steel, and cement manufacturers. Possible capture sources have been identified and the overall potential for CO_2 capture has been estimated based on the following assumptions:

- Only large point sources have been assumed to be suitable for CO_2 capture. In this study, 0.5 Mt CO_2/year is arbitrarily chosen as representing an emission level which will give CO_2 avoidance costs that would make capture economically viable.

- Branch specific conditions; CO_2 capture is not applicable in all manufacturing processes. Individual plants have been classified depending on process route (e.g. integrated steel plants and mini mills).

- Plant specific conditions; total emissions from a plant are typically the sum of several separate emission sources. The different flue gas streams differ with respect to their suitability for CO_2 capture. Capture is assumed to be limited to the major flue gas streams of the respective processes.

- Capture technology; there are a number of alternative capture technologies that are applicable to industrial processes. Technological and economical challenges vary depending on the capture option chosen. To illustrate the varying potential of options two alternative setups of capture technologies have been used in the assessment.

Finally, the spatial distribution of emission sources has been considered. One way to limit costs would be to create capture clusters in regions with several emission sources located relatively close to each other. Such clusters would be a way to facilitate the development of integrated transportation networks. The geographical distribution of point sources, the occurrence of potential capture clusters and their location in relation to suitable storage sites have been assessed via geospatial analysis in ArcMap.

2.1. The Chalmers industry database

To analyse the possibilities and limitations imposed by the present energy infrastructure a database of facility level data on key processes and plant components related to energy use and CO_2 emissions has been created. The Chalmers energy infrastructure database has been designed to cover both the supply side and the demand side of the European energy systems (Kjärstad and Johnsson, 2007). The database is divided into a set of sub-databases: the Chalmers power plant database (Chalmers PP db), the Chalmers fuel database (Chalmers FU db), the Chalmers CO_2 storage database (Chalmers CS db) and the Chalmers member states database (Chalmers MS db). The databases are being continuously updated and their scope is gradually being widened. As part of the study presented in this paper the database has been updated with facility level data on ~4000 industrial installations included in the EU ETS. This new sub-database, the Chalmers industry database (Chalmers IN db), includes the following features:

- Covers EU27+ Norway and Liechtenstein
- Includes industrial installations in seven industry subsectors including; mineral oil refineries, coke ovens, metal ore roasting or sintering installations, installations for the production of pig iron or steel including continuous casting, installations for the production of cement clinker or lime, installations for the manufacture of glass including glass fibre, installations for the manufacture of ceramic products and industrial plants for the production of pulp, paper or board
- Exact location of each plant; country, city, address and geographical coordinates

- Emissions and allocated emission allowances; verified CO_2 emissions and allocated emission allowances for the period 2005-2008 and allocated emission allowances for 2005-2012
- Plant level characteristics; Installations are classified depending on type of production process, e.g. Integrated steel plants (Blast Furnaces) and Minimills (Electrical Arc Furnaces). For large emission sources (>0.5 Mt CO_2/year) the database include information on, process technologies, production capacity, fuel mix and age of capital stock.

The primary data source has been the Community Independent Transaction Log (CITL, 2009). Other information sources include the European Pollutant Emission Register (E-PRTR, 2010), the IEA GHG CO_2 Emissions database (for more details see (IEA GHG, 2006)) and the Plantfacts database (described in (Steel Institute VDEh, 2006)).

