THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Pathways to deep decarbonisation of carbon-intensive industry in the European Union

Techno-economic assessments of key technologies and measures

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ABSTRACT

By Year 2050, the EU has committed itself to reducing greenhouse gas emissions by 80%–95% relative to the levels in 1990, so as to contribute to global efforts to limit the long-term global average temperature increase to <2°C. This thesis investigates the prospects for and the practical implications of contributing towards this goal for three of the most CO_2-emission-intensive industrial activities in the EU, petroleum refining, iron and steel production, and cement manufacturing, collectively referred to as 'the carbon-intensive industry'. The thesis consists of six papers, Papers I–III explore the potentials and limitations for CO_2 emission reductions in carbon-intensive industry in the EU as a whole. Papers IV–VI take as the point of departure carbon-intensive industry in the four largest Nordic countries of Denmark, Finland, Norway, and Sweden. All of the studies are based on a bottom-up approach with representation of the current technology stock and of emerging technologies and processes. In Papers I and II, the potentials for reductions in emissions of key mitigation technologies and measures are provided as fixed estimates without any explicit consideration of the timing of their implementation. In Papers III and IV, different future trajectories of technological developments are explored through scenario analyses, explicitly considering the rate of capital stock turnover. Based on the work reported in Papers I–IV, it is concluded that: 1) the combined effects of extensive deployment of available abatement measures and proven best-available process technologies are not sufficient to comply with more stringent emission reduction targets in the medium term (to Year 2030) and long term (to Year 2050); and 2) unless production levels are significantly reduced, only ambitious deployment of CO_2 Capture and Storage in the carbon-intensive industry result in emissions reductions that are in line with the targets. To date, progress with respect to overcoming the technical, infrastructural and financial barriers to the uptake of alternative low-CO_2 technologies has been slow.

With the price of emission allowances under the EU Emission Trading System currently far below the levels required to unlock investments in low-CO_2 production processes in the carbon-intensive industry Papers V and VI investigate the impacts of intermediate and final consumers of steel- or cement-containing products bearing the full costs of CO_2 trading and investments in CO_2 abatement in the steel- and cement-industries. The results from these two papers, using the supply of cement and concrete to a residential building (Paper V) and the supply of steel to a passenger car (Paper VI) as case studies, suggest that while covering the costs of investing in new low-CO_2 steel- and cement-making processes would require substantial increases in the selling prices of steel and cement such price increases would neither significantly alter the cost structure nor dramatically increase the price to be paid by a car buyer or a procurer of a building or an infrastructure project.

Keywords: Carbon-intensive industry; Carbon dioxide; Emission reduction; CCS; Refinery; Iron and steel; Cement; Scenario analysis; Costs; Supply chain

List of publications

The thesis is based on the following appended papers:

I. Rootzén, J., Kjärstad, J. and Johnsson, F., 2011. **Prospects for CO_2 capture in European industry**. *Management of Environmental Quality: An International Journal*, Vol. 22 No. 1, pp.18–32.

II. Johansson, D., Rootzén, J., Berntsson, T. and Johnsson, F., 2012. **Assessment of strategies for CO_2 abatement in the European petroleum refining industry**. *Energy*, 42, pp.375–386.

III. Rootzén, J. and Johnsson, F., 2013. **Exploring the limits for CO_2 emission abatement in the EU power and industry sectors — Awaiting a breakthrough**. *Energy Policy*, 59, pp.443–458.

IV. Rootzén, J. and Johnsson, F., 2015. **CO_2 emissions abatement in the Nordic carbon-intensive industry – An end-game in sight?** *Energy*, 80, pp.715–730.

V. Rootzén, J. and Johnsson, F., 2015. **Perspectives on the costs of reducing CO_2 emissions from industry: the case of the Nordic carbon intensive industry**. To be submitted for publication (2015).

VI. Rootzén, J. and Johnsson, F., 2015. **Paying the full price of steel – Perspectives on the cost of reducing carbon dioxide emissions from the steel industry**. To be submitted for publication (2015).

Johan Rootzén is the principal author and was responsible for the data collection and analysis of Papers I and III–VI. Paper II is co-authored with Daniella Johansson. In Paper II, Johan Rootzén was responsible for the aggregated assessment of the CO_2 mitigation potential for the European petroleum refining industry, as well as the review of CO_2 capture technologies and key market trends. The data collection, analysis of the role of adjacent infrastructure, the review of energy efficiency measures, fuel substitution and utilisation of excess heat in Paper II were performed by Daniella Johansson. Professor Filip Johnsson, who is the main academic supervisor, contributed with discussions and to the editing of all the papers. Jan Kjärstad contributed with discussions and to the editing of Paper I. Professor Thore Berntsson supervised the work and contributed with discussions and to the editing of Paper II.

Related work not included in the thesis

Rootzén J., Kjärstad J. and Johnsson F., 2009. *Assessment of the potential for CO_2 capture in European heavy industries*. In: Proceedings of 5th Dubrovnik Conference on Sustainable Development of Energy, Water and Environment Systems, September 29th – October 3rd, 2009; Dubrovnik, Croatia.

Rootzén, J. and Johnsson, F., 2013. Deployment of CCS in Industrial Applications in the EU – Timing, Scope and Coordination. Energy Procedia, 37(0), pp.7186–7198.

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Thanks to Jan Kjärstad for helping out in the process of finishing what would later become Paper I in this thesis and for all our talks about work and life. Thanks, too, goes to Daniella Johansson, with whom I cooperated when exploring the world of petroleum refining and piecing together Paper II. Your custom made bow tie holds a prominent place in my cupboard.

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Closing in on an important milestone in life, naturally, makes you think about what has brought you to this point and what lays ahead. Completing this thesis would not have been possible without support from the people who are closest to me and while I know little about what lies ahead I know that with you close to me I will be fine.

To my family and friends, I hope you all know how much I appreciate you.

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Gothenburg, June 21, 2015

Johan Rootzén

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1 Introduction

The processing on an industrial scale of petroleum oil to fuel, iron ore to steel, and limestone to cement has been and continues to be central to the construction of modern societies. A cursory glance at major cities around the world immediately reinforces how central these three basic commodities are to our everyday lives, in providing mobility for people and goods, shelter from the elements, and as parts of the infrastructures that supply water, electricity and heat. While they are unevenly distributed temporally and spatially across the world, human population increases and economic growth have spurred a seemingly limitless appetite for energy and material services at the global level. Whereas continued technological developments across the respective supply chains, from the extraction of raw materials to the delivery of the final products, have facilitated ready access to a variety of high-quality low-cost fuels, steels and cements, the unprecedented rises in the levels of productions and consumption have come at a cost. Externalities include environmental impacts on the local (e.g., noise and dust), regional (e.g. acid deposition), and global (e.g. greenhouse gas (GHG) emissions) scales. The latter is the motivation for this thesis. Petroleum refining, iron and steel production, and cement manufacturing are among the most energy- and CO_2-intensive industrial activities. The accumulated direct energy- and process-related CO_2 emissions from these three activities account for approximately 12% of total global emissions of CO_2 (10% of GHG emissions) (IPCC, 2005; DNV, 2010; Fischedick et al., 2014a).

The Intergovernmental Panel on Climate Change's Fifth Assessment Report (IPCC, 2014) concluded that in order to limit the long-term global average temperature increase to <2°C, relative to pre-industrialisation levels, GHG emissions would need to be reduced by at least 40%–70% by Year 2050, as compared to the levels in Year 2010. To achieve this target, developed countries as a group would need to reduce GHG emissions by 80%–95% by Year 2050, as compared to the levels in Year 1990 (IPCC, 2007).

It is clear that achieving this target for GHG emissions reduction requires fundamental changes across all sections of the global economy. Whereas the question as to how best to share the burden of mitigating global climate remains to be resolved, a heavy responsibility falls on the regions of the world that have benefitted the most from the energy and material revolution of the twentieth century. The European Union (EU) has committed itself to take a leading role in this challenge (European Commission, 2011; European Commission, 2014). While progress has been made towards reducing overall GHG emissions, when it comes to the 'high-hanging fruits' (e.g., decarbonising the transport and industry sectors), the EU and its Member States face the same challenges as the rest of the world. When it comes to the carbon-intensive industries that are in focus in this thesis, there is plenty of evidence to suggest that policy measures in place are insufficient to bring about the changes required to reduce CO_2 emissions to levels consistent with the EU climate policy targets. Given the limited time-frame to Year 2050, less than four decades, and in light of the long investment cycles involved in capital-intensive industries, such as refineries, steel works and cement plants, there is a sense of urgency with respect to identifying and enforcing measures, technical and other, that would contribute to reducing significantly emissions associated with the production and consumption of petroleum fuels, steel, and cement.

This thesis explores various pathways towards deep decarbonisation of carbon-intensive industry within the EU. The analysis is based on a thorough description and characterisation of the current industrial infrastructure and of the key mitigation technologies and measures available in each sector. A range of different future trajectories of technological developments is analysed to: 1) evaluate the abatement potential of alternative low-CO_2 technologies; 2) identify the barriers to the uptake of these technologies and measures, as well as policies to overcome these barriers; and 3) assess the consistency of current and proposed climate policies.

1.1 Aims and scope

The European Commission (EC) has estimated the magnitude of reductions required in each sector of the economy to achieve an 80% reduction of GHG emissions by Year 2050, as compared to the respective levels in Year 1990 (European Commission, 2011). The Commission estimates that CO_2 emissions from the industrial sectors will need to be reduced by 34% –40% by Year 2030 and by 83%–87% by Year 2050. The overall objective of this thesis is to explore the prospects for and the practical implications of contributing towards this goal for three of the most CO_2 emission-intensive industrial activities in the EU: petroleum refining, iron and steel production, and cement manufacturing. The specific aims are to: (i) provide a comprehensive and transparent account of the current status of each respective industry; and (ii) assess the potentials and limitations of different mitigation options and to explore the effects of different future trajectories of technological developments. The ambition here is to provide a basis for evaluating current climate policies that target the industry sectors and to pave the way for a discussion on complementary policy options that would enable significant reductions in CO_2 emissions in the medium term (up to Year 2030) and long term (Year 2050). Thus, the main questions addressed in this thesis can be summarised as follows:

Q1. Where do we stand today? What is the current status of each respective sector in terms of the production process being employed, the characteristics of the capital stock and the associated flows of energy, material, and CO_2?

Q2. What measures – technical and other – do we have at our disposal and how far can they take us towards the proposed emission reduction targets for Year 2030 and Year 2050? By analysing different future trajectories of technological developments, we can evaluate the prospects for meeting the emission reduction targets and explore the implications of the required changes in technological infrastructure. The proposed emission reduction targets for Year 2030 and Year 2050 function as benchmarks throughout this work, and they indicate the magnitude, scope, and timing of the required transformation process. While the roles to be played by material efficiency, material substitution and continued process optimisation are considered, the emphasis is on abatement measures that are currently available or that are emerging, which could contribute to reducing significantly the direct emissions from the basic production processes in the respective industries.

Q3. How do we implement these measures? What are the potential barriers to the uptake of alternative, low-CO_2 technologies in carbon-intensive industries and how can climate policies be designed to overcome these barriers.

1.2 Outline of the thesis

This thesis consists of six papers (referred to as Papers I–VI) and an introductory essay. This introductory section places the appended papers in a broader context and presents and discusses the methodologies and main results.

Section 2 gives a brief introduction to the three industries under scrutiny, provides an overview of currently available and emerging measures for emissions abatement, discusses the drivers of industrial CO_2 emissions, and offers perspectives on the costs of industry CO_2 abatement. Section 3 outlines the challenge that has to be faced by providing information on CO_2 emissions trends and targets in the EU and the Nordic countries and by discussing briefly the structures of the economies and energy systems in the respective regions. Section 4 reflects upon the benefits and limitations with regard to the methodological approaches applied in studies presented in this thesis. Section 5 summarises and discusses some of the key findings of the thesis work. Finally, Section 6, offers some concluding remarks and suggestions for future work.

2 Carbon-intensive industry

The thesis covers petroleum refining, integrated iron and steel production, and cement manufacturing in the EU (Papers I–III) and the Nordic countries (Papers IV–VI). These three industries all belong to the largest stationary sources of CO_2 emissions (in both regions), with a relatively low number (~270) of large industrial plants (>0.5 $MtCO_2$/yr), including refineries (~85), integrated steel plants (~35), and cement plants (~150), which together are responsible for approximately 10% of the CO_2 emissions in the EU. Since Year 2005, all countries and industries covered by this study have participated in the EU Emissions Trading System (EU ETS). Whereas the emphasis in this thesis is on options to reduce direct on-site CO_2 emissions per unit of output from refineries, steel works, and cement plants (indirect CO_2 emissions from electricity production or emissions from the combustion of petroleum fuels in the end-use sectors are not accounted for directly), the linkages to and strategies for mitigating other drivers of industry-related emissions are also considered and discussed.

The following sections provide a brief introduction to the respective industries (collectively referred to as the carbon-intensive industry) and an overview of currently available or emerging measures for emissions abatement. In addition, the drivers of industrial CO_2 emissions are discussed, and finally, some perspectives are offered on the costs of industrial CO_2 abatement. Sections 2.1–2.3 are reworked and updated versions of materials that first appeared in Rootzén (2012).

2.1 Petroleum refining

Up to World War II, the European petroleum refining industry was limited in size. After the war, rapid economic growth, an abundant supply of inexpensive crude oil, and the discovery of domestic oil and gas deposits resulted in a rapid increase in oil consumption and expansion of the petroleum refining industry. In Western Europe, oil-refining capacity grew 40-fold in the period 1950–1970 (Molle and Wever, 1984). A considerable share of the current capital stock is a legacy of this post-war expansion. More than 90% of European refineries were built before 1980 (Barthe et al., 2015). Most of the European refineries were originally built to produce petrol for cars and fuel oil for power generation, although product demand has gradually changed (UKPIA, 2006). Currently, there are 114 refineries in the EU-27 (of which ~85 emit >0.5 $MtCO_2$/yr), with a combined capacity of approximately 770 Mt/yr. Refineries are located in 22 of 27 EU Member States, and they range in size from small topping and specialty refineries to high-conversion cracking refineries (Barthe et al., 2015). While there are differences between Member States in terms of the supply and demand equilibrium, the European petroleum refining industry as a whole is struggling to meet the domestic demand mix. The demand for diesel currently exceeds production capacity, whereas European refineries produce an excess of gasoline. The total demand for refined petroleum products is predicted to grow slowly over the coming decades. The widening gap between the demands for gasoline and diesel and the market penetration of alternative fuels and powertrains are expected to exert increasing pressure on EU refineries. A percentage of the demand changes is likely to be met through increased trade (i.e., gasoline export and imports of gasoil/diesel and alternative fuels) and the emergence of new actors in the fuel/powertrain markets (i.e., shifts towards alternative fuels and increased penetration of electric vehicles). To maintain their roles in the internal fuel markets, EU refineries will have to invest in technologies that will allow them to adapt output to the changing demand profile. Investments in new processing capacity (e.g., hydro cracking and desulphurisation) will likely lead to increased energy intensity and will off-set some of the potential for CO_2 abatement.

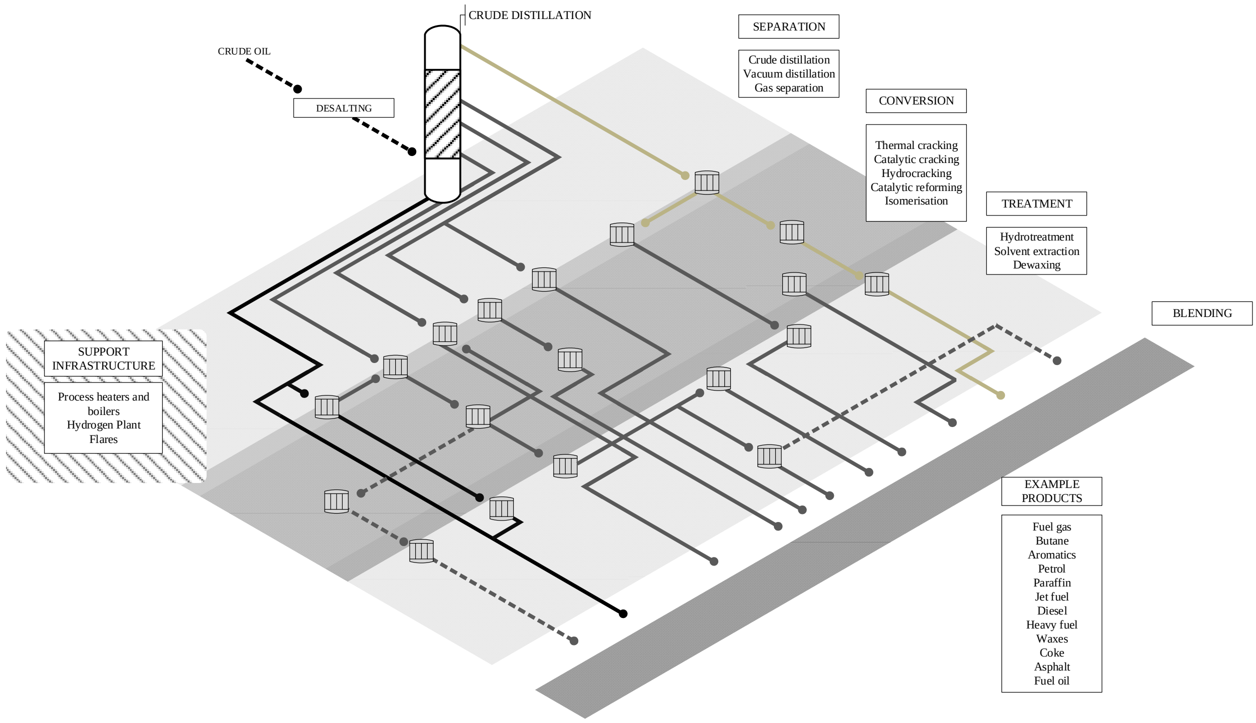

Figure 1. Simplified flowchart of the petroleum refining process and product flows. Adapted from: USEPA (2010) and Barthe et al. (2015).

