CO2 emissions abatement in the Nordic carbon-intensive industry – an end-game in sight?

CO_2 emissions abatement in the Nordic carbon-intensive industry – an end-game in sight?

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Abstract

Analysing different future trajectories of technological developments we assess the prospects for Nordic carbon-intensive industries to significantly reduce direct CO_2 emissions in the period 2010–2050. This analysis covers petroleum refining, integrated iron and steel production, and cement manufacturing in the four largest Nordic countries of Denmark, Finland, Norway, and Sweden. Our results show that the implementation of currently available abatement measures will not be enough to meet the ambitious emissions reduction targets envisaged for the Year 2050. We show how an extensive deployment of CCS could result in emissions reductions that are in line with such targets. However, large-scale introduction of CCS would come at a significant price in terms of energy use and the associated flows of captured CO_2 would place high requirements on timely planning of infrastructure for the transportation and storage of CO_2. Further the assessment highlights the importance of, especially in the absence of successful deployment of CO_2 capture, encouraging increased use of biomass in the cement and integrated iron and steel industries, and of promoting the utilisation of alternative raw materials in cement manufacturing to complement efforts to improve energy efficiency.

Keywords: CO_2 abatement, Nordic industry, Refinery, Iron and steel, Cement, Scenario analysis

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1. Introduction

The reputation, which is partly self-imposed, of the Nordic countries as front-runners in addressing the challenge to mitigate global climate change may be justified but deserves closer critical scrutiny. On the one hand, efficient utilisation of natural and energy recourses in the region and pro-active policy interventions have resulted in the decoupling of economic growth from domestic greenhouse gas (GHG) emissions (Skjelvik et al, 2007; IEA, 2013a; Nordic Council, 2014). On the other hand, the GHG emissions associated with Nordic consumption (accounting for both domestic and international emissions associated with the overall consumption within a country) continue to increase (Davis and Caldeira, 2010; SEPA, 2013). Of greater relevance to the present study, when it comes to the 'high-hanging fruits' (e.g., decarbonising the transport and industry sectors), the Nordic countries face the same challenges as most of the other countries in the EU – and around the world.

All Nordic countries have presented long-term visions for large reductions in GHG emissions up to Year 2050. Achieving these goals would entail a drastic deviation from the historical trend and would require profound changes across all sectors of the Nordic economies. While there is evidence that the determination to sustain the competitiveness of domestic industry will continue to limit the room for manoeuvring for climate policy that targets the industrial sectors, both nationally and regionally, there is a clear desire among Nordic legislators to identify and enforce strategies that would enable and facilitate decarbonisation (POF, 2009; The Swedish Government, 2009; NOU, 2012; The Danish Government, 2013; SEPA, 2012). Several studies have explored how such a transition could be realised on a national level in: Denmark (e.g., 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 (e.g., POF, 2009; Heaps et al., 2010; Heinonen and Lauttamäki, 2012; VTT, 2012); Norway (e.g., NOU, 2006; NEA, 2010); and Sweden (e.g., Gode et al., 2010; Gustavsson et al. 2011), and on the Nordic regional scale (e.g., Benestad et al, 1993; Nordic Council, 2007). While the sectoral coverage and the methodological approaches of these studies vary, the treatment of the Nordic industry sector is often crude. Yet, the Nordic countries are highly industrialised and hold many energy and carbon intensive industries, which are linked to domestic natural resources (e.g. iron and steel, oil and gas and cement) and/or rely on the burning of fossil fuels (iron and steel and cement). Thus, there is a need to assess how such industries can be transformed to comply with the Nordic long-term visions for large reductions in GHG emissions up to Year 2050.

This study covers three carbon-intensive industry sectors, petroleum refining, integrated iron and steel production, and cement manufacturing in the four largest Nordic countries of Denmark, Finland, Norway, and Sweden (i.e. Island not included). In Year 2010, total emissions from the 23 industrial plants covered within the scope of the study amounted to 25 $MtCO_2$ as shown in Table 1 (CITL, 2013; EEA, 2013). This corresponds to approximately 10% of the total CO_2 emissions in the Nordic region. Carbon-intensive industry accounts for approximately 20% of the total CO_2 emissions in Finland and Sweden, the corresponding shares in Denmark and Norway are considerably lower at 6%–7%.

Several studies have assessed the potential for future CO_2 emission reductions for global industry, as well as for the industrial sectors of selected regions and countries (e.g., Croezen and Korteland, 2010; UNIDO, 2010a; Saygin et al. 2013; IEA, 2013b). Similarly, previous studies by the authors have explored the prospects for presently available abatement technologies (Rootzén and Johnsson, 2013a) and CCS (Rootzén and Johnsson, 2013b) to achieve significant reductions in CO_2 emissions from carbon-intensive industries in the EU (EU-27). As Nordic legislators have gradually intensified efforts to identify workable long-term climate policy strategies, studies are increasingly focusing on the role of domestic industry in the process of decarbonising the Nordic economies (e.g., SINTEF, 2009; Teir et al., 2010; Økstad et al., 2010; Åhman et al. 2012; IEA, 2013a). However, there is a scarcity of studies that account specifically for the technological heterogeneity of the energy-intensive process industry, and that in comprehensive and transparent ways, explore the potential of each industrial sector to meet stringent CO_2 reduction targets in the long term. By placing emphasis on the technological feasibility of achieving significant reductions in CO_2 emissions from Nordic carbon-intensive industry the present work contributes to defining the scope of action for Nordic climate policy. To assess the more radical system changes necessary to reach almost zero CO_2 emissions our approach has been to combine the traits of both bottom-up type studies (technology explicitness) and top-down type studies (capturing economy wide trends) in one accounting framework (as discussed in e.g. Greening et al., 2007; Algehed et al., 2009; Söderholm et al., 2011). This by accounting for the technological heterogeneity within and between the studied sectors, while also, considering wider trends relevant to future CO_2 emissions in each industry. Given the time horizon chosen for the study (2010–2050), the future trajectory of technological developments is obviously associated with significant levels of uncertainty. To illustrate and analyse how different strategic choices influence the prospects for achieving the long-term goals of CO_2 emissions reduction in the Nordic carbon-intensive industry, we have used an exploratory scenario analysis, as described by van Notten et al. (2003) and Börjeson et al. (2005). The aims were to: (i) investigate the prospects for further CO_2 emissions reduction within current production processes; (ii) assess the extent to which the implementation of CO_2 capture in industrial settings might contribute to reducing

CO_2 emissions; and (iii) evaluate the effects and policy implications of different future trajectories of technological developments for the Nordic carbon-intensive industry.

Table 1. Characteristics of the industries covered in the analysis.

	Number of installations	Capacity	Average annual CO_2 emissions (2008–2012)	Average annual allocations of emissions allowances[a]	
				2008–2012	2013–2020
		Mt crude oil/year	$MtCO_2$/year	Million EUA/year	Million EUA/year
Petroleum refining					
- Denmark	2	8.7	0.9	0.9	0.8
- Finland	2	13.0	3.3	3.2	2.3
- Norway	2	15.9	1.9	1.9	1.5
- Sweden[b]	5	21.8	3.0	3.2	2.6
Total	*11*	*59.3*	*9.1*	*9.2*	*7.3*
		Mt crude steel/year	$MtCO_2$/year	Million EUA/year	Million EUA/year
Integrated iron and steel					
- Finland[c]	2	3.5	4.6	5.7	4.5
- Sweden[d]	2	4.1	5.0	7.0	4.8
Total	*4*	*7.6*	*9.6*	*12.7*	*9.4*
		Mt cement/year	$MtCO_2$/year	Million EUA/year	Million EUA/year
Cement manufacturing					
- *Denmark*	1	3.0	1.7	2.6	1.9
- *Finland*	2	1.5	0.8	1.2	0.9
- *Norway*	2	1.9	1.2	1.3	1.0
- *Sweden*	3	3.0	2.2	2.2	1.7
Total	*8*	*9.4*	*5.8*	*7.5*	*5.6*

[a] EU allowance (EUA) refers to the carbon credits traded under the EU Emissions Trading System (EU ETS). One EUA represents one tonne of CO_2 that the holder is allowed to emit. All of the industries assessed here belong to the industrial sectors deemed to be exposed to a significant risk of carbon leakage under the EU ETS.

[b] The two Swedish 'specialty refineries' are not included in the analysis.

[c] The smallest of the two Finnish integrated steel plants, Koverhar Steel Works, has been mothballed since 2012. With the exception of the sintering plant (closed in 2011) the Raahe steel plant is fully integrated with coke ovens, blast furnaces, steel plant, rolling mills and power plant (Rautarukki, 2009; Rautarukki, 2011).

[d] The reported emissions include CO_2 emissions that result from the combustion of energy gases sold by SSAB to Lulekraft AB. With the exception of the sintering plant the Oxelösund plant includes the entire production line stretching from raw materials to rolled plate. The Luleå plant, have neither sintering plant nor rolling mill, steel slabs is the final product.

2. Methods

2.1 Data collection

A key component of the analysis is the provision of a good representation of the energy, material, and CO_2 flows at each of the industry plants included in the study. For this purpose, the Chalmers Industry Database (Rootzén et al., 2011; Rootzén and Johnsson, 2013a; Rootzén and Johnsson, 2013b) has been updated and used. Table 2 outlines the main components of the database for the four countries in focus in the present study, and presents the data sources used to update the database so as to meet the requirements of the present study and ensure the quality of the data. The database has been further complemented and validated with statistics from national (Statistics Denmark, 2014; Statistics Finland, 2014; Statistics Norway, 2014; Statistics Sweden, 2014) and international (WBCSD, 2011; Cembureu, 2012; Europia, 2012; WSA, 2013; Eurostat, 2014; E-PRTR, 2014) sources.

Table 2. Components of the Chalmers Industry Database applied in the current analysis.