3. Opportunities for CO_2 capture in European industry

Investments in CO_2 capture technologies involve high capital costs. For CO_2 capture to be economically and technologically feasible particular CO_2 sources need to emit significant quantities of CO_2 (to minimize the CO_2 capture cost in €/tCO_2). Capture is thus likely to be applicable only for large stationary emission sources. There are a number of industrial activities that generate flue gas streams with high concentrations of CO_2 (e.g. natural gas processing installations and ammonia and hydrogen production plants). These high concentration sources (with CO_2 concentration close to 100%) have been pointed out as possible early prospects for the implementation of CCS (IPCC, 2005). Their share of total emissions from large stationary sources are, however, low. Fossil fuelled power plants, particularly coal fired power plants, are generally thought to be most suitable for a large-scale deployment of CO_2 capture. A number of pilot scale demonstration projects have been initiated and several more are being planned (European Commission, 2009a). In addition to the power sector some energy intensive manufacturing industries have been pointed out as suitable for CO_2 capture. Manufacturing of primary materials such as chemicals, petrochemical, iron and steel, cement, paper and aluminium require significant inputs of electricity, heat and steam. Fossil fuels remain the most important source of energy. Many industries have managed to lower their energy use and CO_2 emissions considerably through increased energy efficiency and through alterations in production processes and in fuel and feedstock mixes. Still however, manufacturing industries account for roughly 10% of the total CO_2 emissions in the EU. Many of these industries are now included in the EU ETS. The power and heat sector dominates the trading system both in terms of number of installation (>7000) and actual emissions (72% of the overall emissions covered by the EU ETS). Mineral oil refining, iron and steel manufacturing and cement and lime production together account for more than 22% of the emissions (EEA, 2009b). A relatively small number (~800) of large emission sources (> 0.5 Mt CO2/year) are collectively responsible for more than 80% of all EU ETS emissions (~30% of EU's total GHG emissions). Figure 1 provides an overview of the distribution of CO_2 emissions between the different sectors in EU27.

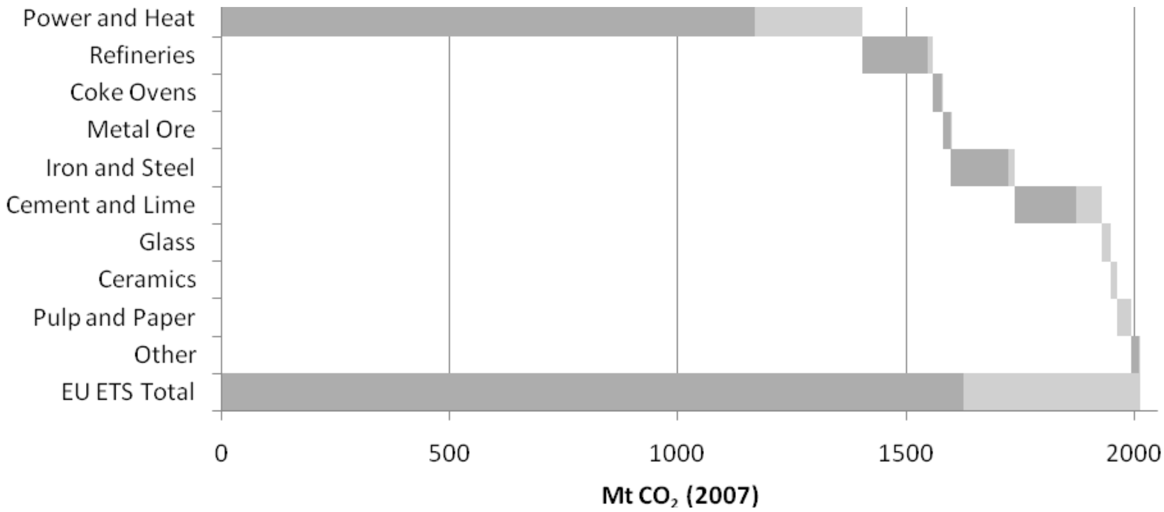

Figure 1. Sectoral breakdown of the EU ETS. Large emission sources (>0.5 Mt CO_2/year) share of sectors total emissions, grey, and smaller emissions sources (<0.5 Mt CO_2/year), light grey. A relatively small number of large emitters dominate the overall emissions of the trading system (CITL, 2009).

In theory it would be possible to apply CO_2 capture to all of these large point sources. In practice, however, opportunities for capture vary across the different branches and between individual plants. Important considerations for the prospects for CCS for a given point source are:

- The possibility to limit the costs associated with CO_2 capture. The cost of CO_2 capture depends primarily on the properties of their flue gas streams and the flue gas flow. CO_2 typically represents only a small portion of the flue gas.
- Location in relation to other large CO_2 emission sources and to storage sites, i.e. to facilitate integrated transportation networks to suitable storage sites.
- The prospects of applying CO_2 capture without disrupting the core production processes.