Petroleum refining involves several production steps, whereby crude oil is purified, separated, and transformed into an array of petroleum products. A modern refinery typically consists of an integrated network of separate processing units. Figure 1 shows a simplified flowchart of the petroleum refining process and the typical product pathways. Most of the 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 mixture of petroleum coke, still gas (refinery gas, i.e., by-products of the refining process), petroleum fuels, and natural gas. The levels of energy use and CO_2 emissions vary depending on the type of crude oil being processed and on the mix and quality of the final products. Therefore, the total level of CO_2 emissions from a refinery is the sum of several emission sources of various sizes. Process heaters and steam boilers account for the major share of the CO_2 emitted from a typical refinery.

While both overall GHG emissions and fossil fuel-related CO_2 emissions have declined in the EU since 1990 (*cf.* Figure 5), the emissions from European (EU-27) petroleum refineries increased by approximately 18% between 1990 and 2008. This increase was largely driven by increasing demand for fuel in the transport sector in general and by increasing demand for lighter distillates in particular. However, in Year 2009, as a result of the economic crisis, the total level of annual CO_2 emissions from petroleum refineries in the EU-27 and Norway was 147.4 $MtCO_2$, corresponding to a decrease of 6.5% from Year 2008. In the subsequent years emissions levels remained relatively stable, in 2013 total emissions were approximately 142 $MtCO_2$ (EEA, 2014). Seven countries, Germany, UK, Italy, France, Spain, The Netherlands, and Belgium, account for 75% of the total crude capacity, as well as 75% of the total CO_2 emissions from the oil refining industry in the EU.

2.1.1 Key emissions abatement options in the petroleum-refining industry

The petroleum refining industry is, by its very nature, part of the fossil fuel supply chain, which means that it is unlikely to contribute significantly to the shift away from fossil fuels. Nonetheless, a development whereby the refinery industry uses its know-how and infrastructures to engage in the development and supply of fossil-free fuels is not inconceivable. As discussed in Paper IV, Neste Oil in Finland and Preem AB in Sweden have already responded to this development by investing in capacity to produce biodiesel, albeit still on a modest scale.

Abatement measures that could be implemented in the near future include: continued improvements in energy efficiency; fuel switching (e.g., using natural gas instead of residual fuels as energy source); and increased use of biomass feedstock as fuel. Providing excess heat for district heating or integrating process flows with adjacent industries (e.g., petrochemical industries) are additional ways for refineries to contribute to reducing CO_2 emissions off-site. It should be noted that few of these abatement strategies are directly additive.

Paper II and the references cited therein give a more thorough review of strategies for reducing CO_2 emissions in the refining industry.

2.2 Iron and steel production

Steel production has been a cornerstone of European industry and many European economies for more than a century. Rising demand and technological breakthroughs (i.e., the introduction of the oxygen steelmaking process) prompted the European steel industry to increase capacity considerably during the 1950's and 1960's. The predecessor to the EU, the European Coal and Steel Community, was established in 1951 to facilitate the management of European coal and steel resources (Poelmans, 2009). Given its strategic importance, much of the European steel industry remained either state-owned or under stringent governmental regulation up until the 1990's. Thereafter, the industry became largely privatised, and it has undergone large-scale consolidation, to the point that today the five largest steel companies account for more than 60% of steel production in the EU.

Even though the European share of the global steel market has gradually declined, the EU remains the second largest steel-producing region in the world. From 2005 to 2008, the total annual output of crude steel in the EU-27 remained consistently within the range of 195–210 Mt. Similar to most other manufacturing industries, the iron and steel industry was severely affected by the financial crisis and economic crisis, which caused crude steel output to fall by 30% in Year 2009, as compared to Year 2008. While recovering somewhat in the period 2010–2014, crude steel production has remained well below the levels prior to the crisis, with an average annual production of approximately 170 Mt crude steel/yr. Currently, the four largest steel-producing countries in the EU, Germany, France, Italy, and Spain, account for more than 55% of steel production (Eurofer, 2015).

The iron and steel industry is highly energy-intensive and the production of primary steel is associated with significant CO_2 emissions. Although the sector has a complex industrial structure, the following two production routes dominate production (Remus et al., 2013):

- Integrated steel plants. This is the most common production route. It involves a series of interconnected production units (coking ovens, sinter plants, pelletising plants, blast furnaces, basic oxygen furnaces, and continuous casting units), which process iron ore and scrap metal to crude steel. Coke, which is derived from coal, typically functions as both a fuel and reducing agent. Figure 2 provides a simplified flow chart describing the integrated iron- and steel-making process.
- Mini-mills. Scrap metal, direct reduced iron, and cast iron are processed in electrical arc furnaces to produce crude steel.

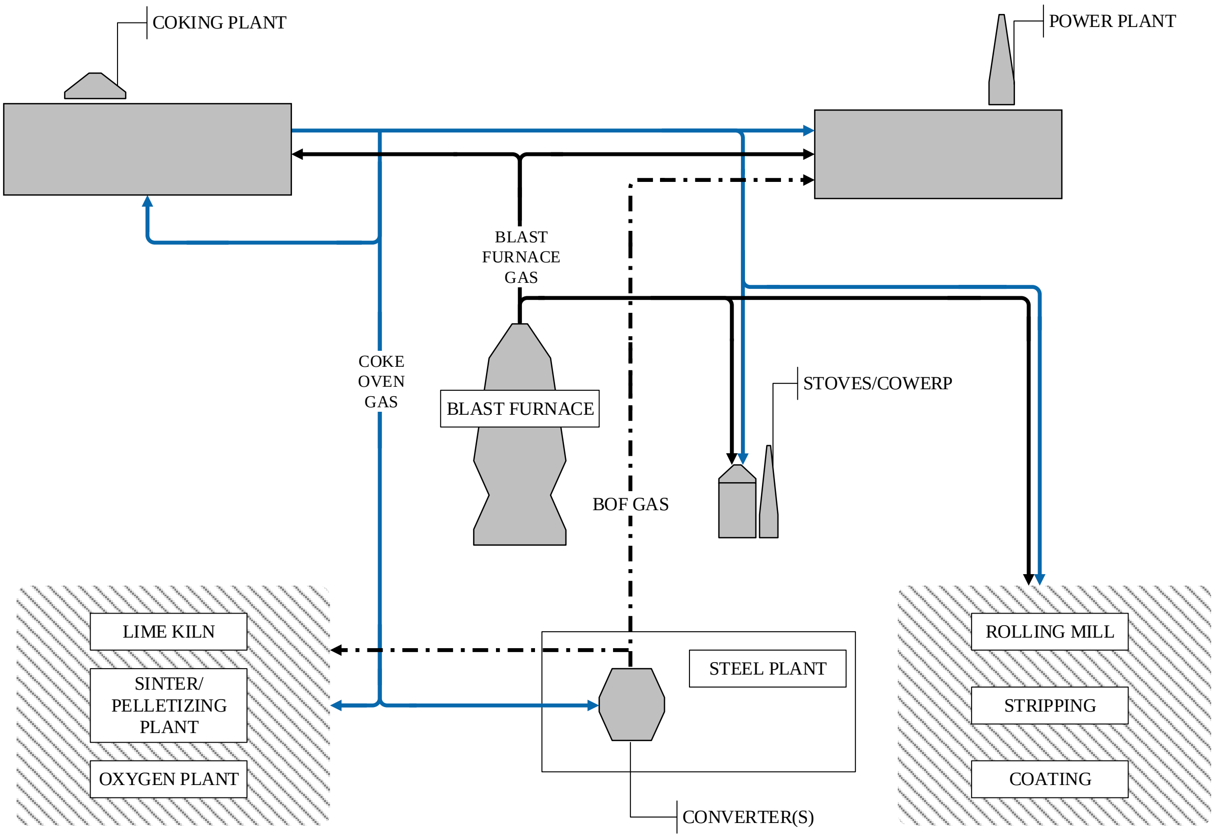

Figure 2. Simplified flow chart describing the integrated iron- and steel-making manufacturing process including typical process gas flows. Adapted from: Birat (2010); Kuramochi et al. (2011) and Remus et al. (2013).

Nearly 60% of the steel produced in the EU-27 is produced through the integrated route (coking oven, blast furnace, basic oxygen furnace) – the remainder is produced in electric arc furnaces. Whereas primary steelmaking (integrated route) dominates EU production, the secondary steelmaking route (electrical arc furnaces) is gradually gaining market share.

Currently, there are 36 integrated steel plants (with 85 blast furnaces and 102 basic oxygen furnaces) and 222 electrical arc furnaces operating in the EU-27 (Plantfacts, 2009; Remus et al., 2013). A large proportion of the capital stock involved in primary steelmaking in the EU was commissioned during the post-war period of expansion of the steel industry. More than 80% of the blast furnaces (corresponding to approximately 80% of the production capacity) were commissioned before 1980.

The total level of CO_2 emissions from installations involved in the production of iron and steel in the EU-27 was approximately 160 Mt CO_2/yr before the economic recession which caused steel demand, and consequently, CO_2 emissions, to fall drastically in 2009. In 2013 total annual emissions were down to approximately 140 MtCO_2 (EEA, 2014; EUTL, 2015). Primary steelmaking in integrated steel plants is responsible for more than 85% of the direct CO_2 emissions from the iron and steel industry. The predominant steel-producing countries, Germany, France, and the UK account for more than 50% of the CO_2 emissions. The blast furnaces utilised in the integrated route represent the single largest source of CO_2 emissions in the steel industry. The direct CO_2 emissions associated with the secondary route are relatively low, since the electrical arc furnace uses electricity as its primary energy input; secondary CO_2 emissions associated with the electrical arc furnace process are highly dependent upon the energy mix in the electricity supply system.

2.2.1 Key emissions abatement options for the steel industry

The list of emissions reduction measures presented below is not meant to be exhaustive. Instead, it functions to introduce, briefly, some of the key options that have been considered in the studies of this thesis in which the steel industry has been part of the scope (Papers I, III, IV and VI).

Improved energy efficiency. In recent decades, the European steel industry has managed to improve considerably the energy efficiency of the production process. However, a multitude of measures, both in primary and secondary steelmaking, could be implemented that would reduce significantly energy use and associated CO_2 emissions (for a comprehensive review, see e.g., Remus et al., 2013).

Fuel shift. The blast furnace is the single most energy-consuming process in the production of steel. Coke, which is derived from coal, typically functions as both a fuel and reducing agent. Replacing coke with natural gas or bio-coke might reduce CO_2 emissions from the blast furnace process.

Carbon capture and storage. The opportunities for CO_2 capture in steel production vary depending on the process and the feedstock used (Paper I). The largest flow of CO_2 in a conventional integrated steel mill is generated in the blast furnace, as mentioned above. Recovery of CO_2 from the blast furnace gas is a feasible capture option for the steel industry (IPCC, 2005; Eurofer, 2013). Applying current end-pipe technologies to existing blast furnaces, ~30% of the overall CO_2 emissions from a conventional integrated steel plant could be captured. While CO_2 capture could be applied to other gas flows in the production process, the costs would likely be higher, since the volumes and concentrations CO_2 are lower. One of the most promising opportunities for CO_2 capture in the steel industry is to replace or retrofit a conventional blast furnace with a Top Gas Recycling Blast Furnace (TGR-BF). In a TGR-BF, the CO_2 is separated from the BF gas, and the remaining CO-rich gas stream is recirculated back into the furnace. Simultaneously replacing the preheated air with pure oxygen would ensure that the blast furnace gas stream was free of N_2, thereby simplifying CO_2 capture. It has been estimated that 70% of the CO_2 emitted from an integrated steel plant could be recovered by the introduction of a TGR-BF with CO_2 capture (IPCC, 2005; Eurofer, 2013).

Structural change. Secondary steelmaking in electrical arc furnaces is expected to continue to gain market share at the expense of primary steelmaking in integrated steel plants, with consequent lowering of the carbon intensity of EU steel production.

New steelmaking processes. The Ultra-Low Carbon dioxide Steelmaking (ULCOS) consortium is investigating innovative steelmaking processes that have the potential to reduce considerably CO_2 emissions from the EU steel industry (for a review, see ULCOS, 2015). The ULCOS consortium has identified a number of process technologies that could reduce CO_2 emissions by at least 50% compared to current best practices (in most cases in combination with CCS).

2.3 Cement manufacturing

Reconstruction programs that were implemented after World War II created a strong demand for cement, and this marked the start of the expansion of the European cement industry. Developments of industry and infrastructure and increased urbanisation stimulated cement demand until the oil crisis of the 1970's. More than 70% of the cement kilns in the EU-27 were commissioned during this period. Currently, there are 268 cement plants in the EU-27 (of which ~150 emit >0.5 $MtCO_2$/yr), with a total of 377 kilns. Production capacities range from a couple of hundred to several thousand metric tonnes of cement per day. Dry process kilns account for approximately 90% of European cement production. The remainder is produced in semi-dry or semi-wet process kilns (7.5%) and in wet process kilns (2.5%).

Before 2009 the annual production of cement in the EU-27 remained between at 230–270 Mt cement/yr. Year 2009 marked the beginning of a significant downturn, as the cement industry was seriously affected in that year by the general downturn in the European economy; cement production dropped by more than 20% between 2008 and 2009. The continuing recession has resulted in production levels significantly below capacity. In the period 2010–2014 annual production of cement in remained between at 150–200 Mt cement/yr (Cembureau, 2015). As cement production peaked in 2007, the total direct CO_2 emissions from the EU cement industry were just over 170 $MtCO_2$, in 2013 total annual emissions were down to approximately 130 $MtCO_2$ (EEA, 2014). The countries with the largest outputs, Italy, Spain, Germany, France, Greece, and Poland, together account for approximately 65% of the total CO_2 emissions.

Imports to and exports from the EU of cement have to date been relatively limited, although concerns have been raised regarding competition from cement producers located in countries that lack carbon constraints, i.e., certain countries of North Africa (BCG, 2013; Ecorys, 2013). The transport of cement is costly, especially via road, with the consequence that cement markets have traditionally clustered in regions that are located in proximity to the end-use markets. Shipping allows for more cost-efficient transportation and permits cement producers that are located near the sea (or inland waterways) to access a wider market (Ligthart, 2011; ICR, 2014). The European cement industry is one of the most concentrated in terms of ownership in the world. The five largest European companies account for almost 60% of the total European cement output (Ecofys, 2009).

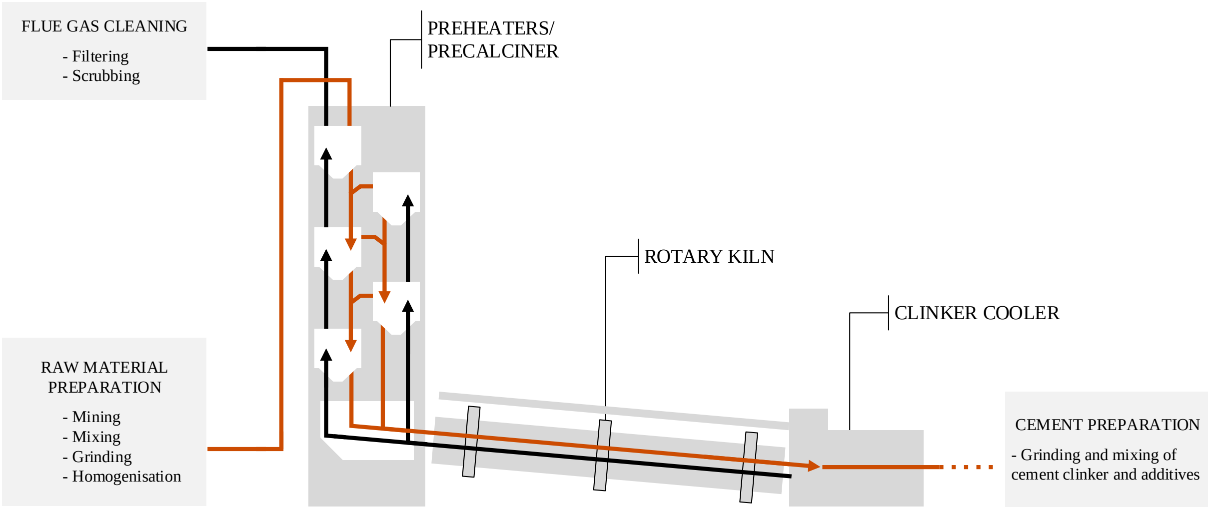

Figure 3. Flow chart of the cement production process. Adapted from: Cementa (2009) and Schorcht et al. (2013)

Figure 3 gives an overview of the cement production process. In a cement plant, calcium carbonate ($CaCO_3$) and different forms of additives are processed to form cement. Significant amounts of electricity are used to power both raw material preparation and cement clinker grinding, and large quantities of fuel are needed in the clinker burning process. The levels of energy use and related CO_2 emissions vary depending on the choice of production route and kiln technology. Depending on the efficiency of the process, the mix of fuels used, and the specifications of the cement, the production of one tonne of cement currently results in the release of 0.65–0.95 tCO_2. Almost all of the direct CO_2 emissions from cement production arise from the clinker burning process. Approximately 60% of the CO_2 emissions originate from the calcination process, with the remaining CO_2 emissions being linked to fuel combustion (Schorcht et al., 2013).