	Scope	Data sources
Petroleum refining	- Includes 11 petroleum refineries in Denmark, Finland, Norway, and Sweden. The two Swedish 'specialty refineries' are excluded from the analysis. - Classification of refineries according to configuration/complexity - Includes installation-level information on crude input, main process equipment, and process capacities for this equipment. - Details regarding internal fuel use and thermal and electrical energy usages	*General*: Oil and Gas Journal, 2013; CITL, 2013 *Denmark*: Dansk Shell, 2011; Statoil Refining Denmark, 2011; Statoil, 2012 *Finland*: EAF, 2006; EAF, 2007; IFEU, 2006; Neste Oil, 2012; Pöyry, 2013; FEA, 2014 *Norway*: Statoil, 2005; Statoil, 2012; Esso Norge, 2013a, Esso Norge, 2013b, NEA, 2014 *Sweden*: Preemraff Göteborg, 2011; Preemraff Lysekil, 2011; St1 Refinery, 2012
Integrated iron and steel	- Includes four integrated steel plants in Finland and Sweden (six blast furnaces [BF], six basic oxygen furnaces [BOF], and three coking plants). The Finnish Koverhar Steel Works is excluded from the analysis. - Details of production routes and production capacities - Reducing agent/fuel mix and thermal and electrical energy usages - Information on the age structure of the capital stock	*General*: Steel Institute VDEh, 2009; CITL, 2013 *Finland*: Rautarukki, 2008; Rautarukki, 2011; FEA, 2014 *Sweden*: Profu, 2008; SSAB Oxelösund, 2012; SSAB Luleå, 2013; SSAB, 2013
Cement manufacturing	- Includes eight cement plants with eighteen cement kilns in Denmark, Finland, Norway, and Sweden. - Includes installation-level information on kiln-types (including pre-heaters and pre-calciners), main fuel, and production capacities. - Clinker to cement ratio, fuel mix and thermal and electrical energy usages - Information on the age structure of the capital stock.	*General*: GCD, 2009; CITL, 2013 *Denmark*: Aalborg Portland, 2012; DEPA; 2012 *Finland*: VTT, 2009; Finnsementti, 2013; FEA, 2014 *Norway*: Norcem, 2007; Norcem Kjøpsvik, 2009; Norcem Brevik, 2011; NEA, 2014 *Sweden*: Cementa, 2007; Cementa Degerhamn, 2012; Cementa Skövde, 2012; Cementa Slite, 2012

2.2 Scenario generation and quantification approach

The scenario analysis approach used in this work combines and further develops the methodological approaches reported by Rootzén and Johnsson, 2013a and Rootzén and Johnsson, 2013b. The improved and more comprehensive approach, described in the following sections, in combination with the application of facility-level data for each of the industry plants included in the study, as described above, allows for analysing the prospects for future CO_2 emissions reductions in a comprehensive and transparent way while accounting for the technological heterogeneity within and across the respective industry sector.

For each of the studied industrial sectors, one scenario that describes the future development of overall activity levels, the respective facility's share of production, fuel, and production mixes have been developed. Furthermore, for each sector, three to five cases that describe different future trajectories of technological developments have been developed.

For each scenario case, the total annual CO_2 emissions (E_T) from industry sector i in year t are calculated based on the following general relationship:

$$E_{Tit} = A_{it} \times (E_{Cit} + E_{Pit}) \tag{1}$$

where A_{it} denotes the total activity level in industry sector i in year t, E_{Cit} is the average specific emissions arising from the combustion of fossil fuels from industry sector i in year t, and E_{Pit} represents the process-related emissions from industry sector i in year t. The combustion-related emissions (E_C) are calculated as the product of the average specific energy use and the weighted emissions factor in industry sector i in year t:

$$E_{Cit} = \sum_{j=1}^{m} \left(a_{itj} s_{itj}\right) \times \sum_{k=1}^{n} \left(f_{itk} \theta_k\right) \tag{2}$$

where a_{itj} is the market share of industrial plant j in industry sector i in year t, s_{itj} is the thermal energy use per tonne of product at industrial plant j in industry sector i in year t, m is the total number of industrial plants j in industry sector i, f_{itk} is the share of fuel k in the total fuel energy mix in industry sector i in year t, θ_k is the CO_2 emission factor for fuel k, and n is the total number of fuels used in the fuel mix in industry sector *i* in year *t*. The average specific energy use (GJ/t output) in industry sector *i* in year *t*, hereinafter referred to as H_{it}, is given by the first term in Eq. 2.

The process-related CO_2 emissions (E_P) are calculated from:

$$E_{Pit} = \varepsilon_{it} \sum_{j=1}^{m} a_{itj} p_{itj} \tag{3}$$

where ε_{it} denotes the emissions per unit of output from process *p*, a_{itj} is the market share of industrial plant *j* in industry sector *i* in year *t*, p_{itj} is the output from process *p* relative to the total output industrial plant *j* in industry sector *i* in year *t*, and *m* is the total number of industrial plants *j* in industry sector *i*. For the refinery industry *p* corresponds to the annual production of hydrogen from the hydrogen production unit (where applicable) relative the total annual throughputs. ε gives the specific CO_2 emissions per normal cubic meter hydrogen produced ($tCO_2/10^6\ Nm^3\ H_2$) (API, 2009). For the integrated steel industry, whereas the primary purpose of the use of coke (or coal) is to function as reducing agent, all emissions are treated as combustion-related emission (i.e. E_p=0). For the cement industry *p* corresponds to the clinker to cement ratio and ε gives the specific CO_2 emissions arising from the calcination of limestone per tonne of clinker produced (tCO_2/t clinker) (IPCC, 2006).

The current conditions are used as the starting point for all the scenarios. Only direct CO_2 emissions are included in the estimates. Emissions that result from the combustion of biomass are excluded from the emission estimates. With a few exceptions, CO_2 emissions stemming from off-site generation of electricity, steam or heating and cooling but imported by the entity are not taken into account. In those cases in which process gases are currently transferred off-site, the CO_2 emissions that arise from the combustion of the same gases are attributed to the original source. Any exceptions from these general assumptions are described in Section 2.4.

2.2.1 Trajectories of technological developments and technology stock turnover

For each of the studied industrial sectors, three to five cases have been developed in which the effects of different future trajectories of technological developments are explored. Thus, the following main trajectories are investigated:

- No major changes take place in the present technology stock, i.e., energy efficiency improvements are limited to modifications to the remaining current capital stock.
- The current technology stock is gradually renewed as older process equipment is replaced with proven best-available technology (BAT), with similar characteristics, albeit with improved energy efficiency and lower specific emissions. The age of remaining existing process equipment determines the turnover rate. For the petroleum refining industry, no case involving capital stock turnover is applied.
- Cases with deployment of CO_2 capture. For all industries, CO_2 capture is assumed to be available on a commercial scale from Year 2030. The rate of deployment of CCS depends on the rate of turnover of the existing technology stock. Two CCS cases are investigated for the petroleum refining industry, one for integrated iron and steel manufacturing, and three for the cement industry.

In the Nordic refining industry, new investments are assumed to be directed towards conversion or treatment and/or capacity to produce biofuels; no new investments occur in primary refining capacity. In this respect, Nordic refineries have been divided into four categories (Configurations 1–4) based on level of complexity (Reinaud, 2005; European

Commission, 2012a; Johansson et al., 2012; Oil and Gas Journal, 2013). The share of the total transformation output in the Nordic region from the complex refineries (Configurations 3 and 4) is assumed to increase at the expense of simpler refineries that are less flexible and have lower conversion capacities (Configurations 1 and 2).

For the Nordic steel and cement industries, the age profile of the remaining capital stock, and the typical technical lifetime of key plant equipment (i.e., blast furnaces and cement kilns), set at 50 years, determine the rate of stock turnover (cf. Rootzén and Johnsson, 2013a; Rootzén and Johnsson, 2013b). Obsolete capacity is assumed to be replaced with new BAT process technologies (or to undergo major refurbishment), with improved performance profiles in terms of energy efficiency and CO_2 intensity. Although the use of technical lifetime and age as indicator for the turnover of industrial process equipment has certain drawbacks (Lempert et al., 2002; Philibert, 2007; Worrell and Biermans, 2005), it is widely used as the basis for describing technology diffusion when modelling the development of industry energy usage (see discussions in e.g., Lempert et al., 2002 and Fleiter et al., 2011).

2.2.2 Sensitivity analysis

Inputs to the basic scenarios and the cases investigated have been selected to describe a development in which the strategies to reduce emissions that are available in each industry sector are fully exploited. However, to assess and illustrate how sensitive the estimated CO_2 emissions trajectories are to changes in key scenario inputs basic sensitivity analysis was carried out. For each industry and for each scenario case, we re-calculated the CO_2 emissions estimates for Year 2050 (cf., Eq. 1–5) with low and high values for each parameter, while all the other parameters were held constant. The ranges of the input variables were selected so as to represent a reasonable variety of alternative development paths.

2.3 Basic assumptions

2.3.1 Future activity levels and emission reduction targets

Table 3 summarises the assumptions made regarding future activity levels, by country and by sector of industry. Overall refinery throughput in the Nordic countries are assumed to decline throughout the studied period, primarily as a result of changing and declining demand in the transport sector (cf. IEA, 2013a). For both integrated iron and steel manufacturing and cement production, the assumed average annual output in the period 2020–2050 are in level with production levels before the financial and economic crisis of 2008–2009 (WSA, 2013; UNFCCC, 2014).

Table 3. Activity levels by country and by sector of industry – scenario assumptions.