There are several methods to separate and capture CO_2 in industrial processes. Capture technologies are often divided into three main categories:

- Pre-combustion processes, where carbon is separated from the fuel before combustion.
- Post-combustion processes, where CO_2 is removed from the flue gas.
- Oxyfuel combustion, where fuel is combusted in oxygen (mixed with recirculated flue gas) instead of air creating a more or less pure CO_2 stream in the off gases.

In principle, most of these technologies are applicable to the industrial processes examined in this study. Post combustion capture through chemical absorption could be applied to almost all industrial processes (Ecofys, 2004). Process specific capture technologies could, however, provide more cost effective options. A summary of the assumptions made on possible capture options in the three branches assessed here are presented in Table 1. The following sections describe the challenges associated with CO_2 capture in each branch more thoroughly.

Table 1. Summary of the characteristics of the capture options considered in this study

Source type	Targeted flue gas stream	CO_2 concentration in gas stream[d] (% by gas volume)	Capture technology	Cost per tonne of CO_2 captured (€/t)	Average recovery rate (% of plants total CO_2 emission)
Mineral oil refineries[a]	Furnaces and boilers	3-13	Oxyfuel combustion	~30	65
	CHP Plant + Catalytic cracker		Post combustion capture	~45	80
Integrated steel plants[b]	Blast furnace	20	Top Gas Furnace Recycling	~20	70
Cement plants[c]	Precalciner	14-33	Oxy combustion	~34	50
			Post combustion capture	~60	80

[a] Estimations based on (IPCC, 2005; Allam *et al.*, 2005; StatoilHydro, 2009).
[b] Estimations based on (IPCC, 2005).
[c] Estimations based on (IEA GHG, 2008)
[d] CO_2 concentrations in dominating flue gas stream in conventional production processes.

3.1. Refineries

Mineral oil refining involves several production steps where crude oil is purified, separated and transformed into a wide array of petroleum products. A modern refinery typically consists of an integrated network of separate processing units. Most flue gas emissions result from the generation of heat and electricity. The furnaces and boilers that feed the different sub processes are fuelled by a mix of petroleum coke, still gas (refinery gas, i.e. by products in the refining process), petroleum fuels and natural gas. Energy use and CO_2 emissions vary depending on what type of crude oil is being processed and on the mix and quality of the final products.

The total CO_2 emissions from a refinery are therefore the sum of several emission sources of varying size. The flue gases from these different sources have different properties and have varying degree of suitability for CO_2 capture. As indicated in Table 2 process heaters and steam boilers are responsible for the major share of the CO_2 emitted from a typical refinery. There are two main options for targeting the CO_2 emissions from furnaces and boilers; either CO_2 is separated from the flue gases through chemical absorption (post combustion capture) or heaters and boilers are converted to oxyfuel operation with CO_2 capture (Allam *et al.*, 2005). In addition, some European refineries have invested in combined heat and power (CHP) plants covering almost all of the electricity demand and a large share of the internal heat demand. If targeting the CHP flue gas and the off-gas from the catalytic cracker ~80% of the direct CO_2 emissions from the refining process would be available for capture (StatoilHydro, 2009). It is technically possible to expand the scope of the capture to include other sub-processes, increasing the overall CO_2 abatement potential, but this would also increase the cost.

3.2. The iron and steel industry

The iron and steel industry is highly energy intensive and the production of crude steel is associated with significant CO_2 emissions. The sector has a complex industrial structure, but two production routes dominate global production (IPPC, 2009a):

- Integrated steel plants; the most common production route. Involves a series of interconnected production units (coke ovens, sinter plants, palletising plant, blast furnaces, basic oxygen furnaces and continuous casting units) which processes iron ore and scrap to crude steel. Coke, derived from coal, often functions both as fuel and reducing agent.

- Mini-mills; where scrap, direct reduced iron and cast iron is processed in electrical arc furnaces to produce crude steel.

Nearly 60% of the steel produced in EU27 is produced through the integrated route (coke oven, blast furnace, basic oxygen furnace). The rest is produced in electric arc furnaces and a very small fraction (~0.3%) in open hearth-furnaces (WSA, 2008).