2.3.1 Key emissions abatement options in the cement industry

This section introduces briefly some of the key emissions reduction measures that are considered in those studies of this thesis in which the cement industry is included in the analysis (Papers I, III, IV and V)

Continued energy efficiency improvements. These improvements involve the retrofitting and replacement of process equipment in existing plants and the deployment of best-available technologies in new cement plants. The theoretical minimum thermal energy demand for the production of cement clinker is 1.60–1.85 GJ per tonne of clinker. In Europe, the specific thermal energy demand currently ranges from 3.0 GJ per tonne for dry-process manufacturing with multistage preheating and precalcining to 6.5 GJ per tonne clinker for wet-process long kilns and the production of special cements (Schorcht et al., 2013). Electricity accounts for 10%–20% of the energy consumed during cement manufacturing, and electricity demand ranges from 90–150 kWh/t cement.

Alternative fuel use. The replacement of conventional fuels (typically coal and pet-coke) with less-carbon-intensive fuels is an option. Alternative fuels include both fossil-based (e.g., industrial and municipal waste) and biomass-based fuels (animal meal, agricultural residues, recycled wood and paper). The average substitution rate in the EU-27 is currently around 30%.

However, the use of alternative fuels varies widely between Member States; in some countries, the substitution rate is >50% (WBCSD, 2012; Aranda Usón et al., 2013).

Clinker substitution. Replacing the clinker in the cement with additives that have similar properties reduces energy usage and the CO_2 emissions per unit mass of the finished cement product. Substitutes include blast furnace slag (a by-product of primary steelmaking) and fly ash (from coal-fired power plants). In Europe, the average clinker content of cement is currently in the range of 78%–85% (Schorcht et al., 2013). The clinker-to-cement ratio could probably be lowered further without compromising either product quality or performance.

Carbon capture and storage. With high absolute levels of CO_2 emissions and relatively high concentrations of CO_2 in the flue gas streams (~20%), the cement industry is an early candidate for the implementation of CCS. However, the European cement industry is still in an early phase of CCS implementation in pilot or demonstration projects. Two options for CO_2 capture in the European cement industry have been identified as being of particular interest, namely post-combustion capture and oxy-combustion with CO_2 capture (see Paper I and IV and references therein). Post-combustion capture could be applied by utilising 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 could be avoided if post-combustion capture was introduced. However regeneration of the CO_2 capture solvent would require additional generation of steam, thereby increasing slightly the overall level of CO_2 emissions. Oxy-combustion with CO_2 capture could be applied both in the precalciner and in the kiln; by targeting the precalciner exclusively, the impacts on the clinkerisation process could be minimised. Approximately 50% of the CO_2 from a cement plant could be captured using the oxy-combustion precalciner setup.

New cement-making processes. Several alternative materials, that have mechanical properties similar to those of Portland cement, are currently being developed (for a review, see WBCSD, 2009). Innovative low-carbon (and/or negative-carbon) cements could replace Portland cement and offer opportunities for extensive reductions in CO_2 emissions. However, these processes are still in the early stages of development and remain to be proven technically or to be demonstrated as being economically viable.

2.4 Drivers of industrial CO_2 emissions

The field of energy and material systems studies are full of examples where the issues studied – e.g. forecasting future levels of; material use, energy consumption, or GHG emissions – are overwhelmed by much larger social forces that have their origins in, for example, political or economic crises or the unforeseen introduction of new technologies or materials (Loucks et al. 2000; Smil, 2005; Morgan and Keith, 2008).

With a time horizon of 40 years, any notions as to the future development of the complex economic, social, and technical dynamics that govern demand for energy and materials, and the associated CO_2 emissions, are likely to be speculative. Nevertheless, decisions as to how best to tackle, in this case, industrial CO_2 emissions must be made taking the future into account.

Therefore, to formulate the discussion on the drivers of emissions, as well as the prospects and measures for emissions reductions, the linkages from demography and the economy to resource use and emissions are herein decomposed, by analogy to the Kaya identity (Kaya, 1990; Nakicenovic and Swart, 2000; Azar et al., 2002; Allwood et al., 2011a; Fischedick et al., 2014a), using the following simplified conceptual expression:

$$E = \frac{(e_F + e_P)}{M} \times \frac{M}{D} \times \frac{D}{A} \times \frac{A}{P} \times P \tag{1}$$

where E is the total GHG emissions from industry, e_F is the emissions that arise from the combustion of fossil fuels, e_P represents the process-related emissions, M is the amount of materials (or fuels in the case of the refining industry) produced, D is the demand for products or services, A is economic activity, and P is population. The first term on the right-hand side of Eq. (1) would then represent the level of specific emissions (tCO_2/t material) from the primary production of petroleum fuels, steel or cement; the second term, the amount of material consumed per unit of product or services (t material/unit of product); the third term, the amount of product or services consumed per unit of income (goods or services/GDP) with the latter measured as, e.g., Gross Domestic Product (GDP); the fourth term, income per capita (GDP/capita); and the fifth, again, is population (capita). Following Azar et al. (2002) and Fischedick et al. (2014a), the first three terms will be referred to respectively as: emissions intensity ($(e_F+e_P)/M$); material intensity (M/D); and products or services demand intensity (D/A).

At the global level, Eq (1) illustrates the dual challenge of finding ways to meet a growing demand for products and services, driven by the increasing global population and efforts to improve material living standards in many parts of the world, while contemporaneously reducing anthropogenic GHG emissions. Whereas the majority of this growth will occur in developing or newly industrialised countries, such as China, India, Brazil, the Middle East, and Africa (IEA, 2012a), there is little to suggest that the demand for CO_2-intensive commodities such as petroleum fuels, steel, and cement will drop significantly in the more developed economies of the world in the absence of additional policy interventions.

Recent projections for the EU (EU28) suggest that the population will grow from approximately 500 million inhabitants in Year 2010 to approximately 525 million by Year 2050, with GDP increasing from approximately 12.3 to 21.9 trillion (10^{12}) Euro during same period (European Commission, 2013). With respect to the prospects for reducing CO_2 emissions from EU industry to levels consistent with the EU climate policy targets – given continuous growth in population and under the customary [albeit not indisputable (see for example Meadows et al., 1972; Jackson, 2009)] assumptions of continued economic growth – decoupling of CO_2 emissions from economic growth will likely require utilisation of the full range of mitigation measures available across the supply chain of basic commodities, including, emissions- and material- efficiency and product-service demand reductions (Kram et al., 2001; Allwood et al., 2010; Fischedick et al., 2014a).

Whereas the emphasis in this thesis is on emission intensity, i.e., on options to reduce the direct on-site CO_2 emissions per unit output from refineries, steel works, and cement plants (indirect CO_2 emissions from electricity production and emissions from the combustion of petroleum fuels in the end-use sectors are not accounted for directly), the linkages to and strategies for mitigating other drivers of industry-related emissions also deserve attention. Thus, Section 2.5 briefly introduces a selection of emerging low-CO_2 processes that, at least in theory, has the potential to contribute to reduce significantly the CO_2 emissions from the respective industry.

Table 1 explores how the notions of material efficiency (M/D) and product-service demand reduction (D/A) could be implemented in practice in the context of the production, intermediate processing and use of petroleum fuels, steel, and cement.

Table 1. Examples of measures to improve material efficiency and to reduce product-service demand in the production, intermediate processing and use of petroleum fuels, steel and cement. For a comprehensive review, see Ayres and van den Bergh (2005); Allwood et al. (2011a); Allwood et al. (2011b), and Fischedick et al. (2014a).

	MATERIAL EFFICIENCY	**DEMAND REDUCTION**
LIQUID FUEL	The processing, supply and use of petroleum fuels is a special case. Using the *supply of diesel/gasoline to (ultimately) provide mobility* as an example, the possible strategies include: - Avoiding flaring and spills at the refinery. - Improved fuel efficiency of the vehicle fleet.	In this case reducing the amount of product (*diesel/gasoline/liquid fuel*) or level of services (*mobility*) consumed per unit of income involves: - Shifting to alternative fuels/power-trains. - Increasing the use of alternative (more efficient) modes of transportation. - Reducing the *per capita* transport demand through encouraging the use of public transport, city planning and car sharing.
PRIMARY STEEL	Using the *supply of steel to a passenger car* as an example, the possible strategies include: - Near net shaping in primary production. - Using more efficient designs to avoid material losses during the blanking and stamping of sheet metal for components manufacturing. - Increasing the use of high-strength steels to reduce the weight and the total amount of steel required per unit of car.	Strategies to reduce the amount of *steel-containing products* consumed per unit of income include: - Shifting to alternative materials (including secondary steel). - Increasing the useful lifetime, by means of repair, renovation, and remanufacturing. - Recycling/reuse (e.g., reusing structural steel or car components).
CEMENT/CONCRETE	Using the *supply of cement and concrete to a residential building* as an example possible strategies include: - Avoiding spill throughout the supply chain (primary production, concrete manufacturing and construction) - Increased use of alternative cementitious binders. - Optimised construction (using high-quality high-strength concrete to reduce the amount of concrete/cement required).	Strategies to reduce the amount of *cement/concrete-containing products* consumed per unit of income include: - Shifting to alternative structural materials (e.g., the use wood in buildings). - Extending the lifespans of buildings and infrastructures or using them more intensely/efficiently.

2.5 Alternative break-through processes

Assumptions regarding the types of process technologies that will be available to replace the current stock and the timing of a possible breakthrough in new low-carbon process technologies will obviously have major impacts on the outcome of an analysis that examines the prospects for meeting the proposed emission reduction targets. This section briefly introduces and provides an overview of alternative low-CO_2 processes that, at least in theory, have potential to contribute to reducing significantly CO_2 emissions from the respective industry. While a range of alternative low-CO_2 processes have been investigated, typically at the laboratory scale or pilot plant scale, most of these potential breakthrough technologies remain to be proven from the technical and economic viability perspectives. Moreover, even if they are proven to be both technically and economically feasible, the timeframes for the commercialisation of these technologies are typically long.

The summary presented in Table 2 is not intended to be comprehensive, but rather it reflects the variety of innovative technologies currently under development in the respective industries. The options listed here have not been considered in the six sub-studies (Papers I–VI) that form the basis of this thesis. More detailed accounts of the technologies considered in the six sub-studies that form the basis of this thesis are given in the respective papers (Papers I–VI). It is noteworthy that while they offer significantly lower specific emissions (tCO_2/t product), few of these options would result in complete decarbonisation.

Table 2. Overview of a selection of innovative technologies currently under development in the respective industry, refineries, steel plants and cement factories (See also Sections 2.1–2.3 above). The options listed here are not described in the appended papers (Papers 1–VI).

	Description	Technology	Status	References
REFINERIES	Use of existing/complementary equipment and infrastructures to supply biomass-based fuels	- Co-feeding of biomass (hydro treatment of bio-oil) - Biomass gasification for production of hydrogen or Fischer-Tropsch fuels	Commercial (currently only on a modest scale) Laboratory/development stage	Johansson et al. (2009) Johansson (2013)
PRIMARY STEEL	Coke-free steelmaking Fastmelt reduction (Direct reduction of iron) Electrolysis	- Direct use of coal and ore. Omits coking and sintering. With or without CCS. - Replacing coal/coke with natural gas or hydrogen. With or without CCS - Reduce iron oxides electrochemically, without using any direct carbon.	Pilot/demonstration stage Pilot stage Laboratory/development stage	Daniëls (2002) Birat et al. (2008) Croezen and Korteland, (2010) Åhman et al. (2012) Eurofer (2013) Fischedick et al. (2014b)
CEMENT	Shift to production of alternative cement products	- Cement and construction materials based on magnesium oxide - Geopolymer cement - Cement primarily composed of fly ash and recycled materials	Pilot stage Demonstration stage Semi commercial	WBCSD (2009) Hasanbeigi et al. (2012) Åhman et al. (2012)
	Alternative CO_2 capture technologies	- Carbonate looping technology - Membrane-based technology	Laboratory/development stage	Hasanbeigi et al. (2012) ECRA (2009) ECRA (2012)

2.6 Perspectives on the costs of industrial CO_2 abatement

Given that some technologies and measures are already commercially available and are widely implemented while others are still at an early phase of development, and considering that there exist many different types of plants, process lay-outs, and levels of complexity, comparisons of the relative costs of the different abatement options are not trivial. Furthermore, assessments of the costs associated with reducing industrial CO_2 emissions tend to produce different results depending on the analytical approach applied (Wene, 1996; Greening et al., 2007; Algehed et al., 2009). However, while the cost estimates available in the literature vary significantly some general observations can be made that have relevance for the EU carbon-intensive industry. Process optimisation and other measures to improve energy efficiency still have the potential to reduce industrial CO_2 emissions at a relatively low cost (<20 €/tCO_2) (Overgaag et al., 2009; Fischedick et al., 2014a). At the other end, abatement costs associated with many of the technologies that are expected to contribute significantly to reducing CO_2 emissions are generally at the high-cost end of the portfolio of abatement measures available to industry. Estimates of the abatement costs of new advanced technologies and processes, which in many cases include the application of CCS, in the industries covered here are in the ranges of approximately; 30 to >80 €/t CO_2 avoided for the refining industry, 55 to >85 €/t CO_2 avoided for the cement industry and 45 to >110 €/t CO_2 avoided for the cement industry (Kuramochi et al., 2011; IEA, 2013a; Fischedick et al., 2014a).

Marginal abatement cost curves (MACCs), which are commonly used to compare and illustrate the relative abatement costs and potentials for a set of mitigation activities, typically apply to a sector, country or region for a specified time period (see for example, Overgaag et al., 2009; McKinsey, 2009; Klif, 2010). The method has its drawbacks and MACCs should be interpreted with some caution (Murphy and Jaccard, 2011; Kesicki and Ekins, 2012; Vogt-Schilb and Hallegatte, 2013). With this in mind, Figure 4 gives an example of how the costs of abatement measures available to industry compare internally and to the costs of emissions reductions in other sectors of the economy. Figure 4a shows the estimated potentials and costs for selected emissions reduction measures across different sectors of the economy for Norway in Year 2020 (Klif, 2010; Økstad et al., 2010). Figure 4b shows the estimated reduction potentials and associated costs for abatement measures in the Swedish industry sector in Year 2020 (McKinsey, 2008; Von Bahr et al., 2010). This type of bottom-up assessment frequently reports significant opportunities for low-cost (or negative-cost) energy efficiency improvements. However, a common critique is that analyses that show strong profitability for energy efficiency, as is the case for both of these examples, must have overlooked some real (but perhaps intangible) costs for consumers or firms, otherwise such strategies would already have been implemented (Murphy and Jaccard, 2011; Kesicki and Ekins, 2012). Similarly, for the high-cost end of abatement measures available to industry, past experiences suggest that cost estimates for technologies that are at an early stage of development are often unreliable and overly optimistic (Merrow et al., 1981; IPCC, 2005).

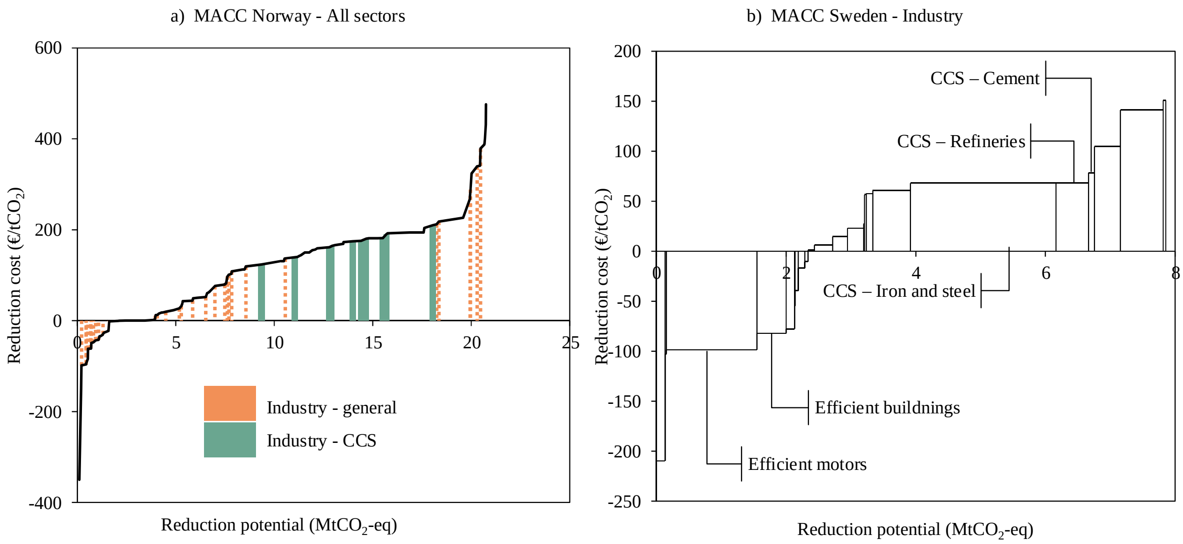

Figure 4. Emission reduction potentials and costs for selected measures in Norway (all sectors of the economy) and Sweden (industry) for the year 2020. a) Potentials and costs for emissions reductions measures in the Norwegian industry sector relative to potentials and costs in other sectors of the economy. Elaborations on data from Klif (2010) and Økstad et al. (2010). b) Abatement potentials and costs for emissions reductions measures in the Swedish industry for the year 2020. Elaborations on data from McKinsey (2008) and Von Bahr et al. (2010).