	2010	2030	2050	Specific energy use in 2010 (GJ/t output)
Petroleum refining				
Total transformation throughput[a] (Mt/year), of which (%):	56.4	35.9	20.6	
- Denmark	13	13	0	1.8 – 1.9
- Finland	23	23	51	2.1 – 3.0
- Norway	29	29	0	1.1 – 2.6
- Sweden	34	34	48	1.7 – 2.5
Iron and steel industry				
Integrated iron and steel (BF/BOF) (Mt crude steel/year), of which (%):	6.1	6.6	6.6	
- Finland	45	45	45	19.1
- Sweden	55	55	55	17.2 – 17.6
Cement manufacturing				
Total cement production[b] (Mt cement/year), of which (%):	6.6	9.4	9.4	
- Denmark	23	32	32	4.1 – 6.9
- Finland	18	16	16	3.5 – 3.6
- Norway	24	20	20	3.5 – 3.6
- Sweden	35	32	32	3.7 – 4.5

[a] Assuming a decline in demand in all end-use sectors throughout the studied period (cf., Europia, 2011; European Commission, 2011; IEA, 2013a). The most complex refineries, currently found in Finland and Sweden, are assumed to endure the longest (see also section 2.4.1).
[b] Between 5% and 10% of total cement production is currently white cement (the rest is grey cement), and this share is applied throughout the studied time period of 2010–2050. From the Year 2020 all Nordic cement plants are assumed to operate at close to full capacity (which was not the case in 2010). The total production capacity in each country is assumed to remain largely unchanged throughout the studied period.

The emissions trajectories that define the indicative caps for the period 2010–2050 corresponds to the total amount of emissions allowances distributed to the industries included in this study under the EU ETS for the period 2010–2020 and the proposed reduction targets for 2030 and 2050, for the period beyond 2020 (as outlined in the European Commission's

"Low-carbon economy roadmap" and "Policy framework for climate and energy in the period from 2020 to 2030"; European Commission, 2011; European Commission, 2014).

2.3.2 CO_2 capture options

In principle, both post-combustion capture (PC) and oxyfuel combustion (OF) can be applied in the industrial processes assessed herein (see Rootzén and Johnsson, 2013b and references therein for a more thorough discussion). However, in comparison to application of CO_2 capture in the power sector, there is more to gain by carefully adapting the capture process of choice to the respective production process (see e.g., Johansson et al., 2012; ULCOS, 2012; ECRA, 2012; IEAGHG, 2013). The key characteristics of the CO_2 capture options considered for each of the three industrial sectors investigated in the present work are further described in Section 2.4.

In the three industries analysed in the present work, CO_2 capture is assumed to be available on a commercial scale from Year 2030. While earlier introduction of CCS appears to be less probable given the current rate of development, further delay would limit the prospects for CCS to contribute to reducing substantially CO_2 emissions up to Year 2050 (cf. Rootzén and Johnsson, 2013b).

Where CO_2 capture is assumed to be applied, the aggregated annual CO_2 emissions (e_{itj}) from industry plant j in industry sector i in year t are calculated as:

$$e_{itj} = A_{it} \times a_{itj}\left(s_{itj}\sum_{k=1}^{n}(f_{itk}\theta_k) + (\varepsilon_{it}p_{itj})\right)(1-\eta) \qquad (4)$$

where A_{it} denotes the total activity level in industrial sector i in year t (cf., Eq. 1), a_{itj} is the market share of industrial plant j in industry sector i in year t, s_{itj} is the thermal energy use per tonne of product at industrial plant j in industry sector i in year t, f_{itk} is the share of fuel k in the total fuel energy mix in industry sector i in year t, θ_k is the CO_2 emission factor for fuel k, n is the total number of fuels used in the fuel mix in industry sector i in year t (cf., Eq. 2), ε_{it} denotes the emissions per unit of output from process p, and p_{itj} is the output from process p relative to the total output from industrial plant j in industry sector i in year t (cf., Eq. 3). The average CO_2 avoidance rate η yields the emission reductions achieved relative to a reference plant without CO_2 capture, and can vary from 0 to 1. The CO_2 avoidance rate that can be achieved, both economically and technically, will ultimately depend on the preconditions set at each individual facility, e.g., the number of emission sources at each site, the flue gas flows and composition of the flue gases at each emission source. This has been taken into account in our estimates of the possible avoidance rates in each industry.

2.4 Sector-specific assumptions

While the general approach taken is the same for the three industrial sectors, to represent accurately the heterogeneity within and between the studied sectors, the specific scenario set-up is different. Figure 1 outlines the basic scenarios (and scenario assumptions) and cases explored for each of the three industrial sectors.

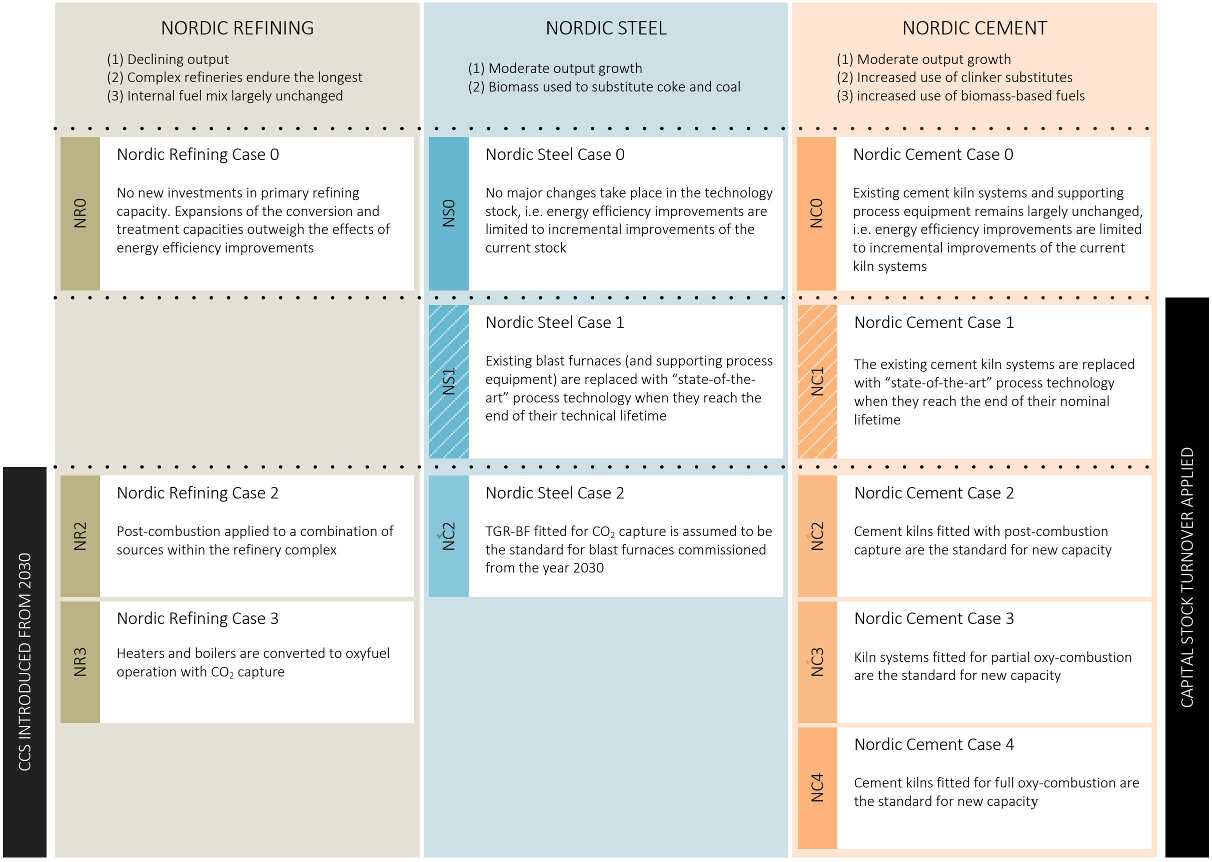

Figure 1. Overview of the relationships between the scenarios (basic assumptions numbered 1–3) and cases investigated for each of the three industrial sectors.

2.4.1 *Petroleum refineries*

Three cases that describe different future trajectories of technological developments in the Nordic petroleum refining industry are explored, referred to here as Nordic Refining Cases 0, 2 and 3 (NR0, NR2–NR3). Table 4 summarises the assumptions and input data used in each of the cases. The following underlying scenario applies to all cases: (1) a steady decline in output from the Nordic refinery industry; (2) the most complex refineries, which are more capable of adapting to changing markets, endure the longest; and (3) the internal fuel mix remains largely unchanged throughout the studied period (cf., Figure 1).

As less complex refineries are assumed to be gradually phased out over the period studied, CCS deployment in the Nordic refinery industry is assumed be limited to more complex refineries and to consist entirely of retrofits. The two following cases for the deployment of CO_2 capture in the petroleum refining industry are analysed:

- NR2: PC applied to a combination of sources within the refinery (together representing approximately 60% of the total CO_2 emissions from the refining process), e.g., applying capture to the combined stack (collecting flue gases from several furnaces, boilers, and/or CHP plant), catalytic cracker and/or hydrogen plant.
- NR3: CHP plant and/or furnaces and boilers are modified for OF operation with CO_2 capture.

To differentiate the effects of the respective CO_2 capture option, the set-up is assumed to be similar across all the Nordic refineries that are remaining in 2030–2050, and in each of the two cases, the dominant capture technology (post-combustion capture in NR2 and oxyfuel combustion in NR3) is assumed to cover the entire market.

Table 4. Nordic petroleum refining – scenario summary.