The opportunities for CO_2 capture in the steel production chain vary depending both on the process and the feedstock. In the integrated steel production route there are three main process gas flows, coke oven gas (COG), blast furnace gas (BF gas) and basic oxygen furnace gas (BOF gas) (Farla *et al.*, 1995). These gas flows typically serve as fuel feedstock throughout the entire chain of production. The largest flow of CO_2 in a conventional integrated steel mill is generated in the blast furnace (see Table 2 below).

Recovery of CO_2 from the BF gas has been recognized as a feasible option for capture in the steel industry (IPCC, 2005). If applying current end-pipe-technologies to existing blast furnaces ~30% of the overall CO_2 emissions from a conventional integrated steel plant could be recovered. Capture could be applied to other gas flows in the production process but costs are likely to be higher, since volumes and concentrations are lower. Apart from the two dominating production routes there are several newer iron making processes compatible with CO_2 capture. Efforts are being made to develop new steel making processes that could facilitate further CO_2 emission reductions. The Ultra-Low CO_2 Steelmaking (ULCOS, 2010) programme have identified a number of process technologies that combined with capture could reduce CO_2 emissions with at least 50% compared to current best routes.

One of the most promising opportunities for CO_2 capture in the steel industry would be to replace or retrofit conventional blast furnaces with Top Gas Recycling Blast Furnaces (TGR-BF). In a TGR-BF the CO_2 is separated from the BF gas and the remaining, CO rich, gas stream is recirculated into the furnace. If simultaneously replacing preheated air with pure oxygen the BF gas stream would be free of N_2 thus simplifying CO_2 capture. It has been estimated that 70% of the CO_2 emitted from an integrated steel plant could be recovered if TGR-BF with CO_2 capture were to be introduced (IPCC, 2005).

3.3. The cement industry

In a cement plant calcium carbonate ($CaCO_3$) and different forms of additives are processed to form cement. The raw material feedstock typically consists of calcareous deposits, such as limestone, marl or chalk. The manufacturing involves three main production steps (IEA, 2007):

- Raw material preparation: mining, grinding and homogenising of raw material.
- Clinker burning: the raw material is gradually heated and finally burned at a peak temperature around 1450°C. At around 900°C the calcination takes place and CO_2 is released from calcium carbonate. As the temperature rises the clinkerisation begins. Calcium oxide reacts and agglomerates with silica, alumina and ferrous oxide, forming cement clinker.
- Cement preparation: grinding and mixing of clinker and additives.

Cement production is very energy intensive. Significant amounts of electricity are used to power both the raw material preparation and the cement clinker grinding and large quantities of fuels are needed in the clinker burning process. The clinker production is the most energy intensive production step, it accounts for more than 70% of the total energy consumed (Worrel *et al.*, 2001). There are two basic types of cement clinker production processes, wet or dry, and a number of different kiln types. Energy intensities vary depending on choice of production route and on kiln technology (IEA, 2007). In Europe around 90% of the production is based on dry processes and most plants use rotary kilns (IPPC, 2009b).
Almost all of the direct CO_2 emissions from the cement production arise from the clinker burning process. Roughly 60% of the CO_2 emissions originate from the calcination, the remaining CO_2 emissions are related to fuel combustion (IPPC, 2009b). In modern cement plants fuel is inserted in two stages: in the precalciner where the raw material is preheated and calcined (>90% of the calcinations takes place in the precalciner) and in the rotary kiln where the clinkerisation occurs (IEA GHG, 2008; IPPC, 2009b).
Two options for CO_2 capture in the European cement industry have been considered here; post combustion capture and oxy-combustion (in precalciner) with capture (IEA GHG, 2008).
Post combustion capture could be applied utilizing the same basic principles that are being developed for coal fired power plants. It has been estimated that 95% of the CO_2 emissions from a cement plant can be avoided if post combustion capture is introduced. The regeneration of the CO_2 capture solvent would, however, require additional generation of steam thus increasing the overall CO_2 emissions slightly.
Oxy-combustion with CO_2 capture could be applied both in the precalciner and in the kiln but by targeting the precalciner only the impacts on the clinkerisation process could be minimized. Around 50% of the CO_2 from a cement plant could be captured using the oxy-combustion precalciner setup.