In Papers I–IV the ambition is to explore the technical feasibility of deep decarbonisation in the industries covered by the thesis; economic considerations are not explicitly part of the analysis. As is clear from the above discussion comparisons of the relative costs of different abatement options available to industry are not trivial especially with a timeframe of 3–4 decades. Acknowledging this, in Papers V and VI where comparisons of the relative costs of different abatement options are a central part of the analysis care has been taken to emphasises that the cost estimates provided are associated with significant uncertainties.

3 Emissions trends and climate policy

The geographic scopes of the studies presented are different. Papers I–III explore the potentials and limitations for CO_2 emission reductions in carbon-intensive industry in the EU as a whole, whereas Papers IV–VI take as their point of departure carbon-intensive industry in the four largest Nordic countries of Denmark, Finland, Norway, and Sweden. The following sections are intended to place the work in context and to offer perspectives by discussing briefly the structures of the economies and energy systems in the respective regions and by providing information on CO_2 emissions trends and targets. Section 3.1 outlines the challenge to be met by exploring the historical trends in CO_2 emissions within the EU as a whole and by comparing these trends with the reductions in emissions that need to be achieved by Year 2050 (an earlier version of this text appeared in Rootzén (2012)). Section 3.2 discusses the challenges associated with decarbonising the Nordic economies in general and the Nordic carbon-intensive industries in particular, and also illustrates how the industrial structure varies significantly across the EU Member States.

3.1 EU greenhouse gas emissions trends

Even though there are significant differences between countries, Europe definitely is one of the regions of the world that have benefitted the most from the “energy revolution” of the twentieth century. Fossil fuels played a vital role in the post-war rebuilding of the European economy. Coal has been the backbone of European economies and energy landscapes throughout the twentieth century. Rapid economic growth, an abundant supply of inexpensive oil, and the discovery of domestic oil and gas deposits have all led to increased consumption of petroleum products and natural gas. A considerable share of the capital stock of the existing European energy system has been inherited from this post-war expansion. Many industries and power plants, which are still in operation, were commissioned in the period from 1960 to 1980 when most externalities associated with the use of fossil fuels were ignored. As a result, with the exception of a slight decline that occurred during the 1973 oil crisis, the levels of CO_2 emissions increased almost continuously in the period 1945–1980.

The 1979 oil crisis marked the beginning of a new era in European energy policy. Growing concern about the security of supply combined with increasing oil prices led to a leveling-out of the growth in energy demand and marked the end of the dominance of oil in the primary energy mix in Europe. The diversification of the energy mix also contributed to a change in CO_2 emissions. Since 1980, the general trend for European CO_2 emissions has been slightly downwards. However, this trend shows differences across the EU Member States and between sectors, and the emissions trajectory is far from smooth.

In 1990, total GHG emissions in EU Member States (EU-27) and Norway amounted to approximately 5650 $MtCO_2$-eq/yr, of which CO_2 accounted for a little less than 80%. By Year 2000, the level of GHG emissions was 5160 $MtCO_2$-eq/yr (EEA, 2015). A large share of the emission reductions achieved in the period 1990–2000 can be attributed to the following three major factors (EEA, 2011; Gummer and Moreland, 2002):

- structural changes in the economies of the new Member States in central and eastern Europe;
- the rehabilitation process in the former East Germany; and

- extensive switching from coal to natural gas usage in the power sector of the United Kingdom.

After Year 2000, the downward trend leveled out somewhat and annual emission levels remained more or less constant until the onset of the global financial crisis. The subsequent economic recession meant that emissions slumped by almost 7% between Year 2008 and Year 2009. In the subsequent years emission levels remained well below the levels prior to the crisis, in 2012 total GHG emissions in EU-27 and Norway amounted to approximately 4570 $MtCO_2$-eq/yr (EEA, 2015). Figure 5 shows the total annual CO_2 emissions in the EU-27 and Norway between Year 1750 and Year 2010, as well as the reductions in emissions required to meet the aforementioned Year 2050 target. Emissions of CO_2 from stationary sources in the power and heat and industrial sectors account for 60% of the CO_2 emissions and 50% of the total GHG emissions. The European Commission (EC) has estimated the magnitude of reductions required in each sector of the economy to achieve an 80% reduction of GHG emissions by Year 2050, as compared to the respective levels in Year 1990 (European Commission, 2011). The Commission estimates that CO_2 emissions from the power sector will need to be reduced by 40%–44% by Year 2030 and by 93%–97% by Year 2050, and that emissions from the industrial sectors will need to be reduced by 34% –40% by Year 2030 and by 83%–87% by Year 2050, as compared to the Year 1990 levels. From Figure 5 it is clear that the required dramatic decline in emissions represents a tremendous challenge from both the technical and political points of view. Meeting this challenge will require commitment from all sectors of society. The CO_2 emission reductions achieved to date are far lower than those required to follow the emission trajectories linked to the target of a <2°C temperature change.

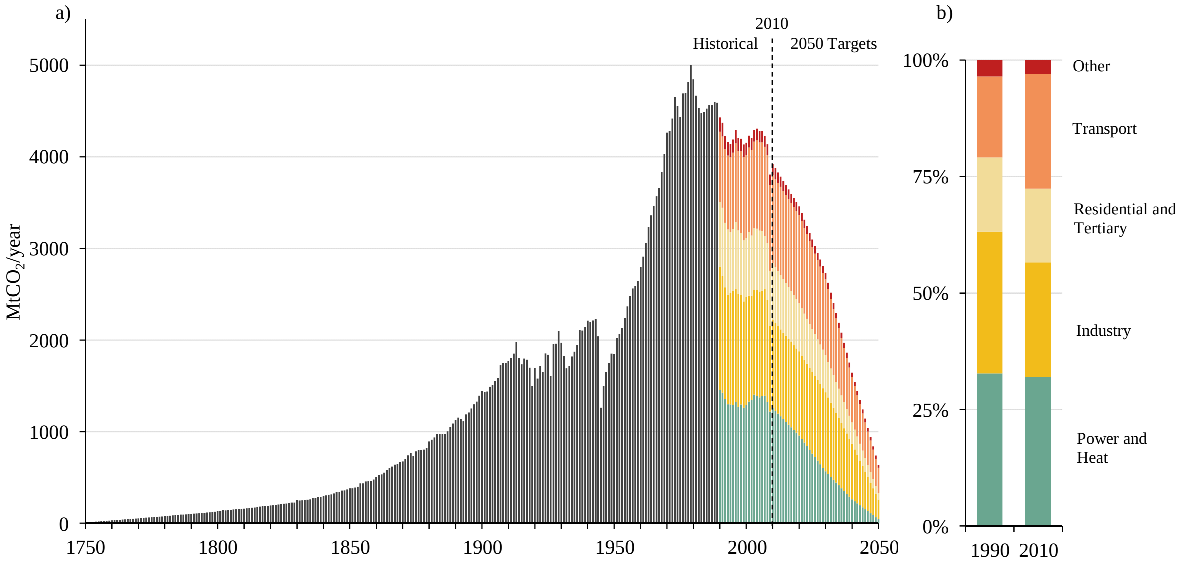

Figure 5. a) Total CO_2 emission in the EU Member Countries (EU-27) and Norway in the period 1750–2010, as well as the emissions reductions required in the period 2010–2050 to achieve an 80% reduction by Year 2050, as compared to Year 1990 levels (European Commission, 2011). The data for the years between 1750 and 1990 are extrapolated based on Boden et al. (2010) and EC-JRC/PBL (2009). Annual CO_2 emissions by source category for 1990–2012 are from EEA (2015), and target emission reduction trajectories by source category for 2010–2050 are from European Commission (2011a). b) The relative contributions to CO_2 emissions of each source category in Years 1990 and 2010.

3.2 The Nordic carbon-intensive industry

The five Nordic countries of Denmark, Finland, Iceland, Norway and Sweden have from an early stage committed to the challenge of mitigating global climate change. Through an ambitious set of energy- and climate-related polices and targets, which often surpass those stipulated in international agreements, the Nordic countries have individually and collectively sought to curb GHG emissions. While preliminary data suggest that cumulative GHG emissions from the Nordic countries fell well below the Year 1990 levels in 2012 the rate of emission reductions has been relatively moderate over the past two decades, i.e., 1990–2010. Nonetheless, in accordance with the Cancun agreement, all the Nordic countries have recently presented long-term visions for radical reductions in GHG emissions up to Years 2050. Achieving these goals implies a drastic deviation from the historical trend and will require profound changes across all sectors of the Nordic economies. There is a relatively large body of literature exploring how such a transition could be realised nationally, in Denmark (Lund and Mathiesen, 2009; Mathiesen et al., 2009; Lund et al., 2011; Richardson et al., 2011; Kwon and Østergaard, 2012; Meibom et al., 2013), Finland (POF, 2009; Heaps et al., 2010; Heinonen and Lauttamäki, 2012; VTT, 2012), Norway (NOU, 2006; NEA, 2010) and Sweden (Gode et al., 2010; Gustavsson et al. 2011), as well as regionally (Benestad et al, 1993; Nordic Council, 2007; IEA, 2013b). The scope and methodological diversity of these studies are in many ways impressive, although the treatment of the Nordic manufacturing industry is often crude.

With rich natural and energy resources the Nordic region provides favourable conditions for energy-intensive industries. The production of basic materials, pulp and paper, iron and steel and chemicals, has long formed the backbone of the Nordic economies. However, this strong presence of energy-intensive industry comes at a cost. Whereas the Nordic manufacturing industry accounts for approximately 15% of the total gross value added, the industry shares of energy use and CO_2 emissions are disproportionally high at >35% of total final energy use and >20% of the annual CO_2 emissions respectively (Eurostat, 2014). In Year 2010 total CO_2 emissions from the 23 Nordic industry plants within the scope of thesis accounted for approximately 10% or the total emissions in the Nordic region (excluding Iceland)(EUTL, 2015; EEA, 2015). These aggregated data, however, conceal several important underlying factors and trends. While the Nordic countries have many common denominators there are also important differences between the individual countries with respect to the structures of their economies and energy systems. Consequently, as illustrated in Figure 6, the developments of CO_2 emissions vary considerably both in absolute terms and with regards to the distribution of emissions across sectors.

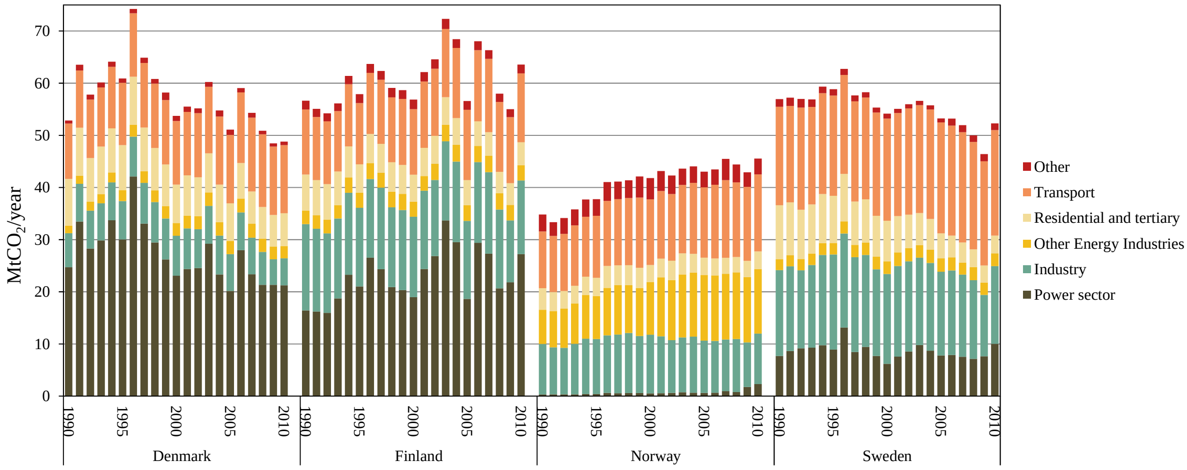

Figure 6. Annual CO_2 emissions by sector in the four largest Nordic countries of Denmark, Finland, Norway and Sweden. Data source: EEA (2015).

The following subsections (3.2.1–3.2.4) give a brief introduction to the challenges associated with decarbonising the Nordic economies in general and the carbon-intensive industries in particular.

3.2.1 Denmark

Denmark stands out as having an economy that is considerably less energy-intensive than the economies of the other Nordic countries. One explanation for this is that the country largely lacked access to the natural and energy resources that formed the basis for growth of energy intensive industries in the neighbouring countries during the first half of the 20th century. The discovery of oil and gas in the Danish sectors of the North Sea, in the late 1970’s, expansion of district heating and combined heat and power production (CHP) and the development and growth of the Danish wind energy industry, later resulted in Denmark becoming net exporter of energy (Sovacool, 2013). In Year 2010, emissions from the industry plants covered herein accounted for half of the total CO_2 emissions from Danish industry, or 6% of the total Danish emissions in the same year (EUTL, 2015; EEA, 2015). The long-term vision for Denmark is an energy system in which the entire energy supply, including electricity, heating, industry and transport, will be covered by renewable energy by Year 2050 (The Danish Government, 2013). As a first step, in March of 2012, a new energy agreement was endorsed by a broad majority of the Danish Parliament. The agreement comprises a series of energy policy initiatives for the period 2012-2020 devoted to energy conservation and the expansion of renewable capacity, including subsidies to promote investment in energy-efficient use of renewable energy in industrial production processes and funding to maintain and promote industrial CHP (DEA, 2012).

Petroleum refineries

The two Danish refineries, the Statoil refinery in Kalundborg and Shell refinery in Fredricia were commissioned in the 1960’s. The Kalundborg refinery, which entered production in 1961, is Denmark’s largest with a crude distillation capacity of approximately 106 kb/d (thousand barrels per calendar day). The Fredricia refinery, inaugurated in 1966, has a distillation capacity of approximately 68 kb/d (Oil and Gas Journal, 2013). Upstream, the bulk share of crude oil imports originates from the Norwegian (Statoil) and Danish (Shell) North Sea oil fields. While recent estimates suggest that Denmark will continue to be a net exporter of crude oil and gas up to around Year 2035 (DEA, 2013), the country relies on trade to balance the supply of and demand for refined petroleum products (IEA, 2011a).

Cement manufacturing

The cement industry has played an important role – both directly and indirectly – in the industrial development of Denmark. The Danish engineering firm F.L. Smidth contributed from an early stage to the development of the technology for the production of cement. The company was the first to introduce the rotary cement kiln to the European market, and the company continues to be one of the largest suppliers of equipment and services to the cement industry globally (Pedersen, 2012). The only remaining Danish cement plant, Aalborg Portland-Cement Factory, established in1889, is one of the world's largest manufacturer of white cement and supplies the bulk of the cement used in Denmark.

3.2.2 Finland

Abundant forests have underpinned Finland's economic progress. Up until the late 1950's around 90% of Finnish export income was derived from the forestry industry (Oinas, 2005). In the absence of domestic sources of fossil fuels initial industrialisation was largely based on the deployment of indigenous biomass and hydropower resources. It was not until the 1960's that the consumption of fossil fuels exceeded the use of biomass and other renewable domestic energy sources (Kunnas and Myllyntaus, 2009). While the Finnish economy has become more diversified over the past decades, energy-intensive industry continues to play a central role. Industry accounts for approximately half of total final energy consumption, with the manufacture of pulp and paper, refined petroleum products, chemicals and basic metals making up the bulk of industrial energy use. In Year 2010, total CO_2 emissions from the industry plants covered in this thesis accounted for approximately 65% of the emissions from Finnish industry, or 17% of the total emissions in Finland in the same year (EUTL, 2015; EEA, 2015). While decarbonising the Finnish economy is the long-term objective, and more specifically the proposed target is to reduce GHG emissions by at least 80% from the Year 1990 level by Year 2050 (POF, 2009). With respect to the industry sector there are few details available regarding concrete actions after Year 2020, as is the case also for the neighbouring Nordic countries.

Petroleum refining

Finland has two refineries both of which are operated by Neste Oil with the Finnish state as the majority shareholder. The largest of the two plants, the Porvoo refinery, which was commissioned in the mid-1960's has a crude distillation capacity of approximately 205 kb/d. The smaller, Naantali refinery, was commissioned in the late 1950's and currently has a capacity of 55 kb/d (Oil and Gas Journal, 2013). Both refineries are equipped with complex units as a result of investments made in the past two decades. Finland is entirely dependent upon crude oil imports, with the bulk of the crude oil originating from Russia, although it is at the same time a net exporter of refined products (IEA, 2012b). Neste Oil is the largest supplier of petroleum fuels to the Finnish market and is also an important actor in the Baltic markets.