	2010	2030	2050	
Structure of production (NR0, NR2–NR3)				
Share of production (%)				
- Configurations 1 and 2	45	13	0	
- Configurations 3 and 4	55	87	100	
Specific thermal energy use (NR0) (GJ/t throughput)				
- Configurations 1 and 2	1.1–2.5	1.9		
- Configurations 3 and 4	2.2–3.0	2.2–3.0	2.2–3.0	
Hydrogen production[a] (NR0, NR2–NR3)				
- Steam reforming ($\times10^6$ Nm^3 H_2/year)	2110	2330	2330	
				Fuel emission factors[b] (tCO_2/GJ)
Fuel mix (NR0, NR2–NR3) (energy-based %)				
- Refinery gas	71	71	71	0.058
- Residual fuel oil	4	4	4	0.077
- Other petroleum products	13	13	13	0.097
- Natural gas	11	11	11	0.056
- Biomass[c]	0	0	0	0
	Targeted emission source	CO_2 emissions avoided (%)	Thermal energy (GJ/t throughput)	Electricity (kWh/t throughput)
Capture options[d]				
NR2: Post-combustion (PC)	Combined stack + FCC/Hydrogen plant	70	5.2 – 6.0	50 – 110
NR3: Oxyfuel combustion (OF**)**	Furnaces and boilers	70	2.2 – 3.0	440 – 550

[a] Does not include hydrogen produced as a by-product of catalytic reforming. The specific CO_2 emissions per normal cubic meter hydrogen produced was set to 473.6 $tCO_2/10^6$ Nm^3 H_2 (API, 2009).
[b] Estimated based on previous report (European Commission, 2012b).
[c] The use of biomass as an internal fuel in the refining process has not been considered in any of the cases of NR0 and NR2–NR3. However, the effects of an increased share of biomass on the internal fuel mix are explored in the sensitivity analysis (see Section 4.1.1).
[d] The authors' own estimations based on previous reports (van Straelen et al., 2010; Allam et al., 2005; Kuramochi et al., 2012). The category 'CO_2 emissions avoided' reflects the emission reductions achieved relative to a plant without CCS. 'Thermal energy' is the specific thermal energy use, including the energy penalty related to CO_2 capture, per tonne of output. 'Electricity' denotes the specific electricity usage, including the additional electricity usage associated with CO_2 capture, per tonne of output.

2.4.2 Integrated iron and steel manufacturing

Three cases that describe different future trajectories of technological developments in the Nordic primary steel industry are explored, referred to as Nordic Steel Cases 0–2 (NS0–NS2). Table 5 summarises the assumptions and input data used in each of the cases. The same basic scenario is applied to all cases (cf., Figure 1): (1) integrated iron and steel production in the remaining Nordic steel plants return to the levels that existed prior to the financial and economic crisis of 2008–2009 and remain constant thereafter; and (2) biomass is reintroduced as a source of renewable carbon, partly substituting for coke and coal as the reducing agent and fuel.

Here, the top gas recycling blast furnace (TGR-BF) is assumed to hold the greatest promise for applying CO_2 capture without disrupting the core production processes (IEAGHG, 2013). Thus, in the third case:

- NS2: A TGR-BF adapted for CO_2 capture is the standard for blast furnaces commissioned from Year 2030 (cf. Rootzén and Johnsson, 2013b). As in NS1, the age of the existing blast furnaces determines the rate at which the current technology stock can be replaced. In this case, however, the replacement of existing blast furnaces is assumed to be somewhat delayed in anticipation of further development of the TGR-BF process.

Table 5. The Nordic integrated iron and steel industry – scenario summary.

	2010	2030	2050	
Structure of production (NS1–NS2)				
NS1: Share of production (%) for				
- Existing capacity	100	10	0	
- New capacity (no CCS)	0	90	100	
NS2: Share of production (%) for				
- Existing capacity	100	100	0	
- New capacity (TGR-BF + CCS)	0	0	100	
Specific thermal energy use (NS0-NS1) (GJ/t crude steel) for				
- Existing capacity	17.2 – 19.1	16.7 – 18.7	16.5 – 18.4	
- New capacity[a]	16.5	16.3	16.0	
				Fuel emission factors[b] (tCO_2/GJ)
Reducing agent/fuel mix (NS0-NS2) (energy-based %)				
- Coal	85	80	65	0.095
- Coke (imported)	3	3	3	0.107
- Fuel oil	11	11	11	0.077
- LPG	1	1	1	0.063
- Biomass[c]	0	5	20	0
	Targeted emission source	CO_2 emissions avoided (%)	Thermal energy (GJ/t throughput)	Electricity (kWh/t throughput)
Capture options[d]				
NS2: Top Gas Recycling Blast Furnaces (TGR-BF + CCS).	Blast furnace	60	16.5	333

[a] Energy intensity values for "state-of-the-art" process technologies estimated based on previous studies (Fruehan et al., 2000 and Worrell et al., 2008).
[b] Estimated based on a previous report (European Commission, 2012b).
[c] The potential share of biomass estimated based on previous studies (Norgate et al., 2012; Suopajärvi et al., 2013).
[d] The authors' own estimations based on previous studies (Birat J-P et al., 2008; UNIDO, 2010b; Kuramochi, 2012; ULCOS, 2012; Eurofer, 2013; IEAGHG, 2013). The category 'CO_2 emissions avoided' reflects the emission reductions achieved relative to a plant without CCS.

2.4.3 Cement industry

In the basic scenario, which forms the basis for all cases for the Nordic cement industry, we assume that: (1) all Nordic cement plants return to almost full capacity utilisation by Year 2020 and that overall cement production remains constant thereafter; (2) the share of alternative raw materials in the finished cement continues to increase; and (3) the share of biomass-based fuels in the fuel mix increases. Five cases that describe different future trajectories of technological developments in the Nordic cement industry are explored, referred to herein as Nordic Cement Cases 0–4 (NC0–NC4). Table 6 summarises the assumptions and input data used in each of the cases. Three cases for the introduction of CO_2 capture to the Nordic cement industry are analysed (cf. Rootzén and Johnsson, 2013b):

- NC2: Cement kilns with post-combustion capture are the standard for new capacity.
- NC3: Cement kilns with partial oxy-combustion (targeting the precalciner alone) are the standard for new capacity.
- NC4: Cement kilns adapted for full oxy-combustion (CO_2 capture applied to both the precalciner and the cement kiln) are the standard for new capacity.

CCS retrofit is not included as an option in any of the cases (NC2–NC4). Thus, as in NC1, the rate of CCS deployment will depend on the rate of turnover of existing kiln systems. However, in these cases, the process of replacing existing kiln systems is assumed to be slightly delayed pending the commercial deployment of the CO_2 capture technologies. Cement kiln systems that are dedicated to the production of white cement are assumed not to apply CCS in any of the cases.

Table 6. The Nordic cement industry – scenario summary.

	2010	2030	2050	
Structure of production (NC1–NC4)				
NC1: Share of production (%) for				
- Existing capacity	100	71	20	
- New capacity (no CCS)	0	29	80	
NC2-4: Share of production (%) for				
- Existing capacity	100	96	6	
- New capacity (TGR-BF + CCS)	0	4	94	
Specific thermal energy use[a] (NC0–NC1) (GJ/t cement clinker) for				
- Existing capacity	3.6 – 4.6 (7.0)	3.3 – 4.4 (6.6)	3.2 – 4.1 (6.2)	
- New capacity[b]	3.1 (5.5)	3.1 (5.4)	3.0 (5.2)	
Clinker to cement ratio[c] (NC0–NC4) (%)	80 – 90	70 – 80	60 – 70	
Reducing agent/fuel mix[e] (NC0–NC4) (energy-based %) for				Fuel emission factors[d] (tCO_2/GJ)
- Coal	50	30	25	0.098
- Pet-coke	22	0	0	0.098
- Fuel oil	1	0	0	0.077
- Alternative fuel	15	30	25	0.100
- Biomass	11	40	50	0
Capture options[f]	Targeted emission source	CO_2 emissions avoided (%)	Thermal energy (GJ/t throughput)	Electricity (kWh/t throughput)
NC2: Post combustion (PC)	Kiln + Precalciner	90	6.1	180
NC3: Partial oxy-combustion (POC)	Precalciner	65	3.5	200
NC4: Full oxy-combustion (FOC)	Kiln + Precalciner	90	3.2	220

[a] Numbers in parentheses refer to the estimated specific thermal energy usage for white cement production. BAT values estimated based on previous reports (WBCSD, 2011; European Commission, 2013).
[b] Energy intensity values for "state-of-the-art" cement kiln systems, estimated based on a previous report (European Commission, 2013).
[c] The specific CO_2 emissions per tonne of clinker produced, arising from the calcination of limestone, was set to 0.51 tCO_2/t clinker. The default cement clinker is assumed to have a 65% CaO fraction (IPCC, 2006).
[d] Estimated based on a previous report (European Commission, 2012b).
[e] The shares of alternative and biomass fuels, estimated based on previous reports (ECRA, 2009; Aranda Usón et al., 2013).
[f] The authors' own estimations based on previous studies (IEAGHG, 2008; ECRA, 2009; ECRA, 2012; Kuramochi, 2012). The category 'CO_2 emissions avoided' denotes the emission reductions achieved relative to a plant without CCS; 'Thermal energy' reflects the specific thermal energy usage, including the energy penalty related to CO_2 capture, per tonne of output. The category of 'Electricity' represents the specific electricity use, including the additional electricity usage associated with CO_2 capture, per tonne of output.

3. Results

3.1 Petroleum refining

Figure 2 shows the estimated annual CO_2 emissions and total thermal and electrical energy usage levels for Nordic refineries in the period 2010–2050, for the cases without (NR0) and with (NR2 and NR3) introduction of CCS. In the base case (NR0) reductions in the levels of

CO_2 emissions and energy usage are primarily a result of the assumed reduction in total output from the Nordic refineries, from 56.4 Mt/year in Year 2010 to 20.6 Mt/year in Year 2050. In NR2 and NR3, in which CO_2 capture is introduced from Year 2030, CO_2 emissions are reduced to target levels by the Year 2050. However, this additional CO_2 abatement comes at the cost of increased energy usage. In case NR2, where post-combustion capture is assumed to be the preferred capture technology, total annual thermal energy use in Year 2050 is just 10% below the level in Year 2010, despite a 65% reduction in refinery throughputs. In NR3, where oxyfuel combustion is assumed to be applied, total electric energy usage in Year 2050, is more than double that in Year 2010. Again, this occurs despite the assumed decline in total output of petroleum products from Nordic refineries during the same period.