Table 2: Breakdown of CO_2 emissions from industrial production processes

	Source	Fraction of CO_2 emissions
Refineries[a]	Furnaces and boilers	65%
	Regeneration of cat. cracker catalyst	16%
	Power (55% imported)	13%

	Other sources	6%
Integrated steel plants[b]	Coking plant	5%
	Sinter plant	10%
	Blast furnace	65%
	Other sources[a)]	20%
Cement plants[c]	Pyroprocessing (in precacliner and rotary kiln)	>80%
	Other sources	<20%

[a] Based on (IEA GHG, 1999). Other emission sources include flaring, methane steam reforming, effluent processing and incineration.
[b] Estimations based on (Wang *et al*., 2009; IPPC, 2009a). Other emission sources include palletising plant, continuous casting, basic oxygen furnace, rolling and finishing, oxygen plant and power plants.
[c] Estimations based on (IEA GHG, 2008). In a modern cement plant a large share of the CO_2 emissions originates from the precalciner (~60%).

4. Results

4.1. Mapping the large point sources

A total of 270 installation have been identified as large emission sources (>0.5 Mt/year), including 89 refineries, 33 integrated steel plants (with 74 blast furnaces in operation) and 148 cement plants (with more than 260 cement kilns in operation). Together these installations emit over 430 MtCO_2/year, more than 8% of EU's total GHG emissions. Consequently changes in each single plant could have significant effects on the overall GHG emissions of the EU. The occurrence of large emission sources vary considerably between EU member states. Five countries, Germany, Spain, United Kingdom, Italy and France stand out as having both large overall emissions and many large emitters. The heavy industries share in the total GHG emissions also vary across member states. Large industry point sources typically accounts for between 8% and 12% of the total GHG emissions (12 countries fall into this category). In the Czech Republic, Denmark, Ireland, Poland, Slovenia the contribution from large industry emission sources to the total GHG emissions is smaller with a share of less than 5%. In Slovakia the contribution is much larger with three large industries responsible for more than a quarter of the total GHG emissions. In Estonia, Latvia and Malta there are no industries with emissions exceeding 0.5 Mt CO_2/year. These differences may affect the priority given to industry CO_2 capture in the different member states.

4.2. Potential for industry CO_2 capture

If realizing the full potential of the CO_2 capture technologies considered in this study 60-75% of the emissions from large industry point sources could be avoided (see Table 3.). In Scenario A, post combustion capture technologies dominate in the refinery and cement industry and conventional blast furnaces are replaced with Top gas recycling blast furnaces in integrated steel plants. In Scenario B, refinery furnaces and boilers are converted to oxyfuel operation, oxy combustion is applied in cement plant precalciners and Top gas recycling blast furnaces with CO_2 capture dominate the steel industry. The mitigation potential is significantly larger in Scenario A where approximately 330 Mt CO_2 would be captured annually, compared to roughly 270 Mt CO_2 per year in Scenario B. The cost associated with CO_2 capture would, however, most likely be higher in Scenario A than in Scenario B. These estimations should be seen as illustrations of the potential role of CO_2 capture in large industry point sources, i.e. a first estimate.

Table 3. Potential for CO_2 capture at large industrial emission sources in EU.

Industry category	CO_2 emission captured (Mt CO_2/year)	
	Scenario A	Scenario B
Mineral oil refineries	116	94
Integrated steel plants	106	106
Cement plants	107	67
Total	329	267

4.3. Distribution of emission sources

As illustrated in Figure 2 the large industry point sources are unevenly distributed over the European continent. By aggregating industry CO_2 emissions on regional level (the Nomenclature of territorial units for statistics, NUTS regions, has been used to represent the regions of the EU (European Commission, 2009b)), 23 regions with more than one large industrial point source and where aggregated emissions exceed 5 Mt CO_2/year, have been identified (highlighted in grey (>5 Mt CO_2/year) and dark grey (>10Mt CO_2/year)). The aggregated emissions from large industry point sources in these regions amount to approximately 200 Mt CO_2/year. Furthermore, based on the relative distance of the individual point sources and the emission density of these sources, 22 regions have been singled out as possible capture clusters (dashed contours).