Integrated iron and steel

With annual emissions of approximately 4 $MtCO_2/yr$, the Ruukki Raahe Steel Works, which is the only remaining integrated iron and steel plant in Finland, is the largest CO_2 emitting facility in the Nordic countries. With the exception of the sintering plant (closed in 2011) the Raahe plant is fully integrated with coke ovens, blast furnaces, steel plant, rolling mills and power plant (Rautarukki, 2011). Ruukki sources most of its iron ore pellets needs from Sweden with supplementary imports from Russia. Coking coal is imported from the United States, Canada, Australia and Russia. While Ruukki Metal has a presence on several global markets the Nordic countries and the Baltic States continue to be its core markets.

Cement manufacturing
Finnsementti Oy, which is Finland’s only cement manufacturer with 85% of the domestic cement market, operates plants in Parainen and Lappeenranta (Finnsementti, 2013). With an annual production capacity of 0.85 Mt cement/yr the Parainen plant is the largest and oldest cement plant in Finland, the first kiln being inaugurated in 1914. After investing in a new cement kiln system in Year 2007, the smaller Lappeenranta plant has an annual capacity of approximately 0.5 Mt cement/yr.

3.2.3 Norway

The Norwegian energy system and economic structure are atypical. Norway is the third-largest exporter of oil and gas in the world, and hydropower continues to dominate Norway’s electricity supply, accounting for almost 95% of the supply (Tjernshaugen and Langhelle, 2009). Most of the existing energy-intensive industry was established in the 1950s and 1960s, coinciding with the expansion of the hydropower capacity. Mainland industry (i.e., excluding the offshore oil industry) currently accounts for approximately two thirds, i.e., 80 TWh, of the total final energy use with electricity-intensive manufacturing industry, which includes the production of aluminium, ferroalloys, pulp and paper and chemicals, responsible for the majority of the energy use. In Year 2010, the total CO_2 emissions from the industrial plants covered herein accounted for one-third of the emissions from Norwegian industry, corresponding to approximately 7% of the total emissions in Norway in the same year (EUTL, 2015; EEA, 2015). The Norwegian government (2013–2017) have declared that they will pursue an ambitious national climate policy based on a long-term transition to a low-carbon society by 2050 (The Norwegian Government, 2013). Thus, Norway plays an unusual dual role as a major oil and gas producer and as a strong advocate for ambitious climate policy. One way to address this contradiction has been to take a leading role in the development and deployment of CCS. The current aim is to realise at least one full-scale carbon capture pilot plant by Year 2020 (The Norwegian Government, 2013).

Petroleum refining
The Norwegian refining industry consists of two refineries. The Statoil refinery in Mongstad, which was completed in 1975, has a crude distillation capacity of approximately 203 kb/d, which means that it is the third largest refinery in the Nordic region and the largest in Norway. The Mongstad refinery is the largest source of CO_2 emissions in Norway and was intended to host the first large-scale industrial CO_2 capture projects in the world (StatoilHydro, 2009; DNV, 2012). However, due to cost overruns and delays, the project was officially terminated in Year 2013 (Bloomberg, 2013). The Esso refinery in Slagentangen, which was commissioned in 1961, has a distillation capacity of approximately 116 kb/d (Oil and Gas Journal, 2013). The combined supply from these two refineries significantly exceeds domestic demand. Thus, in addition to being a major oil and gas exporter Norway is also a net exporter of refined products. Upstream, North Sea oil dominates the crude intake at both refineries (IEA, 2011b).

Cement manufacturing
Norcem, which is part of the HeidelbergCement group, owns and operate both of the two cement plants in Norway. The Kjöpsvik plant (30% of the capacity) and the Brevik plant (70% of the capacity) together have an annual production capacity of approximately 1.8 Mt

cement/yr. Both plants date back to the late-1910's. Norcem dominates the domestic cement market but also exports a significant share of its production to the neighboring Nordic countries and to the Baltic States (DNV, 2012). In Year 2013, the Brevik plant was singled out as the site for construction of a research facility for the testing of post-combustion CO_2-capturing technologies (ECRA, 2012).

3.2.4 Sweden

During the 20th century, Sweden's industrial structure was dominated by mining, iron and steel works, paper and pulp mills, and large-scale manufacturing, based on abundant forests and minerals, and an electricity supply that was dominated by easily exploitable hydropower, later complemented with nuclear power (Lönnroth, 2010). Although the Swedish economy gradually has become more diversified, heavy industry continues to be the backbone of the economy. Over the past four decades energy efficiency has been significantly improved across most branches of industry and total annual CO_2 emissions have been reduced by approximately 50% since the early 1970s. However, total industry energy use has remained in the range of 130–160 TWh per year in the same period (SEA, 2014). In Year 2010 total carbon dioxide emissions from the Swedish industry plants covered in the present study accounted for approximately 70% of the emissions from industry, or approximately 20% of the total emissions in Sweden in the same year (EUTL, 2015; EEA, 2015). Sweden has a vision of zero net emissions of GHGs in Year 2050 (The Swedish Government, 2009). Just as in the neighbouring Nordic countries, apart from the price signal imposed through the EU ETS, there are few details as to concrete policy actions that target carbon-intensive industry.

Petroleum refining
There are five petroleum refineries in Sweden the three largest of which account for 90% (396 kb/d) of the crude distillation capacity. The two Preem refineries in Lysekil and Gothenburg together have a distillation capacity of 316 kb/d, and the St1 refinery, also located in Gothenburg, has a capacity of 80 kb/d (Oil and Gas Journal, 2013). As was typical for the rest of Europe, the Swedish refineries were originally optimised to produce gasoline for cars and fuel oil for power generation. Consequently, over the past decades considerable investments have been made to meet the changing market conditions. Initially, there was the phasing out of heavy fuel oils in the power and industry sectors and, more recently, the shift is underway from gasoline to diesel in the transport sector. With no oil resources Sweden depends completely on imports, with the major share of the crude oil currently processed in Swedish refineries coming from Russia and the Danish and Norwegian North Sea fields. Downstream, since refining output exceeds domestic demand, Sweden is a net exporter of refined products (IEA, 2012c).

Integrated iron and steel
SSAB's integrated iron and steel production plants in Luleå and Oxelösund are the largest point sources of GHG emissions in Sweden. The Oxelösund plant includes the entire production line, extending from raw materials to rolled plate. At the Luleå plant, which does not have a rolling mill, steel slabs are the final product. The final stages of the steel processing are carried out in Borlänge where SSAB has hot and cold roll mills in addition to coating and finishing lines. All of the three blast furnaces (one in Luleå and two in Oxelösund) use iron ore pellets, which are mined and processed in Sweden, as the main raw material input. The majority of the finished steel is exported, and while SSAB is present in several global markets, the bulk of the exports goes to the European market (SSAB, 2013).

Cement manufacturing
Cementa, which is part of the HeidelbergCement group, owns the three remaining cement plants in Sweden. The plants, which are located in Slite, Degerhamn and Skövde, together have a capacity of approximately 3 Mt cement/yr (HeidelbergCement, 2014). The largest of the three, the Slite plant, accounts for more than 70% of Swedish cement production. With a market share of 90% Cementa dominates the Swedish market and one-third of the production is exported.

4 Methodology

The six sub-studies (Papers I–VI) that form the basis of this thesis aim, from different perspectives, to provide a better understanding of the implications that the EU climate policy targets will have for the magnitude, scope, and timing of changes required from the carbon-intensive industry.

Although the scopes, problem statements, and methodological approaches differ, all of the studies build on the basic recognition that understanding the magnitude and sources of GHG emissions is a critical first step to managing such emissions (Ritter et al., 2005). While this may seem obvious, the limited availability in the public domain of good quality data, describing for example energy use and fuel mixes at individual plants, is a real obstacle to assessing the performance, mitigation potential, and costs for abatement measures in the industrial sector (Fischedick et al., 2014a). Thus, providing a comprehensive and transparent account of the current status of the respective industries has represented both the means and the ends throughout the work in this thesis.

Furthermore, an underlying assumption has been that, while barriers and constraints other than technological ones, e.g., economic and institutional, will contribute to determining whether the required emission reductions will be achieved or not (Hughes and Strachan, 2010; Nilsson et al., 2011; Söderholm et al. 2011), technology will be a key enabler. Thus, the role of technical change is a recurring theme throughout the work. In Papers I and II, the potentials for key mitigation technologies and measures to reduce emissions are provided as fixed estimates without an explicit consideration of the timing of their implementation. Thus, neither of these papers considers the dynamics of technical change, i.e., the expected rate of capital stock turnover. Papers III and IV take the analysis a step further using scenario analysis to examine how the expected turnover in capital stock of the existing infrastructure will contribute to facilitating or hindering the shift towards less-emission-intensive production processes.

In Papers I–IV, the emphasis is on exploring the limits for CO_2 emission abatement within existing and emerging production processes. Economic considerations are not explicitly part of the analysis. An obvious and valid objection is that by not including economic considerations in the analysis we may have overlooked or underestimated important economic constraints and not captured the relative cost-effectiveness of the various abatement measures.
With the price of emission allowances under the EU ETS currently far below the levels required to unlock investments in low-CO_2 production processes in the carbon-intensive industry, Papers V and VI seek to pave the way for a discussion on complementary policy options by examining how CO_2 trading and investments in low-carbon production processes in the steel and cement industries affect costs and prices further up the supply chain of steel and cement, respectively.

The following subsections present and discuss four of the most distinctive features of the analysis: 1) the description and characterisation of the current industry structure; 2) the formulation and use of scenarios; 3) the treatment of capital stock turnover; and 4), the representation and analysis of material and value flows involved in the supply of basic commodities. More detailed accounts of the choice of methodology, methodological trade-offs and limitations are given in the respective papers (Papers I–VI)

4.1 Description of the current industry structure

Although the research questions and scopes are different – explorations of the limits for current and emerging CO_2 abatement measures in Papers I–IV and of the cost increases along the value chain of cement and steel owing to carbon trading and investments in CO_2 abatement in Papers V and VI – all of the studies in this thesis are based on a bottom-up approach, taking as their point of departure the primary production of petroleum fuels, steel, and cement and the associated flows of energy, materials, and CO_2.

Studies related to industry energy use and GHG emissions range from bottom-up modelling studies of entire sectors to detailed engineering studies of specific processes (e.g., based on detailed process simulations). These studies have nonetheless a common basis in focusing on the technological (or techno-economic) potentials for improvements with regards to energy use and/or CO_2 emissions, and typically involve precise descriptions of the capital equipment and technical options (Greening et al. 2007; Pathways, 2010).

In the present work, while care has been taken to consider wider trends relevant to future CO_2 emissions in each industry, i.e., the future evolution of demand and production levels, future activity levels have been exogenously defined. To assess the more radical system changes necessary to reach almost zero CO_2 emissions, the emphasis has instead been placed on accounting for the technological heterogeneity within and between the studied industries. An essential element of this approach is to consider how specific aspects, such as the age structure of the capital stock, technology and fuel mix, and spatial distribution of the plant stock, contribute to facilitating or hindering the shift towards less-emission-intensive production processes. Therefore, considerable efforts have been devoted to collecting reliable data and the establishment of a detailed database that reflects the infrastructure of EU industry.

The Chalmers Industry database (Chalmers IN db), which is one of five sub-databases in the Chalmers Energy Infrastructure database (Kjärstad and Johnsson, 2007; Pathways 2011b), is continuously updated and its coverage has been expanded throughout the work reported in Papers I–IV. In its present form, the database includes information on more than 12,000 stationary CO_2 emission sources in the energy and industrial sectors. Together, these installations account for approximately half of the EU's total CO_2 emissions (~1,980 $MtCO_2$ in Year 2013). For large emission sources (>0.5 $MtCO_2$/yr), the database carries information on process technologies, production capacity, fuel mix, and the age of the capital stock. This category includes a relatively small number of large emission sources, i.e., thermal power plants (~540), refineries (~85), integrated steel plants (~35), and cement plants (~150), which are collectively responsible for almost 40% of the total CO_2 emissions in the EU. The only major stationary CO_2 emission sources currently not covered in the database are the petrochemical and other chemical industries and ammonia production plants, which together emit approximately 180 $MtCO_2$/yr (Ecofys, 2006; Cefic, 2013). The main features of the Chalmers IN db are presented in Table 3. For a more detailed account of the data sources and the applications of the Chalmers databases in the respective paper, see Papers I–IV.

Table 3. Main features of the Chalmers IN db. Key data sources include: IEA GHG, (2006); GCD (2009); Steel Institute VDEh, (2009); WBCSD (2012); Oil and Gas Journal (2013); Remus et al. (2013); Schorcht et al. (2013); Barthe et al. (2015); E-PRTR (2015) and EUTL (2015).

- Comprises the EU-27 countries plus Norway and Liechtenstein.
- Covers seven industrial sectors, mineral oil refineries (150)[a], coking ovens (20), metal ore roasting or sintering installations (30), installations for the production of pig iron or steel (240)[a], installations for the production of cement clinker or lime (560), installations for the manufacture of glass (440), installations for the manufacture of ceramic products (1000), and industrial plants for the production of pulp, paper or board (850).
- In addition to the >3200 industrial installations, the database specifies emissions and allocated emission allowances for installations classified as combustion installations[b] in the EU ETS Directive (including >7000 installations for the combustion of fuels with a total rated thermal input >20 MW).
- Specifies emissions and allocated emission allowances, including the verified CO_2 emissions and allocated emission allowances for the period 2005–2012 and the allocated emission allowances for the period 2005–2020.
- Contains the exact locations (country, city, address, and geographical co-ordinates) of plants with CO_2 emissions >0.5 $MtCO_2$/yr.
- Describes plant-level characteristics. For refineries, iron and steel plants, cement plants, and pulp and paper plants, the database contains information on process technologies, production capacity, fuel mix, and the age of the capital stock.

[a] Some of the plants has been closed or mothballed since the Chalmers IN db was first established in 2008.
[b] The category includes activities that range from the relatively small scale, e.g., smaller boilers, furnaces, and heaters, to large coal- and gas-fired power plants.

Figure 7 and 8 show examples of how the data on geographical distribution of large point sources in the European industry (EU27 + Norway) covered in the Chalmers IN db have been used to identify capture clusters and to survey the access to infrastructures, such as district heating networks, natural gas grids, and possible CCS storage sites, which could facilitate cost-efficient CO_2 abatement.

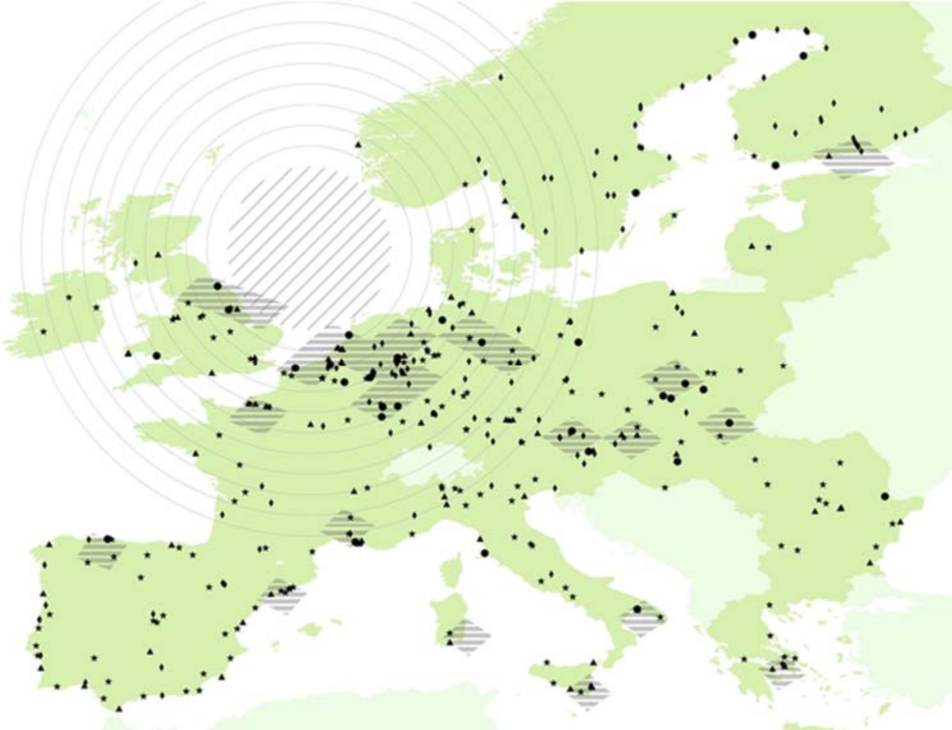

Figure 7. Geographical distribution of large point sources (>0.5 Mt CO_2/yr) in European industry (EU27 + Norway). The dashed circles marks approximate location of potential storage sites. The triangles denote refineries, circles indicate integrated steel plants, stars indicate cement plants, and diamonds designate pulp and paper plants. Regions where emissions from large industry point sources exceed 5 $MtCO_2$ annually are highlighted in grey.