The assumptions that the Nordic refineries with the least flexibility will be phased out and that increased processing intensity will offset the effects from energy conservation measures result in an increase in specific energy usage (GJ/t throughput) in all cases (NR0–NR3). In NR0, the average specific thermal energy usage increases from 2.2 GJ/t throughput in Year 2010 to 2.6 GJ/t throughput in Year 2050. In NR2 (post-combustion capture) energy penalties, which are primarily associated with capture solvent regeneration, result in an increase in specific thermal energy usage from 2.2 GJ/t throughput in Year 2010 to 5.6 GJ/t throughput in Year 2050. Similarly, in case NR3, specific electricity usage increases from 73 kWh/t throughput in Year 2010 to 470 kWh/t throughput in Year 2050 as additional energy is required for air separation.

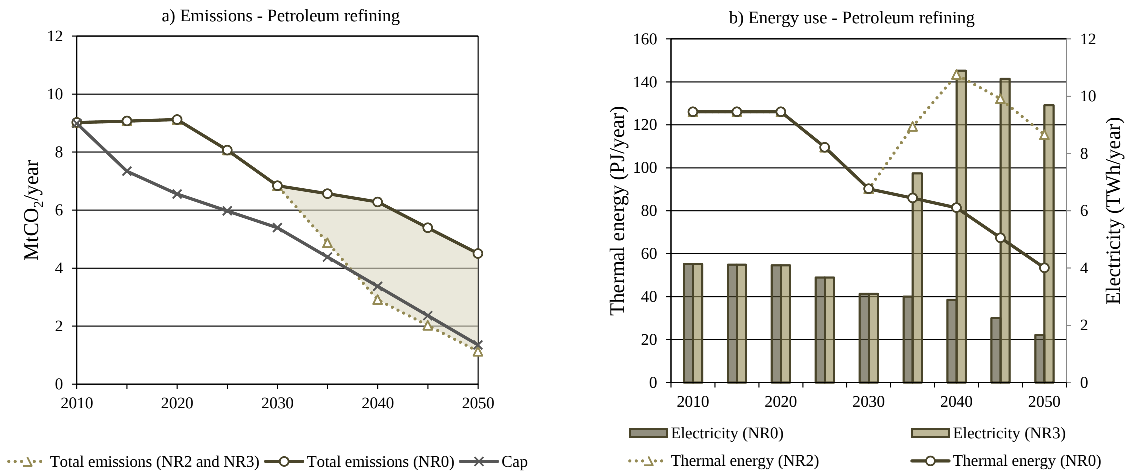

Figure 2. Estimated levels of CO_2 emissions and energy usage from the Nordic petroleum refining industry in the period 2010–2050, as obtained in the present work. The base case (NR0) assumes a steady decline in output from the Nordic refinery industry without any deployment of CCS. Cases NR2 (post-combustion) and NR3 (oxyfuel combustion), in addition to the abatement measures in the base case, assume the deployment of CO_2 capture from Year 2030. (a) Estimated CO_2 emissions from Nordic refineries in the period 2010–2050, with (dashed line) or without (solid line) the introduction of CCS. The emission cap for the period 2010–2050 (crosses) corresponds to the total number of emission allowances allocated to Nordic refineries for the period 2010–2020 and the proposed reduction targets for Year 2030 and Year 2050. (b) Estimated development of thermal (solid/dashed lines) and electrical (bars) energy usage with (light brown) or without (brown) the introduction of CCS. The chart only display the cases with the lowest and highest thermal (NR0 and NR2) and electrical (NR0 and NR3) energy use.

3.1.1 Sensitivity analysis

Table 7 displays a summary of the selected parameters and the lower and upper bounds employed in the sensitivity analysis for the refinery industry (cf., Eq. 1–5, and see Table 2 for references).

Table 7. Parameters used in the sensitivity analysis of Nordic Refining Cases 0, 2 and 3 (NR0, NR2–NR3).

	Notation	Lower value	Base value	Upper value
Nordic Refining Case 0 (NR0)				
Activity level (Mt throughput/year) [a]	*A*	10.0	20.6	56.4
Average thermal energy use (GJ/t throughput)[b]	*H*	1.7	2.6	3.7
Hydrogen production ($\times 10^6$ Nm^3/year) [c]	*P*	1165	2330	4660
Biomass share of refinery fuel (% energy-based)	*f*	0	0	15

Nordic Refining Case 2 (NR2)				
Activity level (Mt throughput/year) [a]	A	10.0	20.6	56.4
Average thermal energy use (GJ/t throughput)	H	4.6	5.6	6.6
CO_2 avoidance rate (%) [d]	η	60	70	80
Nordic Refining Case 3 (NR3)				
Activity level (Mt throughput/year) [a]	A	10.0	20.6	56.4
Average thermal energy use (GJ/t throughput)	H	2.2	2.6	4.6
CO_2 avoidance rate (%) [d]	η	60	70	80

[a] The lower value for the activity levels in corresponds to an 80% reduction in activity levels by Year 2050 relative to Year 2010 (cf., IEA, 2013a). The higher value implies that the activity levels are the same in Year 2050 as in Year 2010.
[b] For the average thermal energy usage of the plant stock the lower and higher boundary correspond to the range of specific energy usage of European refineries (European Commission, 2012a).
[c] The lower value corresponds to, approximately, a halving of the current capacity utilisation, while the upper boundary implies maximal utilisation of the existing hydrogen production units.
[d] The CO_2 avoidance rate that can be achieved, both economically and technically, will ultimately depend on the preconditions set at the individual refineries (Johansson et al., 2012).

Figure 3 shows the results of the sensitivity analysis, whereby the horizontal bars represent the output ranges of the respective scenario parameters. As discussed more thoroughly below, the development of refinery throughput and associated emissions from the Nordic refining industry ultimately depend on how demand develops in the transport sector. The use of biomass as internal fuel in the refining process has not been considered in any of the above cases, NR0–NR3. However, there are indications of increasing interest in the use of biomass, both as feedstock and fuel in the Nordic refinery industry. Neste Oil in Finland and Preem AB in Sweden have already invested in the production of renewable diesel. Overall, the outcome of this part of the analysis suggests that, even in a development where a majority of the Nordic refineries are closed, introduction of CO_2 capture at the remaining refineries may be required to meet stringent CO_2 reduction targets in the long term.

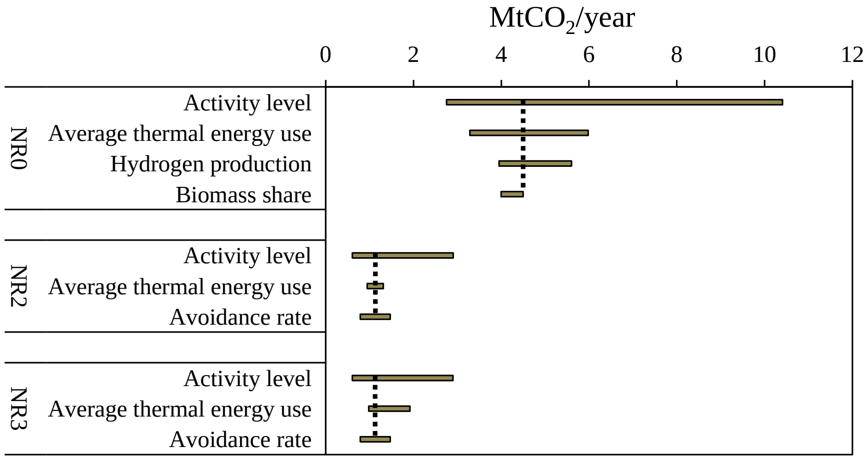

Figure 3. Tornado diagram showing the sensitivity of the CO_2 emissions estimates to changes in key scenario inputs. The horizontal bars indicate the ranges of the emissions estimates in Year 2050 for high and low values of each of the selected scenario inputs. The black vertical lines indicate the base values of the estimated CO_2 emissions, in the same year, for cases NR0, NR2, and NR3.

3.2 Integrated iron and steel production

Figure 4 presents the projected CO_2 emissions trajectories, together with the aggregated level of thermal and electrical energy usage for the Nordic steel industry over the studied period for the two cases in which CCS is excluded as an option (NS0 and NS1) and for the scenario case with deployment of CCS (NS2). In NS0 and NS1, the emission reductions achieved in Year 2050 remain limited. Replacing existing process equipment with BAT (NS1) has limited effect, since Nordic blast furnaces already operate at close to BAT levels. Thus, in both NS0 and NS1, reintroduction of biomass as a source of renewable carbon is the main driver of reductions in emissions.

In NS2, where existing blast furnaces are gradually replaced with TGR-BFs with CO_2 capture from Year 2030, CO_2 emissions are reduced approximately in line with the target levels. TGR-BF consumes less coke than existing conventional blast furnace, thus the introduction of CO_2 capture in NS2 has limited effect on overall thermal energy usage when comparing to present energy use. However, electrical energy use in NS2 (2.2 TWh/year in Year 2050) is significantly higher than in NS1 (1.1 TWh/year in Year 2050). This is due to the loss of blast furnace gas and investments in air separation, CO_2 separation and compression. In NS1 where the existing technology stock is replaced with state-of-the-art process equipment, specific electricity usage is gradually reduced, from an average level of 313 kWh/t steel in Year 2010 to 161 kWh/t steel in Year 2050. In case NS2, specific electricity usage in Year 2050, approximately 330 kWh/t steel, is above present (Year 2010) levels.