To limit the costs of CO_2 capture, transport and storage, clusters need to be matched with suitable storage sites. Potential storage sites are unevenly distributed across EU. Most member states have identified geological structures that could be used for CO_2 storage but the accuracy of the estimated storage potential varies. The potential for geological storage of CO_2 in EU has been assessed in the GESTCO and GeoCapacity projects (Vangkilde-Pedersen, 2008; GeoCapacity, 2009). The GESTCO project covered 7 EU member states and Norway. In the GeoCapacity project which followed the GESTCO project, the geographical coverage has been expanded to include totally 25 European countries (including 20 EU member states and 5 neighboring countries). Potential storage sites include saline aquifers, hydrocarbon fields and unminable coal seams (although coal seams have a limited storage potential and storage can be technologically challenging). The saline aquifers are considered to have the largest storage potential but more detailed analysis is needed to determine site specific capacities. Even though the storage potential is lower, depleted hydrocarbon fields have the advantage of being relatively well explored, the geology has often been carefully examined and the fields have proven capable of retaining fluids and gases for very long time periods. The best matches between industry emission clusters and potential storage sites are found in regions close to the North Sea; in the eastern part of the United Kingdom, northern France, Belgium, Denmark, Netherlands and in north-western Germany.

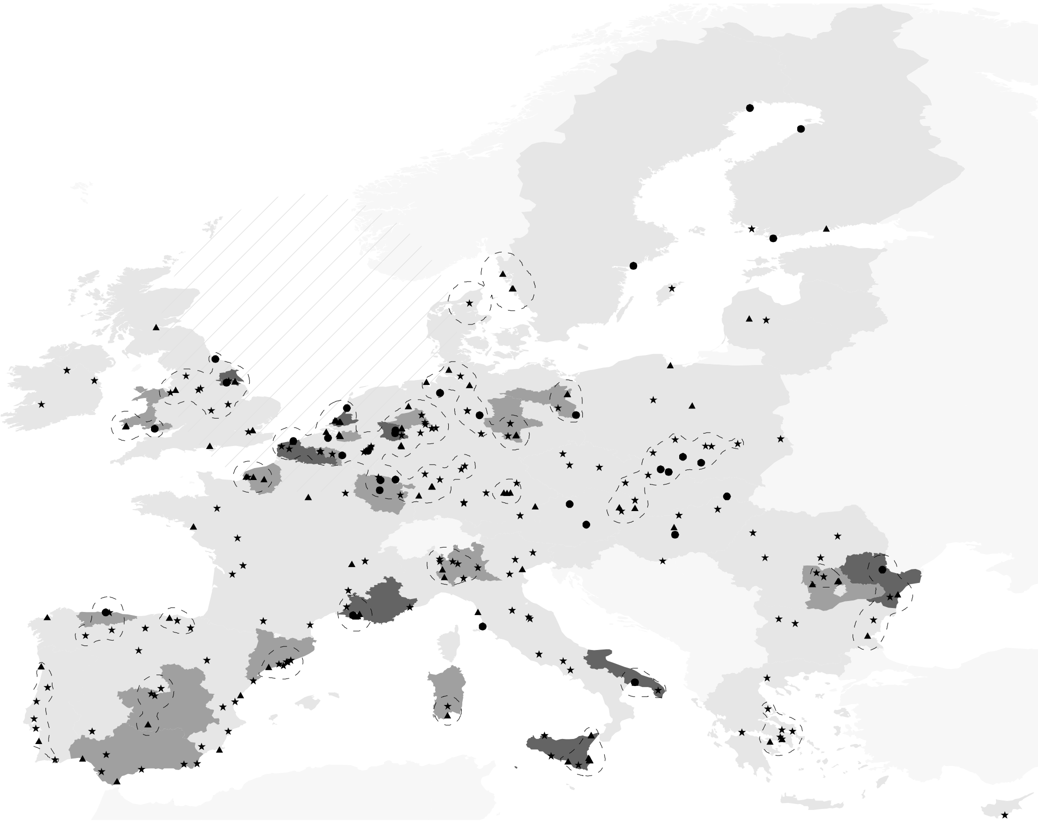

Figure 2. Geographical distribution of large point sources (>0.5 Mt CO_2/year) in the European industry sector. Triangles denote refineries, circles integrated steel plants and stars cement plants. Regions where emissions from large industry point sources exceed 5 Mt CO_2 annually are highlighted in grey (>5 Mt CO_2/year) and dark grey (>10 Mt CO_2/year). Areas with dashed contours represent regions with high densities of large point sources (possible capture clusters).The underlying map was compiled using data from GISCO (European Commission, 2008b) © EuroGeographics for the administrative boundaries.