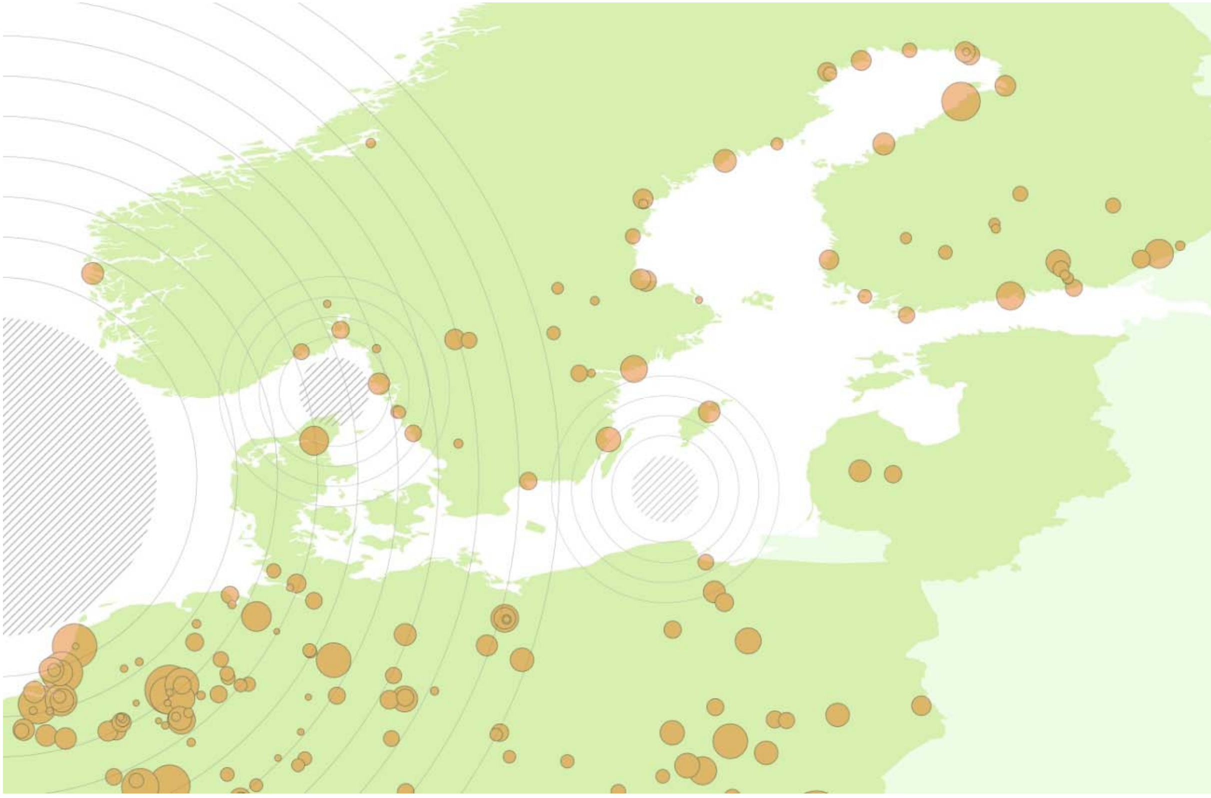

Figure 8. Survey of large industrial point sources around the Baltic Sea, Skagerrak, Kattegat and the western parts of the North Sea. Included are refineries, integrated steel plants, cement plants (>0.5 Mt CO_2/yr) and pulp and paper plants (>0.1 Mt CO_2/yr). The dashed circles marks the approximate location of potential storage sites.

4.2 Scenario analysis

While the first two studies (Papers I and II) represent early attempts to provide an overview of the prospects and limitations of key abatement options in the EU industry, the subsequent studies (Papers III and IV) explore different future trajectories of technological developments or pathways that could link the current system with a future low-CO_2 system, by means of scenario analysis.

It is clear that achieving a state of deep decarbonisation, consistent with the current climate policy targets, regardless of the eventual combination of measures included in the pathways that link the current system with a future low-CO_2 system, will require significant deviations from current practices. Therefore, taking on the challenge of defining the complex dynamics that will govern future flows of energy, materials, and CO_2 also calls for transparency with regards to how the scenario analysis has been implemented in this work and with regards to the shortcomings of the scenario methodology. Since Paper IV is the most recent example of the use of scenario analysis the discussion will revolve primarily around the study reported therein. This discussion is not meant to be exhaustive, but rather to reflect upon some of the limitations of the study in question and to briefly summarise some of the more common criticism of similar scenario studies.

The scenario analysis is performed using a spreadsheet-based accounting framework (in both Paper III and IV). By simulating capital stock turnover (further discussed in Section 4.3), different future trajectories of technological developments are explored and the associated flows of energy and CO_2 quantified. As is commonly the case with this type of accounting tool or accounting model, progression of most of the variables is exogenous and defined within the framework of a scenario (Chateau and Lapillonne, 1990; Fleiter et al., 2011). The focus is on exploring the limits for CO_2 abatement, for existing and emerging mitigation technologies and measures within current production processes and within a limited time-frame. The scenario inputs are chosen to reflect a development in which ambitious measures are taken to exploit the abatement strategies available in each sector. Thus, no claims are made as to its realism with respect to, for example, behaviour at the firm-level with regard to the investment decision, responses to fuel or raw material price changes, or more generally with regards to possible macroeconomic feedback effects. Despite these shortcomings, the main advantage of this approach is that it allows analysis of structural changes, and as a consequence, more profound changes. The possibility to track explicitly alternative technologies is particularly important and useful where the potential exists for large, disruptive advances in the types of technologies employed, as is the case for the carbon-intensive industries covered herein (Algehed et al., 2009). Since the major drivers of CO_2 emissions are treated explicitly, it is possible to compare, in a transparent and comprehensive way, the options and actions available to control the long-term development of CO_2 emissions.

Börjeson et al. (2005), in an attempt to put forward a consistent scenario typology distinguished between three main categories of scenario studies: predictive (What *will* happen?); explorative (What *can* happen?); and normative (How *can a certain objective* be reached?). While the study reported in Paper IV has an explicitly normative starting point, to assess the prospects for Nordic carbon-intensive industries to reduce significantly their direct CO_2 emissions in the period 2010–2050, the scenario analysis as such is probably best described as explorative in that, to span a wide array of possible developments, it is developed around a set of scenarios and scenario cases. For each of the studied industrial sectors, one scenario that describes the future development of overall activity levels, and the shares of production, fuel, and production mixes for each respective facility have been developed. Furthermore, for each sector, three to five cases that describe different future trajectories of technological developments are generated. For each scenario case, the total annual CO_2 emissions (E_T) from industry i in year t are calculated based on the following general relationship:

$$E_{Tit} = (E_{Cit} + E_{Pit}) \times A_{it} \tag{2}$$

where E_C is emissions that arise from the combustion, and E_C represents the process-related emissions. A denotes the total activity level or total output of the respective industry sector. As is clear from the discussion in Section 2.4, the decision as to how to represent the future evolution of demand and production levels is not trivial. While convenient from an analysis standpoint (and arguably no worse than alternative ways of representing demand/output) the bundling together of all the factors that drive demand/output fails to capture strategies to reduce primary materials output (cf., Eq. 1 in Section 2.4).

The use of scenario analysis has a long and rich tradition in the field of energy and material systems studies with its roots tracing back to early energy future studies in the 1960s (Nilsson et al., 2011). Scenario studies are useful to illustrate how long-term goals have implications for short-term actions and the motivation for applying scenario analysis is typically to inform current decision makers by expanding people’s judgment about plausible features and by pointing out key uncertainties, barriers or opportunities. Three more general criticisms of the ways in which scenarios are commonly used to explore different low-carbon futures (which largely applies also to this work) are: 1) a failure to factor in the role of institutional change in achieving different energy futures (Hughes and Strachan, 2010; Nilsson et al., 2011; Söderholm et al. 2011); 2) a tendency to separate technology, in this context of industrial process technologies, from the social, cultural or economic context from which it evolves (Luiten, 2001); and 3) the limitations and perils of using scenarios as a communicative tool (Morgan and Keith, 2008). Based on a review of the literature on human judgment under uncertainty, Morgan and Keith (2008) have argued that while intended to help expand peoples thinking, detailed scenarios may cause users to overlook a wide variety of alternate developments and to overestimate the probabilities of the alternatives that are presented. While the outcomes of the scenario analyses performed in this work should be interpreted in the light of this critique, as long as input data, underlying assumptions and limitations are clearly stated and the framing is probing and critical, as is the ambition in both Paper III and IV, scenarios are useful tools for exploring the consequences of alternative developments.

4.3 Treatment of capital stock turnover

As discussed above (*cf.* Section 2) a characteristic that is shared by all the sectors assessed in the present work is an ageing capital stock that is heavily dependent upon the use of fossil fuels. Since the technological lifetime of a key process technology is typically limited to ~30–50 years (OECD, 2000; OECD, 2001a; OECD, 2001b; Daniëls, 2002) a considerable share of the existing capital stock will have to undergo major refurbishments or will need to be replaced within the coming decades. Yet, until the year 2050, there is typically only one or two investment cycles left for many of the major process steps within the three industries investigated. Thus, assumptions regarding the types of technologies that will be available to replace the current stock and the timing of possible breakthroughs in new low-carbon process technologies will obviously have a major impact on the outcome of the analysis.

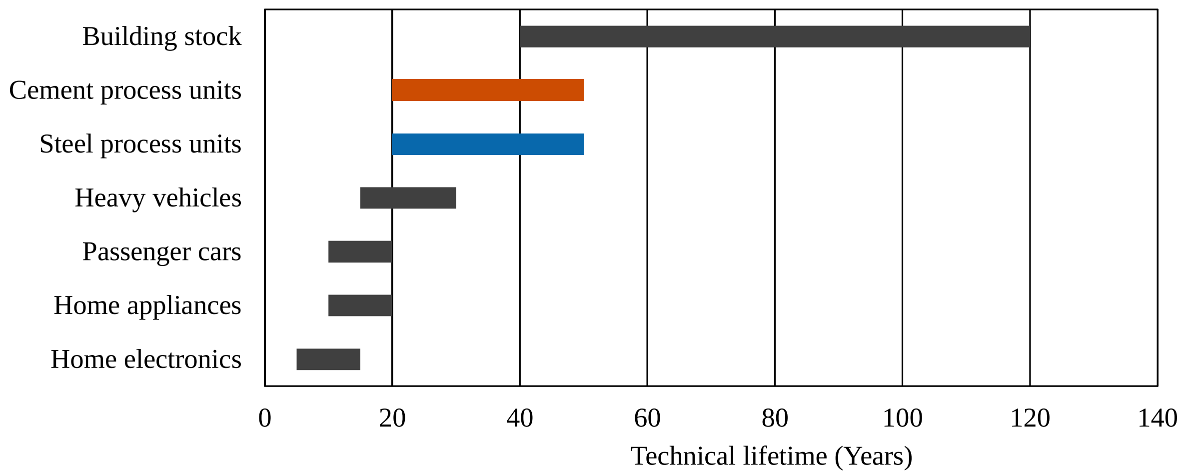

Figure 9. Average technical lifetimes for selected energy-related capital stock. Adapted from: Philibert (2007).

To provide some points of references with respect to the long-lived nature of the capital stock in the manufacturing industry Figure 9 provides estimates of the range of average technical lifetime for selected energy-related capital stocks. It is clear that individual capital stocks have a lifetime that extends from a few years for home electronics, to decades for manufacturing process equipment while building structures may last sixty years, a century or even longer (IEA, 2002; Philibert, 2007; Williams et al., 2014).

The most distinctive feature of the analyses carried out in Papers III and IV is the treatment of capital stock turnover. This approach builds on the assumption that the rate of introduction of low-carbon technologies, in the absence of premature retirement of capital, is limited to the rate of capital stock turnover (Philibert, 2007; Worrell and Biermans, 2005). For the primary steel and cement industries, the pace of capital stock turnover is assessed based on the age structure of the existing capital stock, while the assumed average technical lifetime of key process equipment is set at 50 years. Retired production capacity is assumed to be replaced with new "state-of-the-art" process technology (or to undergo major refurbishment), with improved performances in terms of energy efficiency and CO_2 intensity. In the refining industry, new investments are assumed to be in desulphurisation units or advanced conversion units; no new investments in primary refining capacity are assumed to take place.

Figure 10 illustrates how the vintage structure of operating cement kilns has been used to simulate capital stock turnover in the EU cement industry in Paper III.

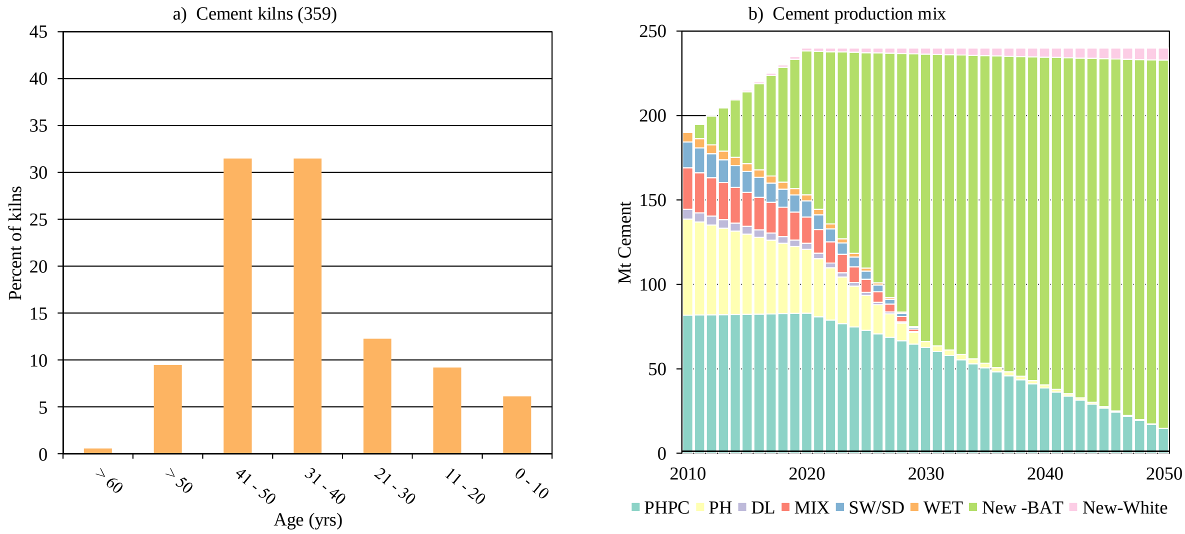

Figure 10. An example of how the vintage structure of operating cement kilns has been used to simulate capital stock turnover in the EU cement industry in Paper III. The assumed technical lifetime of the cement kiln is here set at 50 years. a) The percentages of operating cement kilns commissioned in each decade; 260 of the 359 cement kilns were commissioned before 1980 (Cembureau, 2001; GCD, 2009). b) The annual contribution to total output from each kiln type, including: dry rotary kiln with pre-heater and pre-calciner (PHPC); dry rotary kiln with pre-heater without pre-calciner (PH); dry long rotary kiln (DL); semi-wet/semi-dry rotary kiln (SW/SD); wet rotary kiln (WET); new state-of-the-art kiln (New-BAT); and new white kiln (New-White).

Whereas the use of technical age as the determining driver for stock turnover and technology diffusion is common (Daniëls, 2002; Ruth and Amato, 2002; Ruth et al., 2004; Fleiter et al., 2011; Williams et al., 2014), it is also a rather blunt tool. As discussed by Lempert et al. (2002) and Worrell and Biermans (2005), the use of technical lifetime and age as determining factors in the retirement of industrial equipment has certain limitations. On the one hand, industries often have little economic incentive to retire existing plants, which means that with regular maintenance, the capital stock may last decades longer than its nominal lifetime. On the other hand, stringent emission caps are likely to increase the rate at which old capital is retired.

The average lifetime of an industrial technology can vary substantially from site to site (depending on e.g. its operation and maintenance) (OECD, 2001a; OECD, 2001a). Daniëls (2002) has suggested that, as references, the average technical lifetime for selected energy-related capital stock in the steel industry should be designated as: 20 years for buildings and large installations, 15 years for electro-mechanical equipment (e.g., pumps and motors); 40 years for coke ovens; and 30 years for sinter and pellet production units. The average lifetime of blast furnaces is according to the same source in the range of 20–40 years, although it may exceed 40 years. Philibert (2007) points out that process units with very long lifetimes regularly undergo minor to major refurbishments, and successive overhauls may over the years result in a totally changed installation.

As for the steel industry there are no general standards for the technical lifetime of the equipment in the cement industry. Data reported by the OECD (2001a) suggest that a cement plant may have up to two major refurbishments during its lifetime (up to 50 years is common). However, major process units (e.g., grinders and pre-heaters) would normally only be considered for potential modernisation after 20–25 years or at even longer intervals for the cement kiln. Whether or not refurbishment of a plant occurs will also depend on the remaining lifetime of the quarry that supplies the plant.

Because of the long lifetimes of some key process equipment, e.g., blast furnaces and cement kilns, there is likely to be only one opportunity for replacement during the period up to the year 2050 (Williams et al., 2014). Thus, a failure to bring alternative low-CO_2 technologies to the shelf could lead to infrastructure inertia, that makes the Year 2050 target more difficult to reach, requires expensive retrofits, or puts investments at risk (Grubb, 1997; Sandén, and Azar, 2005; Williams et al., 2014). Therefore, transformation of the carbon-intensive industry to reduce dramatically CO_2 emissions, represents a double-edged challenge. The transition requires measures to incentivise and support both the phasing out of current carbon-intensive technologies and the phasing in of new zero- or low-carbon technologies.