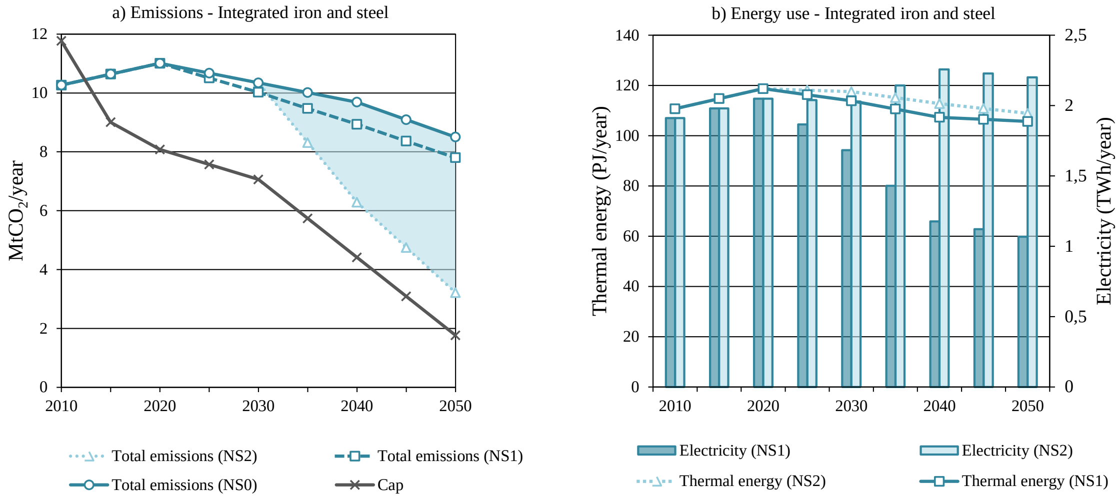

Figure 4. Evolution of CO_2 emissions and energy usage in the Nordic primary steel industry for the period 2010–2050, as obtained from the present work. (a) Estimated cumulative CO_2 emissions from Nordic primary steel production with (blue triangles, NS2) or without deployment of CCS (blue circles, NS0; and blue squares, NS1). The emissions trajectory that define the emission cap for the period 2010–2050 (crosses) are derived from the emission cap for the EU ETS for the period 2010–2020 and the proposed reduction targets for Year 2030 and Year 2050, for the period beyond Year 2020. (b) Estimated development of thermal (solid/dashed lines) and electrical (bars) energy usage with (light blue, NS2) or without (blue, NS1) the introduction of CCS. The chart only display the cases with the lowest and highest thermal (NS1 and NS2) and electrical (NS1 and NS2) energy use.

3.2.1 Sensitivity analysis

Table 8 lists the parameters used and the range of values employed in the sensitivity analysis of the Nordic steel industry (cf., Eq. 1–5 and Table 2).

Table 8. Parameters subjected to the sensitivity analysis of Nordic Steel Cases 0–2 (NS0–NS2).

Scenario case	Notation	Lower value	Base value	Upper value
Nordic Steel Case 0 (NS0)				
Activity level (Mt crude steel/year) [a]	*A*	4.0	6.6	8.0
Biomass share of fuel/reducing agent (% energy-based) [b]	*f*	0	20	40
Average thermal energy use (GJ/t crude steel) [c]	*H*	15.0	17.5	18.2
Nordic Steel Case 1 (NS1)				
Activity level (Mt crude steel/year) [a]	*A*	4.0	6.6	8.0
Biomass share of fuel/reducing agent (% energy-based) [b]	*f*	0	20	40
Average thermal energy use (GJ/t crude steel) [c]	*H*	15.0	16.0	17.5
Nordic Steel Case 2 (NS2)				

Activity level (Mt crude steel/year) [a]	*A*	4.0	6.6	8.0
Biomass share of fuel/reducing agent (% energy-based) [b]	*f*	0	20	40
Average thermal energy use (GJ/t crude steel)	*H*	15.0	16.5	17.5
CO_2 avoidance rate (%) [d]	η	50	60	70

[a] The lower boundary for the activity level corresponds to a 35% reduction relative to the production level in Year 2010. The higher value would entail full capacity utilisation at all existing Nordic integrated steel plants.
[b] Biomass could be used to replace coal and coke in different stages of the integrated route (Norgate et al., 2012). As lower and upper boundaries for the use of biomass as a substitute for coke and coal, both as reducing agent and fuel, f, we used 0% and 40%, respectively.
[c] The lower value for the specific thermal energy usage in Year 2050 is based on estimates of the minimum specific energy usage in the integrated steelmaking route (Fruehan et al., 2000). The higher value corresponds to the average specific thermal energy usage in the Nordic primary steel industry in Year 2010.
[d] The specific application of CO_2 capture will be site-specific. Thus, the CO_2 avoidance rates that can be achieved practically will vary significantly (Ho et al., 2013; IEAGHG, 2013).

Figure 5 shows the lower and upper estimates of the CO_2 emission levels in Year 2050 obtained from the variation of each parameter for all the cases, NS0–NS2. As could be expected the sensitivity analysis confirm that the level of production in the Nordic iron ore based steel industry will be decisive for the future levels of CO_2 emissions. The sensitivity analysis also highlights the potential importance of encouraging the use of biomass as a substitute for coke and coal. Finally, it is clear from the results that among the measures included in this study, apart from considerably reducing the production of iron ore based steel, there is no real alternative to CCS if the goal is to radically reduce CO_2 emissions from the Nordic steel industry up to Year 2050.

Taken together the results reaffirm that out of the options assessed in the present study, unless production levels are significantly reduced, only CCS can deliver the emission reductions required to reach long term targets.

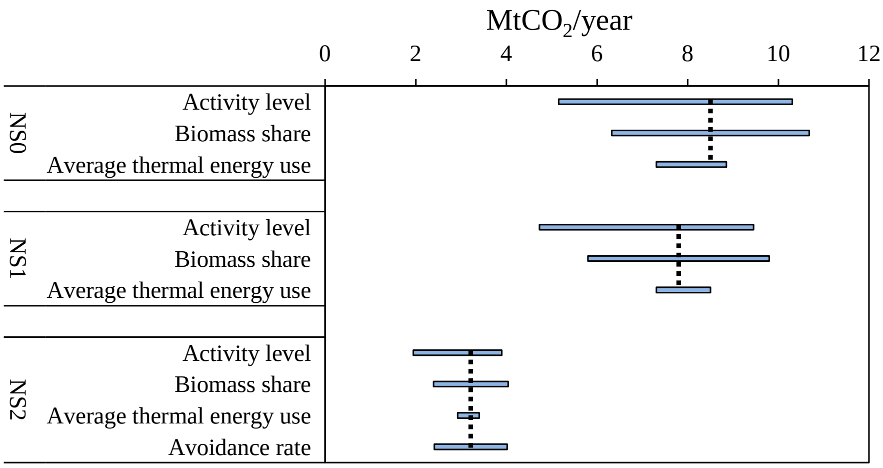

Figure 5. Tornado graph showing the sensitivity of the CO_2 emissions estimates to changes in key scenario inputs. The blue horizontal bars indicate the ranges of emissions estimates in the end year for the high and low values of each of the selected scenario inputs. The black vertical lines indicate the base values of the estimated CO_2 emissions in Year 2050 for cases NS0, NS1 and NS2.

3.3 Cement production

Figure 6 presents the estimated CO_2 emissions trajectories, together with the aggregated values for thermal and electrical energy usage in Nordic cement plants in the period 2010–2050 for the cases without introduction of CCS (NC0 and NC1) and for the cases that assume deployment of CCS (NC2–NC4).

Despite a somewhat higher cement output, enhanced thermal efficiency, increased clinker substitution and the shift away from coal and pet-coke, result in a reduction in total annual emissions from Nordic cement plants in both NC0 and NC1. Whereas the average thermal energy use in Year 2050 is significantly lower in NC1 (3.2 GJ/t) than in NC0 (3.7 GJ/t), this has little impact on the overall level of emissions. In NC1, gradual improvements and replacements of e.g., grinders and fans, lead to a decrease in specific electricity usage, from an average level of 131 kWh/t cement in Year 2010 to 102 kWh/t cement in Year 2050.

In NC2 (post-combustion) and NC4 (full oxy-combustion), assuming an average CO_2 avoidance rate of 90% in both cases, the levels of CO_2 emissions are reduced in line with the targeted levels. Introduction of CO_2 capture would in both cases significantly influence energy usage. In NC2, increases in specific thermal energy usage, due to energy penalties associated primarily with capture solvent regeneration, results in a 35% higher thermal energy use in Year 2050 than in the starting year. Correspondingly, in NC4, energy used for air separation is the main driver behind the increase in electricity use. In Year 2050, specific thermal energy usage in NC2 amounts to 5.8 GJ/t clinker and electricity usage in NC4 is 206 kWh/t cement.

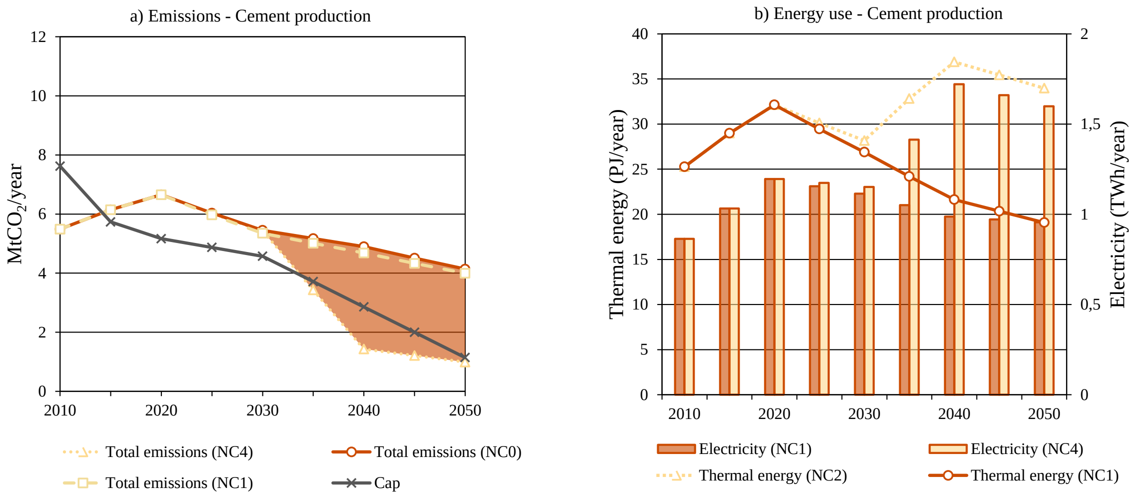

Figure 6. Estimated levels of CO_2 emissions and energy usage in the Nordic cement industry for the period 2010–2050, as obtained from the present work. (a) Estimated annual CO_2 emissions from Nordic cement manufacturing for the period 2010 – 2050, with (triangles, NC4) or without (circles, NC1; and squares, NC1) the introduction of CCS. In all cases, total emissions include both fuel-related and process-related emissions. The emissions trajectory that defines the emission cap for the period 2010–2050 (crosses) corresponds to the total number of emission allowances allocated to Nordic cement plants for the period 2010–2020 and the proposed reduction targets for Year 2030 and Year 2050. (b) Estimated development of thermal (solid/dashed lines) and electrical (bars) energy usage with (light orange) or without (orange) the introduction of CCS. The chart only display the cases with the lowest and highest thermal (NC1 and NC2) and electrical (NC1 and NC4) energy use.