5. Discussion

This study gives an overview of the prospects and practical limitations of CCS in EU industry, considering plant specific conditions as well as wider system aspects. The assessment of this work shows that by adapting a relatively small number of large emission sources in the European industry sector for CO_2 capture, a significant reduction in total EU CO_2 emissions could be achieved. Yet, a number of challenges need to be addressed before CCS can be seen as a viable option for reducing CO_2 emissions from EU industry. Issues such as costs, public acceptance, legal aspects of CO_2 transport and storage and future policy development will be crucial both for the scale and rate of the diffusion of CCS.

All of the industries assessed here involve complex production processes. If CO_2 capture is going to be applicable to industry, capture technologies that do not interfere with the core processes need to be developed. Post-combustion capture could generally be applied without negative impacts on the production processes, but the associated costs are generally high. More process specific capture technologies, with lower costs, are being explored (e.g. oxy-fuel combustion in refinery furnaces and boilers, TGR-BF in integrated steel plants and oxy-combustion processes for the cement industry). Yet, deployment on a commercial scale seems to be at least one decade away. Much development work remains both with the economical and process related aspects of CO_2 capture technologies. Even with these pieces in place,

retrofitting of the existing plant stock and investments in new capture ready plants will take time.
The estimations of the potential for industry CCS presented in this paper are based on a rather simplistic approach and they are meant only to serve as illustrations of the potential role of CO_2 capture in EU industry. The existing industry infrastructure has been used as a reference point for the estimates. The capital age of the existing industry plant stock and its implications for the deployment rate of CO_2 capture have not been considered. CO_2 emissions from the industry sector are assumed to remain relatively constant over time. Increases in CO_2 emission from industry due to increased production are assumed to be offset by CO_2 mitigation measures other than CCS. Further, it should be noted that the assumptions made here about CO_2 capture costs are rather speculative. The industry CO_2 capture projects currently being set up will provide valuable insights on both the technical and economical aspects of industry capture. Most likely, there will be significant development in both policy setting (e.g the future development of the EU ETS and other policy instruments related to climate change mitigation and energy use) and in technology over the coming decades which would alter the prerequisites for the deployment of CCS technologies. Examples of planned industry demonstration projects include a post-combustion capture installation connected to a new refinery CHP plant in Mongstad (Norway) (StatoilHydro, 2009) and the introduction of two TGR-BF's, one mid-sized and one full scale, at the integrated steel plants in Eisenhüttenstadt (Germany) and in Florange (France) (ESTEP, 2009).

6. Conclusion

A first estimate of the potential for CO_2 capture in European industry shows that considerable emission reductions can be achieved if large point sources in the most emission intensive branches (i.e. mineral oil refineries, integrated steel plants and cement plants) are targeted. If realizing the full potential of the CO_2 capture technologies considered in this study 60-75% of the emissions from large industry point sources could be avoided.

Further the spatial distribution of large industry point sources, the occurrence of potential capture clusters and their location in relation to suitable storage sites have been considered. The analysis indicates that opportunities exist in several regions to lower total costs of the CCS value chain if efforts to develop integrated CO_2 transportation networks were coordinated across sectors and between member states. The best matches between sources and sinks are currently found in regions bordering the North Sea.

CCS has been recognized as one of several key abatement options in EU's efforts to reduce GHG emissions. However, many uncertainties remain in all parts of the CCS chain. Efforts need to be intensified from all stakeholders to gain more experience about the technological, economical and social aspects of CCS. In a forthcoming study we will continue to assess the potential, and to identify possible practical limitations, for a ramp-up of a European CCS infrastructure. The aim is to evaluate different transport and storage options for the power and industry sectors.

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