Given the limited timeframe of less than four decades and in light of the long investment cycles involved in capital-intensive industries, such as refineries, steel works, and cement plants, there is a certain sense of urgency with respect to identifying and enforcing measures that could speed up the process of technological development and diffusion. Whereas historical energy technology transitions provide examples of rapid technological change (Wilson and Grubler, 2011; Grubler, 2012), it is important to be aware also of potentially counteracting factors. Path-dependency implies that established technologies have an advantage over emerging alternatives, not because they are inherently better, but because they are widely used and often deeply embedded in the social, economic and political contexts of which they are a part (Arthur, 1994; Sandén, and Azar, 2005). From and industrial end-users perspective, upfront investments are a major barrier, and future (long-term) costs and revenues are typically valued at relatively high discount rates (Overgaag et al., 2009). There is also evidence to suggest that the need to balance competitiveness and environmental effectiveness lead to firms (and legislators) becoming risk-averse (Bennett and Heidug, 2014), and thus less inclined to seek alternatives to current practices, which creates additional barriers to uptake for alternative low-CO_2 technologies.

4.4 Representation and analysis of material and value flows

The work reported in Papers V and VI is motivated by the substantial difference between the pricing of CO_2 emissions and the cost of mitigation at the production sites of energy-intensive industries, such as steel and cement-manufacturing (see *Q3* in Section 1.1).

Climate policies that target the industrial sectors, in the EU as a whole as well as in the Nordic countries, continue to rely almost exclusively on the price signal imposed through the EU ETS. However, in the case of the carbon-intensive industry, as long as the need to balance competitiveness and environmental effectiveness persists and in the absence of additional policy measures, continued and exclusive reliance on the trading system may lead to under-investment in the high-abatement long-lead-time measures required to reach the long-term emissions reduction targets (Vogt-Schilb et al., 2014; Bennett and Heidug, 2014). This part of the thesis work seeks to stimulate discussion of the complementary policy options that could facilitate the sharing of costs associated with developing CCS and other low-carbon technologies for industrial applications. This is facilitated by examining how cost increases in the steel and cement industries, due to CO_2 trading and investments in low-carbon production processes, affect costs and prices further up the respective product chains. This in contrast to much of the previous work that focused primarily on the impact of cost on primary production and the primary product (see for example Kuramochi et al., 2011; IEAGHG, 2013a; IEAGHG, 2013b)

Steel and cement are both intermediates in the supply chain of an extensive range of final goods, and both studies (Papers V and VI) build on the recognition that as these basic materials are transformed and passed along the chain of production their share of the total input expenditures gradually diminishes (Dahlström and Ekins, 2006; Allwood et al., 2011a; Skelton and Allwood, 2013). Neuhoff et al. (2014b) have argued that the incremental increase in carbon cost facing the final consumer of steel and cement would typically have a limited impact on the total cost at the end-user stage, e.g., the increase in price for a car buyer or the procurer of a building or an infrastructure project. Figure 11 serves to illustrate this hypothesis in the case of the supply of automotive steel to the manufacturing of a passenger car.

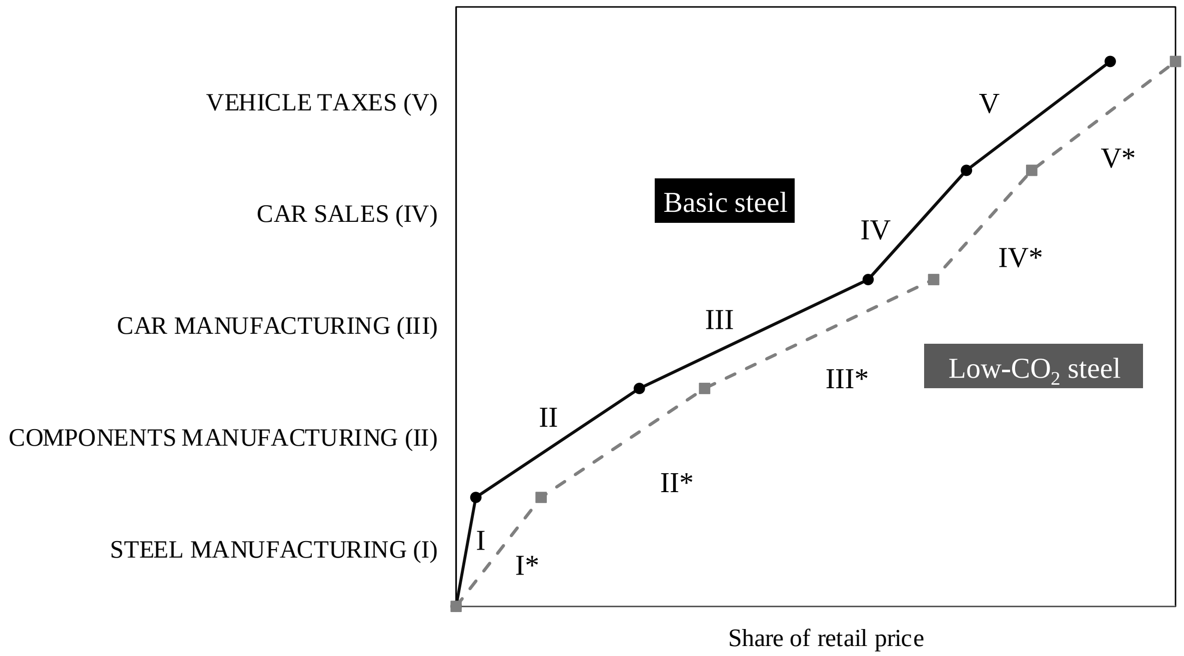

Figure 11. Schematic breakdown of the value added or cost at each step (I–V) of the supply chain from the production of automotive steel to the finished car. Adapted from Allwood et al. (2011a).

Using the supply of cement and concrete to a residential building (Paper V) and the supply of steel to a passenger car (Paper VI) as case studies, the magnitudes of the cost increases that may occur throughout the respective value chains as the result of CO_2 trading and investments in CO_2 abatement in the primary production stage are explored. The assessments, in both cases, rely on rather stylised representations of the material and value flows involved. The set-up of the production process at a hypothetical ‘average’ Nordic cement plant respectively steel works and the market price for emissions allowances decide the price of cement and steel, respectively. Subsequently, based on descriptions of the cost structure in each step of the respective supply chains, the actual expenditure on cement/steel is compared to the expenditure on other inputs.

The issues as to how one can describe the relationships between the cost of production and price and how production cost increases are distributed across the product portfolio and passed along the respective supply chain are not trivial (see for example, Schmidt, 2008 and Neuhoff, 2008). To make the analysis manageable, following Skelton and Allwood (2013), the impacts downstream of cement or steel price increases due to CO_2 trading and investments in CO_2 abatement measures at the cement/steel plant have been evaluated under *ceteris paribus* assumptions. We assume that industry pass-through of cost is complete, in other words that the intermediate and final consumers of the steel- or cement-containing products bear the full costs of CO_2 trading and investments in CO_2 abatement. Furthermore, for the intermediate and final consumers, it is only the cement or steel acquisition costs that change, with all the other costs being kept constant. Finally, increases in the selling price of cement and steel are not assumed to lead to substitution effects.

While the analyses in the two studies rely on a number of tentative assumptions with regards to, for example, the costs associated with investing and operating new production units, and on a stylised representation of the material and value flows involved, the analysis methods as such, and the outcomes, provide valuable inputs to the discussion on how to allocate the costs required to develop and deploy new low-carbon cement-making and steel-making processes.

5 Summary of key findings

This chapter highlights and discusses some of the key outcomes of the six sub-studies (Papers I–VI) that form the basis of this thesis. The selection of results presented and discussed here is intended to provide an overview and is not meant to be exhaustive.

5.1 Current measures will not suffice

Paper III and Paper IV both explore the limits for CO_2 abatement within current production processes in the carbon-intensive industry, albeit with different geographical scopes, the former covering carbon-intensive industry in the EU as a whole, and the latter examining closely the CO_2 emissions abatement potential for Nordic industry. The results from the two studies suggest that the combined effect of massive deployment of available abatement measures (e.g., fuel shifts and raw material substitution) and proven best-available process technology is not sufficient to comply with more stringent emission reduction targets in the medium term (to Year 2030) and long term (to Year 2050).

In Paper III, despite the assumptions made regarding moderate (steel and cement) or negative (petroleum products) output growth, an almost complete renewal of the capital stock (with the exception of the petroleum refinery industry), and extensive implementation of available abatement measures, the results indicate that the total level of emissions from the assessed sectors in Year 2050 would exceed by more than two-fold the targeted levels.

Under similar assumptions, the results from Paper VI show that despite a steady decline in output from the Nordic refinery industry, a significant increase in the use of biomass as a source of renewable carbon in the integrated iron and steel and cement industries, and an increase in the use of alternative raw materials in cement manufacturing, the total annual CO_2 emissions from Nordic carbon-intensive industry would account for approximately 40% of the total Nordic GHG budget in Year 2050.

Figure 12 shows the estimates for the development of CO_2 emissions from the carbon-intensive industry in the EU and the Nordic countries in the period 2010–2050. It is clear from the results that to realise the goal of future deep reductions in emissions from the carbon-intensive industry, unless production levels are significantly reduced (see further discussion in Section 2.4), more radical alterations to production processes are required.

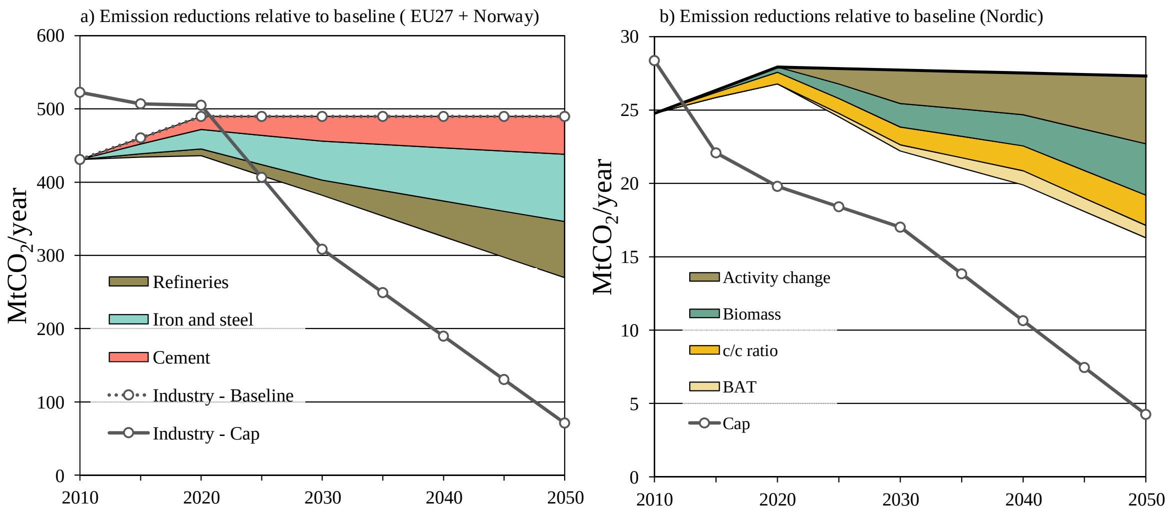

Figure 12. Estimated abatement potentials in the carbon-intensive industry in the period 2010–2050 assuming ambitious deployment of technologies and measures that are currently commercially available a) The emission reductions achieved in EU carbon-intensive industry relative to the baseline case in which technology and fuel mixes are frozen at Year 2010 levels (from Figure 8 in Paper III). b) The wedges define the contribution of each respective mitigation measure to overall emissions reduction relative to a baseline in the Nordic carbon-intensive industry. In the baseline, fuel mixes and the clinker-to-cement ratio (c/c ratio) are frozen at Year 2010 levels and improvements to energy efficiency are limited (adapted from Figure 8 in Paper IV).

5.2 CCS might provide an opening

While there is still room to achieve further reductions in emissions through measures and technologies available today, reducing CO_2 emissions from carbon-intensive industry beyond a certain point will require significant deviations from current practices. With regards to options that significantly reduce the direct on-site CO_2 emissions associated with the production of petroleum fuels, steel, and cement, there are no current viable alternatives to CCS. Papers I, II and IV (and to some extent Papers V and VI) all explore from various perspectives the role of CCS in applications for the carbon-intensive industry.

The results presented in Paper I indicate that some 60%–75% of the emissions from large industry point sources in the EU carbon-intensive industry could be avoided each year if the full potential of emerging CCS technologies was to be realised. However, as discussed in Papers I and II, with the latter focusing on strategies to reduce CO_2 from the European petroleum refining industry, significant obstacles must be overcome before this potential can be realised. With many different types of plants, and process lay-outs, the feasibility, costs, and potential are highly dependent upon site-specific conditions, including the size, age and type of units, the number of exhaust stacks, and the availability of space for accommodating a CO_2 capture system. It is further suggested that the geographical distribution of industrial emitters relative to suitable storage sites and relative to other large stationary CO_2 emission sources (including power plants, refineries, iron and steel industries, cement plants, and pulp and paper plants) will have implications for the potential scope of implementation, and that clustering of emission sources in regions with several large emitters, thereby increasing the scale and use of the transport and storage infrastructure, would be a way to facilitate deployment and to bring down costs.

Paper IV, in addition to assessing the CO_2 emissions abatement potential for current commercially available technologies and measures (see Section 5.1 above), investigates the potential for and implications of large-scale implementation of CCS in the Nordic carbon-intensive industry. The results suggest that ambitious deployment of CCS could produce emissions reductions that are in line with the targets for Year 2050 (see Figure 13a). However, the analysis also illustrates how such a large-scale introduction could come at a high price in terms of energy use and how the proposed flows of captured CO_2 will require careful planning of an infrastructure for the transportation and storage of CO_2.

Figure 13b show how the total thermal energy use in scenario cases in which post-combustion capture is assumed to be the dominant capture technology (NR2, NS2 and NC2) in Year 2050 is in line with thermal energy use in Year 2010. This is the case despite the assumed decline in total output of petroleum products from Nordic refineries during the same period. Total thermal energy use is considerably lower in those scenario cases in which the current capital stock in the iron and steel and cement industries are replaced with "state-of-the-art" process technologies (NS1 and NC1). The aggregate thermal energy use of the industry plants covered in this study in Year 2050 in these BAT cases is 30% below the levels for the cases in which CO_2 capture is assumed to be widely deployed

As indicated by the range depicted in Figure 13c (HIGH/LOW), the volumes of CO_2 recovered vary significantly depending on which CCS technology is chosen. Moreover, the timing of the possible introduction of industrial CO_2 capture on a commercial scale (here set to Year 2030) and the phase in which CCS would then be adopted (here linked to the technical lifetime of key process equipment) will influence the evolution of the captured CO_2 flow over time. Furthermore, the geographical spread of the industries that are subject to CO_2 capture will have implications for the possibilities to coordinate transportation and storage. More than half, approximately 10 $MtCO_2$/yr, of the suggested CO_2 flow in our analysis would come from sources in the Finnish and Swedish parts of the Baltic Sea region. However, the first estimates of the prospects for geological storage of CO_2 in the Swedish and Finnish parts of the Baltic Sea are not encouraging. In contrast, geological surveys of other parts of the Baltic Sea region and of the Norwegian and Danish parts of the North Sea have identified several formations with conditions favourable for CO_2 storage. Thus, it appears that storage constraints can be overcome through regional cooperation provided that CO_2 transportation costs can be kept low.

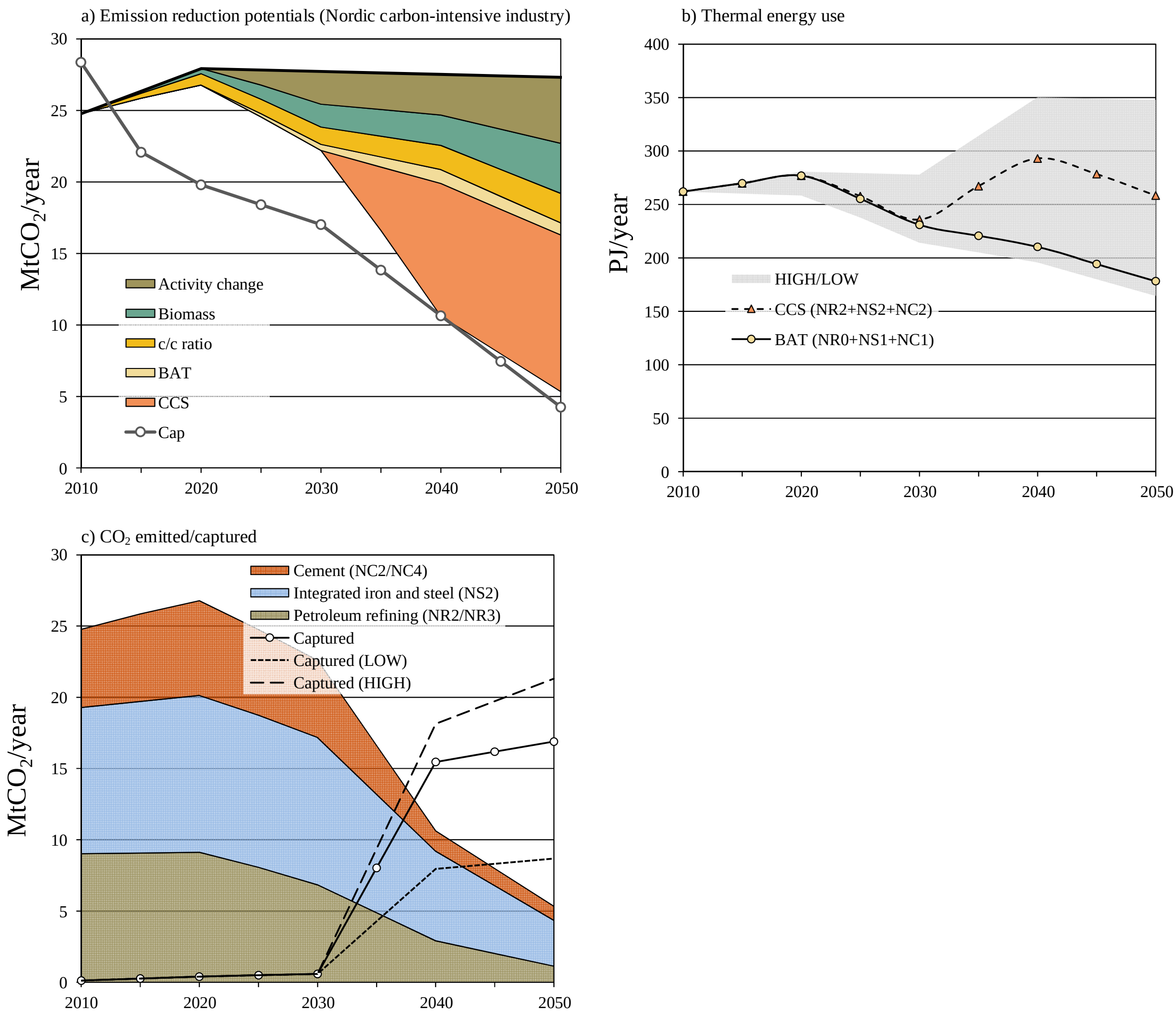

Figure 13. The overall potentials for, and implications of, measures to reduce CO_2 emissions from the Nordic carbon-intensive industry (adapted from Figure 8 in Paper IV). a) The wedges represent the contributions of the respective mitigation measures to overall emissions reduction relative to a baseline. In the baseline, the fuel mixes and the clinker-to-cement ratio (c/c ratio) are frozen at Year 2010 levels and improvements to energy efficiency are limited. b) Projected development of thermal energy use with (triangles) or without (circles) the introduction of CCS. c) Development of CO_2 emissions from Nordic carbon-intensive industry in the scenario cases that assume the most ambitious deployment of CO_2, together with the total amount of CO_2 captured annually.