3.3.1 Sensitivity analysis

Table 9 presents the parameters used and the range of values employed in the sensitivity analysis of the Nordic cement industry (cf., Eq. 1–5 and Table 2).

Table 9. Parameters subjected to the sensitivity analysis of Nordic Cement Cases 0–4 (NC0–NC4).

Scenario case	Notation	Lower value	Base value	Upper value
Nordic Cement Case 0 (NC0)				
Activity level (Mt cement/year) [a]	*A*	5.0	9.4	12.0
Clinker to cement ratio (%) [b]	*P*	50	60	75
Biomass share of fuel (% energy-based) [c]	*f*	37.5	50	62.5
Average thermal energy use (GJ/t clinker)	*H*	3.0	3.7	4.0
Nordic Cement Case 1 (NC1)				
Activity level (Mt cement/year) [a]	*A*	5.0	9.4	12.0
Clinker to cement ratio (%) [b]	*P*	50	60	75
Biomass share of fuel (% energy-based) [c]	*f*	37.5	50	62.5
Average thermal energy use (GJ/t clinker)	*H*	3.0	3.2	3.7
Nordic Cement Case 2 (NC2)				
Activity level (Mt cement/year) [a]	*A*	5.0	9.4	12.0
Clinker to cement ratio (%) [b]	*P*	50	60	75
Biomass share of fuel (% energy-based) [c]	*f*	37.5	50	62.5
CO_2 avoidance rate (%) [d]	η	70	90	95
Nordic Cement Case 3 (NC3)				
Activity level (Mt cement/year) [a]	*A*	5.0	9.4	12.0
Clinker to cement ratio (%) [b]	*P*	50	60	75
Biomass share of fuel (% energy-based) [c]	*f*	37.5	50	62.5
CO_2 avoidance rate (%) [d]	η	55	65	75
Nordic Cement Case 4 (NC4)				
Activity level (Mt cement/year) [a]	*A*	5.0	9.4	12.0
Clinker to cement ratio (%) [b]	*P*	50	60	75
Biomass share of fuel (% energy-based) [c]	*f*	37.5	50	62.5
CO_2 avoidance rate (%) [d]	η	70	90	95

[a] The lower value corresponds to a 25% reduction in activity levels by Year 2050 relative to Year 2010 (i.e., a lower output than in any of the years in the period 1990–2010; UNFCCC, 2014). The higher value corresponds approximately to the maximum capacity of existing Nordic cement plants.

[b] The extent to which clinker substitutes can be used is ultimately limited by for example the availability of alternative materials, material characteristics, price, intended use of the finished cement, national standards, and market acceptance (ECRA, 2009; Cembureau, 2012).

[c] The relative cost of biomass-based fuels, low calorific value of most organic materials and the occurrence of trace elements may restrict the use of biomass in a conventional cement kiln (ECRA, 2009; Aranda Usón et al., 2013).

[d] The CO_2 avoidance rates that can be achieved, practically, at each individual cement plant will be site-specific (ECRA, 2009; ECRA, 2012).

Figure 7 shows the lower and upper estimates of the CO_2 emissions in Year 2050 obtained from the variation of each parameter for all cases, NC0–NC4. The outcome confirms the strong connection between future production levels and the development of CO_2 emissions. The analysis also demonstrates the importance of increasing the market share of blended cements and of encouraging increased use of biomass based fuels in the cement industry. Taken together the results reaffirm that of the options assessed in the present study, unless production levels are significantly reduced, only CCS can deliver the emission reductions required to reach long term targets.

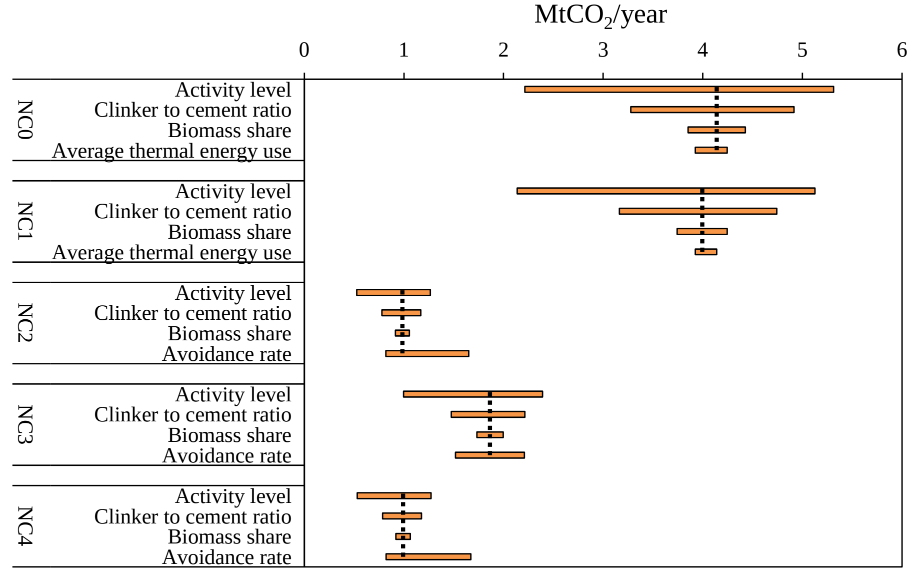

Figure 7. Tornado graph showing the sensitivity of the estimated levels of CO_2 emissions in the end year (2050) to changes in key scenario inputs. The orange horizontal bars give the ranges of the emissions estimates in Year 2050 for the high and low values of each of the selected scenario inputs. The black vertical lines give the base values of the estimated CO_2 emissions in Year 2050 for Nordic Cement Cases 0–4 (NC0–NC4).

3.4 Overall emissions reduction potentials and systems effects

Figure 8 shows the overall potentials for, and implications of, measures to reduce CO_2 emissions from the Nordic carbon-intensive industries. To separate and quantify the effects of the respective mitigation measure, we re-calculated the emissions trajectories for each of the industrial sectors. By holding constant at Year 2010 levels the variables in Eqs 1–5 relevant to each mitigation measure, we estimate their respective contributions to the overall reductions in emissions. To assess their contribution over time, we compared annual emissions for the re-calculated emissions trajectories, one for each of the studied measures, with an emissions baseline. For the baseline, the fuel mix is assumed to remain unchanged in all the sectors over the period studied, and only limited improvements in energy efficiency are assumed to occur, resulting in CO_2 emission intensities that are only slightly lower in Year 2050 than in Year 2010. To capture the effects of the assumed decline in refinery throughputs, in the baseline, the activity levels in the petroleum refining industry are assumed to remain constant at the Year 2010 level throughout the studied period. In the integrated iron and steel and cement industries, activity levels develop in accordance with the basic assumptions, as described in Table 3 above.

Figure 8a reveals the development of emissions over time, relative baseline emissions, given: 1) the assumed decline in refinery throughputs (Activity change); 2) the shift towards increased use of biomass-based fuels in the iron and steel and cement industries (Biomass); 3) the increased clinker substitution (c/c ratio); 4) deployment of proven best-available technology (BAT), in the iron and steel and cement industries; and 5) the large-scale introduction of CO_2 capture (CCS). The cap corresponds to an emissions trajectory for the period 2010–2050 where total direct CO_2 emissions from the industrial plants covered in this study are reduced by 30% by 2030, 40% by 2030 and by 85% by 2050, as compared to the 2010 levels (see Section 2.3.2). In the short term, up to Year 2030, the suggested measures would result in a 10% reduction in CO_2 emissions relative to the Year 2010 levels. In the longer term, up to Year 2050, if restricted to currently available technologies CO_2 emissions would be 35% lower than at the starting point and 40% below the baseline levels of emissions. The reductions are, primarily, a result of the decline in refinery throughputs and the increased use of biomass in the iron and steel and cement industries. An ambitious introduction of CO_2 capture has the potential to reduce significantly the levels of emissions.

Total emissions in Year 2050 in the cases in which the large-scale deployment of CO_2 capture is assumed are 80% below the Year 2010 levels. However, as illustrated in Figure 8b, the introduction of CCS may come at a high cost in terms of energy usage. The total thermal energy usage in the cases where post-combustion capture is assumed to be the dominant capture technology (NR2, NS2, and NC2) in Year 2050 is at the same level as thermal energy usage in 2010. This is the case despite the assumed decline in total output from Nordic refineries during the same period. Total thermal energy usage is considerably lower in the cases in which the current capital stocks in the iron and steel and cement industries are replaced with “state-of-the-art” process technologies (NS1 and NC1). The aggregate thermal energy usage of the industrial plants covered in this study in Year 2050 in these BAT cases is 30% below the levels in those cases where CO_2 capture is assumed to be widely deployed. Figure 8c shows how the demand for bioenergy would increase ten-fold over the studied period if the full potential of biomass-based fuels would be realised in the iron and steel and cement industries. Figure 8d presents the development patterns of total CO_2 emissions in each of the studied industrial sectors for the cases that assume large-scale introduction of CO_2 capture, as well as the amounts of CO_2 captured annually. In Year 2050, the annual flow of captured CO_2 that will have to be transported and stored amounts to approximately 17 $MtCO_2$/year.