5.3 How to finance a breakthrough? Go with the flow!

At this point, it seems uncontroversial to claim that in the absence of significant deployment of CCS or an equivalent breakthrough in the production of materials and fuels, and/or a corresponding drastic departure from current trends on the demand side, carbon-intensive industry will not be able to reduce CO_2 emissions to levels consistent with the EU climate policy targets. Moreover, the policy measures in place that target the production (EU ETS and piecemeal programs to promote energy efficiency in industry) and consumption of CO_2-intensive commodities (with the exception perhaps of fuel taxes and vehicle CO_2 emissions standards in the case of petroleum fuels) are insufficient to bring about the changes required on both the supply-side and the demand-side.

Papers V and VI explore the potential impact of a policy scheme that would facilitate the sharing of costs associated with developing CCS and other low-carbon technologies for industrial applications, e.g., the inclusion of consumption of CO_2-intensive commodities in the EU ETS in combination with the recirculation of revenues to support investments in the development and implementation of such breakthrough technologies.

The results from both studies, using the supply of cement and concrete to a residential building (Paper V) and the supply of steel to a passenger car (Paper VI) as case studies, suggest that a policy scheme designed to allocate a larger proportion of the costs of CO_2 abatement to the end-users would neither significantly alter the cost structure nor dramatically increase the price to be paid by a car buyer or a procurer of a building or an infrastructure project. Covering the costs of investing in new low-CO_2 steel-making and cement-making processes would require substantial increases in the selling prices of steel and cement. However, as illustrated in Figure 14, the results presented in Papers V and VI suggest that such price increases would have limited impact on costs and prices across the supply chains for automotive steel (Figure 14a) and cement (Figure 14b), even though the compliance costs of the steel and cement industries are assumed to be passed through perfectly.

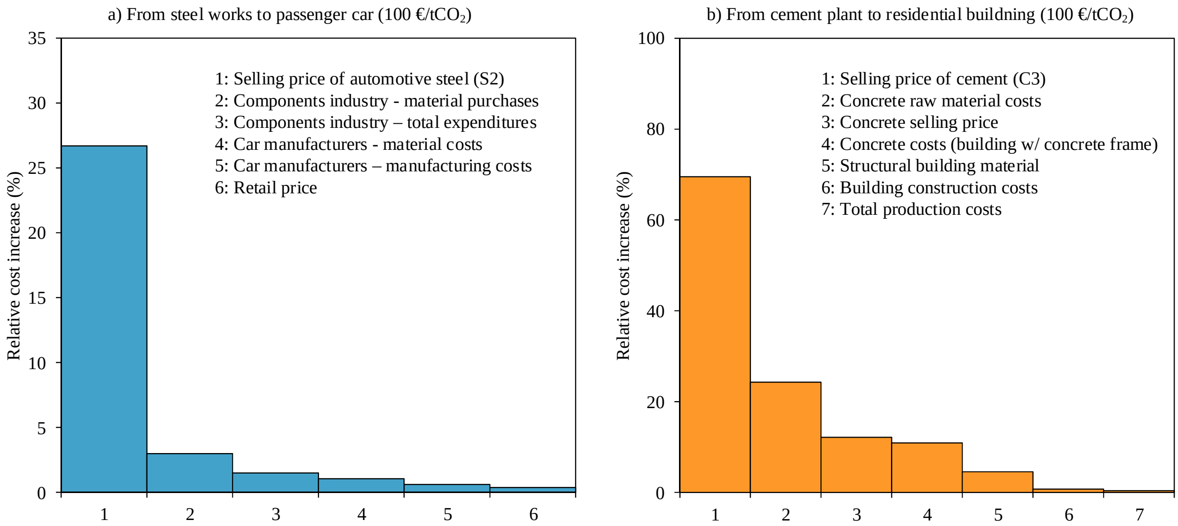

Figure 14. Cost impacts along the supply chains of steel and cement with the price of emissions allowances set at 100 €/tCO_2 in both cases. a) Case in which automotive steel is sourced from a hypothetical average Nordic integrated steel plant where the existing BF is replaced with BF with top gas recycling (TGR-BF) and fitted for CO_2 capture (S2). Cost increases are estimated relative to the reference case in which steel is sourced from the steel plant operating with existing units and with the price of EUA set to zero (*cf.* Figure 5 in Paper VI). b) Case in which cement is produced in a cement plant with a new kiln system adapted for oxy-combustion and CO_2 capture (C3). The current average cement production cost (excluding carbon costs) is set as the reference (68 €/t cement) (*cf.* Figure 9 in Paper V).

6 Concluding remarks and future work

It is becoming increasingly obvious that identifying ways to meet the growing demand for energy and material services, driven by the expanding global population and well-justified attempts to secure improved living standards in many parts of the world, while drastically reducing or possibly eradicating anthropogenic GHG emissions is one of the key challenges of the 21st Century.

The development of the theory of the greenhouse effect ironically coincided closely with the development of the technologies that allowed the processing, on an industrial scale, of petroleum oil to fuel, iron ore to steel, and limestone to cement.

Joseph Fourier introduced the idea of the heat-absorbing capacity of the atmosphere in 1824. In 1861, John Tyndall pointed to the important influence of CO_2 and aqueous vapour (H_2O) in the atmosphere on the temperature and climate on earth. In 1896, Svante Arrhenius estimated fairly accurately the eventual tropospheric temperature increase that would result from a doubling of the concentration of CO_2 in the atmosphere, and together with Arvid Högbom, he identified the combustion of fossil fuel as a source of atmospheric CO_2 (Crawford, 1994).

In the same period technological development in the manufacturing and processing industry was soaring, Joseph was granted (in 1824) the patent for Portland cement making. In 1855, Henry Bessemer patented the Bessemer converter, which allowed the mass-production of steel from molten pig iron, and in 1913, the first commercially successful process to crack heavy hydrocarbons into motor gasoline components was introduced (Enos, 1962, Allwood et al., 2011b)

Whereas the legacy of Arrhenuis and Högbom, the apparent causal connection between fossil fuel combustion, GHG emissions, and global warming, disappeared into obscurity during the first half of the 20th Century, technological advancements in the manufacturing and processing industries kept pace with the increasing appetite for energy and material services.

From its re-emergence in the 1970's, the connection between increasing levels of anthropogenic emissions of GHGs and the risk of rapid global warming has received massive attention in recent decades. Whereas the question as to how to share the burden of mitigating global climate is far from resolved, a heavy responsibility lies on the regions of the world that have benefitted the most from the energy and material revolution of the 20th Century. By Year 2050, the EU has committed to reducing economy-wide GHG emissions by 80%–95% relative to 1990 levels, so as to contribute to the global efforts to limit the long-term global average temperature increase to <2°C. Achieving this goal implies a drastic deviation from the historical trend and will require profound changes across all sectors of society.

Emissions of CO_2 from stationary sources in the power and heat and industrial sectors account for 60% of the annual CO_2 emissions and 50% of the total annual GHG emissions in the EU. With respect to the challenges associated with decarbonising the EU stationary sectors, the emphasis is typically placed on the transformation of the power sector. This thesis adds to the existing body of work by exploring further the potentials and limitations for reductions in CO_2 emissions in three industrial sectors: petroleum refining, iron and steel production, and cement manufacturing. In these industries, the options to reduce significantly CO_2 emissions in the near- to-medium-term tend to be fewer and less-developed than those in the power sector.

6.1 Concluding remarks

Petroleum refining, iron and steel production, and cement manufacturing, herein collectively referred to as the carbon-intensive industry, all belong the most energy- and CO_2-intensive industrial activities in the EU. Whereas the emphasis of this thesis is on options to reduce the direct on-site energy- and process-related CO_2 emissions from refineries, steel works and cement plants, current trends on the demand side and options for curbing and reducing the consumption of CO_2-intensive commodities have also been considered. The overarching ambition of this thesis is to contribute to a better understanding of the types of concrete changes that are required over the next three to four decades, as well as the magnitude and timing of these changes. It is clear from the work reported in this thesis that achieving deep decarbonisation, consistent with current climate policy targets, regardless of the eventual combination of measures that make up the pathways linking the current system with a future low-CO_2 system, will require significant alterations to current practices.

With respect to the on-site energy- and process-related CO_2 emissions from carbon-intensive industry the results from the six sub-studies (Papers I–VI) that form the basis of this thesis suggest that: 1) the technologies and measures that are currently commercially available will not be sufficient to reduce CO_2 emissions to levels consistent with the EU long-term climate policy targets; but 2) implementation, at scale, of CCS in the carbon-intensive industry could result in emissions reductions that are in line with the targets for Year 2050. While, several issues need to be resolved for different parts of the CCS chain before CO_2 capture can be seen as a viable option for reducing CO_2 emissions from EU industry, a policy scheme to facilitate the sharing of costs associated with developing CCS and other low-carbon technologies for industrial applications seems both feasible and desirable, particularly if we are to contribute meaningfully to reducing emissions within the next few decades.

There is, obviously, a strong connection between the future demand trajectories for petroleum fuels, steel and cement and the development of CO_2 emissions in the respective industries. Thus, the development of consumption and the production of CO_2-intensive commodities are issues that need to be addressed collectively. With respect to the petroleum refining industry, the most obvious and straightforward way to reduce the CO_2 emissions associated with the petroleum fuel chain would be to shift away from petroleum fuels in the end-use sectors (i.e., the transport sector), which would gradually make the petroleum refineries obsolete. This is also a prerequisite for meeting the economy-wide GHG emissions reduction targets. With respect to the steel and cement industries, there is, in principle, nothing that prevents the consumption of primary steel and cement to be significantly reduced through a strong commitment to material efficiency, material replacement and product-service demand reduction. In practice, however, the versatility, relatively low cost, and wide availability of steel and cement sets high standards for competing materials. Moreover, there is evidence to suggest that mitigation activities in other sectors, e.g., a large-scale rollout of wind and solar energy facilities, and adaptation measures could result in increased demand for steel and cement and other CO_2 emissions-intensive materials (Vidal et al., 2013; Fischedick et al., 2014a; Jeffries, 2015).

The work of this thesis highlights several areas in which strategic decisions will need to be made by national legislators and companies that will affect the prospects for achieving future reductions in CO_2 emissions in the carbon-intensive industry. Any attempt to suggest priorities with respect to measures that would enable significant reductions in emissions from these industries is of course destined to be subjective and incomplete. One thing is for sure, doing nothing is not an alternative. While there is no guarantee that investments in the development and implementation of CCS and other low-carbon technologies for industrial applications will pay off, choosing not to, or failing to, unlock investments in the development of such technologies within the next few years will severely compromise the chances of a successful and timely rollout of alternative low-CO_2 production processes up to Year 2050. Under the assumption that passing on the mitigation burden to other sectors is neither feasible nor desirable, choosing not to, or failing to bring alternative low-CO_2 technologies to the shelf would instead require significant cuts in the production and consumption of primary steel and cement clinker to achieve reductions in CO_2 emissions consistent with the EU climate policy targets.

6.2 Future work

New insights generate new questions. This is also the case with the work reported in this thesis. The discussions and conclusions indicate several new avenues for future research, five of which will be further elaborated upon below.

It is all connected. A relatively large body of the literature explores how a transition towards a low-CO_2 economy could be realised. The emphasis in those studies has often been on representing energy and/or economic interlinkages and interactions within and across different sectors of the economy. Thus, those previous investigations typically have failed to encompass the cross-sectoral implications of changing patterns in the production and consumption of materials. While there are a few examples of attempts to assess how mitigation activities result in increased industrial product demand (for a review, see Fischedick et al., 2014a), the overall picture remains fragmented. Addressing this gap and developing a more comprehensive framework for assessing how the processes of transforming the energy, transport and building sectors affect the patterns of production and consumption of materials (including current bulk materials such as steel and cement and new innovative materials) could represent a fruitful line of inquiry. A good starting point would be to build on the studies of Kram et al. (2001) and Schade et al. (2009).

How to bring low-CO_2 production processes to the shelf? As discussed throughout this thesis, progress with respect to overcoming the technical, infrastructural and financial barriers to the uptake of alternative low-CO_2 technologies for applications in the carbon-intensive has been slow to date. If the goal is to contribute meaningfully to reducing emissions within the next few decades there is an urgent need to find ways to unlock investments in the development and implementation of such breakthrough technologies. Papers V and VI together with previous studies, e.g., Neuhoff et al. (2014a; 2014b) and Bennett and Heidug (2014), present and discuss policy options aimed at incentivising and supporting accelerated technology development and commercial investments. However, the issue as to how to unlock investments in high-abatement, long-lead-time measures in the carbon-intensive industry deserves more attention than it has hitherto received.

The role of biomass. The results from Papers III and IV point towards the important role, especially in the absence of successful deployment of CO_2 capture, of biomass-based fuels as substitutes for coal and other fossil fuels and reductants in the steel and cement industries (and potentially also as feedstock in the refining industry). While several studies have investigating separately the potentials for, and implications of, increased use of biomass in the refining, steel, and cement industries (for reviews, see Johansson et al., 2009; Aranda Usón et al., 2013; Johansson, 2014); further bottom-up investigations are warranted into the wider systems effect of increased use of biomass in the carbon-intensive industries covered in this thesis and in the manufacturing and processing industries in general.

Connections to the power system. Whereas the emphasis of the work presented in this thesis has been on options to reduce direct fuel- and process-related CO_2 emissions, refineries, steel works, and cement plants, together with (for example) pulp- and paper plants and chemical industries are typically also major consumers (and sometimes suppliers) of electricity. The results presented herein suggest that a large-scale introduction of CCS would come at a significant price in terms of energy use – increasing the use of both fuels and electricity. Thus there is a need to investigate in greater depth the effects on the electricity system of introducing CCS and other low-CO_2 technologies. As the EU electricity supply system is also likely to undergo major transformations in the coming decades, the interplay between manufacturing industry and an electricity system that involves an increasing share of intermittent renewables opens up new research questions (see e.g. IRENA, 2015). In analogy with old windmills and waterwheels, it is possible to imagine, in a carbon-constrained world, a manufacturing industry that is more adapted to interactions with intermittent sources of energy. This might include everything from adapting electric motor systems (pumps, compressors, motors, and fans) to respond in a more flexible manner to load patterns in the electricity grid, to the factoring in of wind conditions and solar radiation in the process scheduling and, in the extreme, to the relocation of electricity-intensive plants to regions with conditions favourable for renewable power production.

Acronyms and definitions

BF	Blast Furnace
$CaCO_3$	Calcium carbonate
Carbon-intensive industry	Petroleum refining, iron and steel production, and cement manufacturing, are herein collectively referred to as ‘the carbon-intensive industry’
CCS	Carbon dioxide Capture and Storage
Ceteris paribus	All other variables except those under immediate consideration are held constant
CHP	Combined Heat and Power production
CO_2	Carbon dioxide
Decarbonisation	The reduction or removal of carbon dioxide from energy sources or industrial processes
EC	European Commission
EU	The European Union
EUA	Emissions allowances under the EU ETS
EU ETS	The European Union Emission Trading System
EU-27	EU-27 Member States include: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovak Republic, Slovenia, Spain, Sweden and the United Kingdom
GDP	Gross Domestic Product
GHG	Greenhouse gas
kb/d	Thousand barrels per calendar day (Used as a measure of the crude distillation capacity of a petroleum refiner)
MACCs	Marginal Abatement Cost Curves
N_2	Nitrogen
TGR-BF	Top Gas Recycling Blast Furnace

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