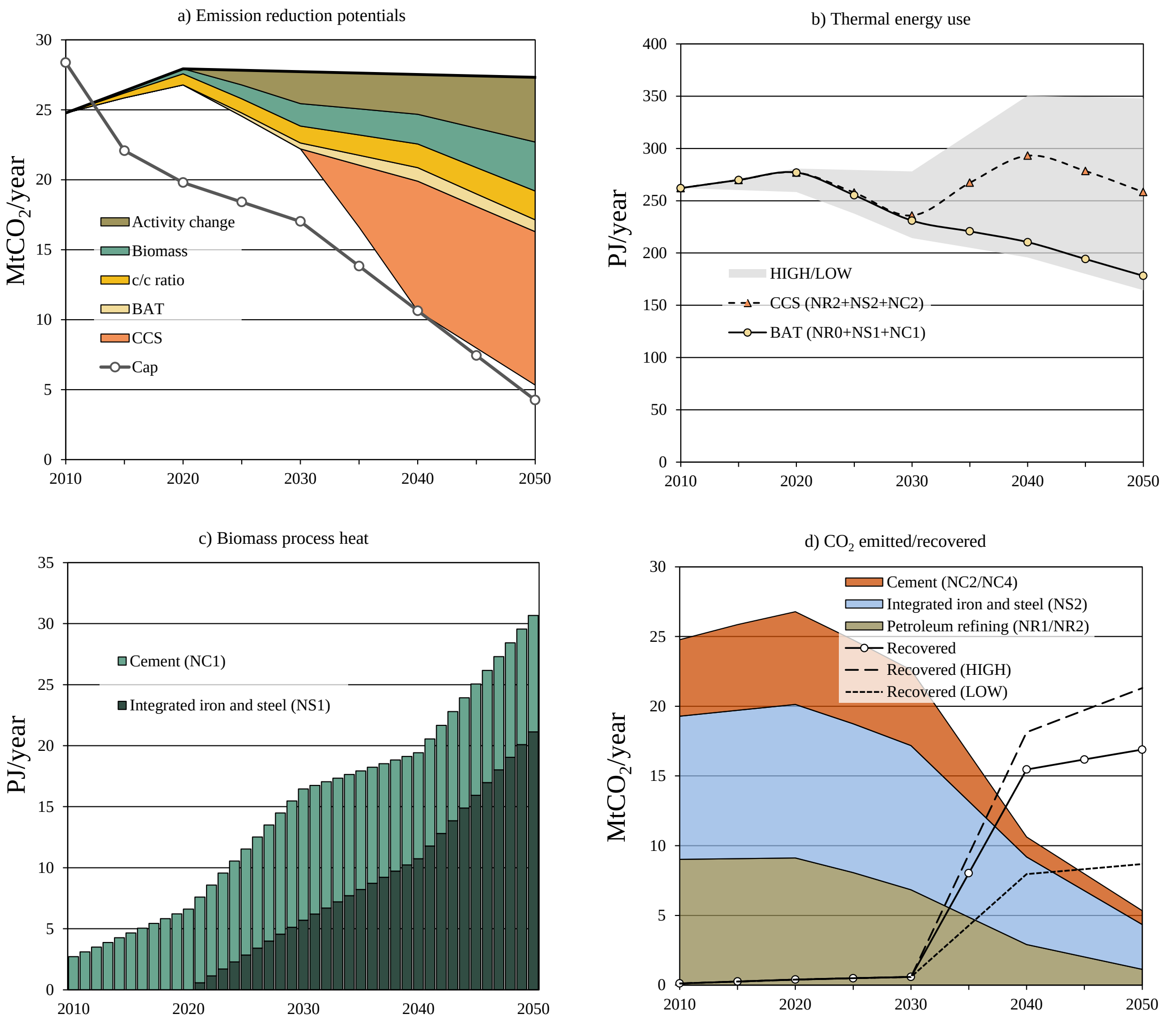

Figure 8. The overall potentials for, and implications of, measures to reduce CO_2 emissions from Nordic carbon-intensive industry. a) The wedges give the contributions of the respective mitigation measures to overall reductions in emissions relative to baseline. In the baseline, the fuel mixes and the clinker to cement ratio (c/c ratio) are frozen at Year 2010 levels and improvements in energy efficiency are limited. b) Estimated development of thermal energy usage with (triangles) or without (circles) the introduction of CCS. c) Process heat levels from biomass (i.e., final energy) in the integrated iron and steel and cement industries (cases NS1 and NC1). d) Development of CO_2 emissions from Nordic carbon-intensive industry in the cases that assume the most ambitious deployment of CO_2, together with the total amount of CO_2 captured annually.

4. Discussion

As expected, there is a strong connection between future production levels and the development of CO_2 emissions in the respective industry sectors (see Figures 3, 5 and 7). In the case of the petroleum refining industry, the fates of individual Nordic refineries are strongly linked to the development of demand on their respective home markets. While the actual policy measures are yet to emerge, Nordic governments have repeatedly proclaimed their commitment to promoting a transport sector that is independent of fossil-fuel consumption, which in the case of Sweden is planned for as early as Year 2030. Such a development would gradually make obsolete the majority of the Nordic petroleum refineries. For the Nordic refining companies, one way to counter this trend would be to use its know-how and infrastructures to engage in the development and supply of fossil-free fuels. As discussed above (see Section 3.1.1), Neste Oil in Finland and Preem AB in Sweden have already responded to this development by investing in capacity to produce biodiesel, albeit on a modest scale to date.

Cement is a heavy bulk commodity with high transportation costs relative to the production costs. Thus, trade is typically limited to national or regional markets. Considerable investment and reinvestment needs in the residential sectors and in public infrastructure throughout the region indicate that Nordic cement manufacturers are likely to profit from stable outlets for their products in the decades to come (GCR, 2013). One of the key challenges will be to increase the market share of blended cements (ECRA, 2009; Cembureau, 2012). This will require the cement manufacturers to continue their efforts to develop cements with lower clinker content than the current standard cements, while maintaining quality standards. Public institutions also have important roles to play, both in overseeing the development of new cement standards and in driving demand through investments in public infrastructure and construction.

Our results show that even with ambitious deployment of "state-of-the-art" process technologies, the contribution of improved industry energy efficiency to overall CO_2 emissions reductions is likely to be limited. Thus, if restricted to currently available technologies, the increased use of biomass in the iron and steel and cement industries would be the single most important strategy to reduce direct fossil CO_2 emissions from Nordic industry. The suggested biomass substitution rates in the iron and steel and cement industries appear to be technically achievable. While low-grade biomass can suffice as a fossil fuel substitute at low substitution rates in the cement kiln (and precalciner), higher substitution rates would likely require biomass of higher quality (ECRA, 2009; Aranda Usón et al., 2013). The same is true if biomass is to be used to replace coal and coke in blast furnaces (Norgate et al., 2012; Suopajärvi et al., 2013). The estimated demand for biomass process heat, which is approximately 30 PJ/year in Year 2050, is modest compared to current bioenergy usage in Nordic industry and in comparison to the available biomass resources (IEA, 2013a). However, competition over biomass resources is already high and is likely to increase further if polices aimed at reducing CO_2 emissions are enforced.

Large-scale deployment of CO_2 capture, as suggested in the above analysis, results in an estimated total annual CO_2 flow of approximately 17 $MtCO_2$/year. However, this aggregate estimate conceals several factors with important implications for the prospect of building up a transportation and storage infrastructure. As indicated by the range depicted in Figure 8d (HIGH/LOW), the volumes of CO_2 captured vary significantly depending on the choice of CCS technology. Moreover, the timing of the possible introduction of industrial CO_2 capture on a commercial scale (here set at Year 2030) and the pace at which CCS would subsequently be adopted (here linked to the technical life-time of key process equipment) will have impacts on the evolution of the captured CO_2 flow over time. Furthermore, the geographical spread of the industries suitable for CO_2 capture will have implications for the potential to coordinate transportation and storage. More than half (or approximately 10 $MtCO_2$/year) of the suggested CO_2 flow in our analysis would come from sources in the Finnish and Swedish parts of the Baltic Sea region, although first estimates of the prospects for geological storage of CO_2 in this region are not encouraging (Teir et al., 2010; SLR, 2014; Elforsk, 2014). Conversely, 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 favourable conditions for CO_2 storage (GeoCapacity, 2009; NPD, 2012; Elforsk, 2014). Thus, storage constraints could be overcome through regional cooperation provided that CO_2 transportation costs can be kept low.

Norway has, partly as a way of overcoming the contradiction it faces in combining the roles as major oil and gas producer and strong advocate of ambitious climate policies, made a commitment to take a leading role in the development and deployment of CCS (Tjernshaugen and Langhelle, 2009). The current aim is to realise at least one full-scale carbon capture pilot plant by Year 2020 (The Norwegian Government, 2013). 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 project in the world (StatoilHydro, 2009; DNV, 2012). However, due to cost overruns and delays, the project was officially terminated in Year 2013 (Bloomberg, 2013). Instead, in Year 2013, the Brevik cement plant was singled out as the site for the construction of a research facility for the testing of post-combustion CO_2 capture technologies (ECRA, 2012). CCS is now part if the official strategy for the Nordic subsidiaries of HeidelbergCement (Norcem (Norway) and Cementa (Sweden)), i.e. they have identified CCS as a technology required to reach long term targets on reduction in CO_2 emissions. Thus, at present different capture technologies are evaluated at the Brevik cement plant using a slip stream from the plant (GCCSI, 2014).

5. Conclusions and policy implications

The analysis presented in this paper shows that, for Nordic carbon-intensive industry, the combined effects of extensive deployment of available measures to reduce CO_2 emissions and proven best-available process technologies will not suffice to meet targeted reduction in GHG emissions in the medium- (up to Year 2030) and long-term (up to Year 2050). This is in line with previous studies assessing the potential for future CO_2 emission reductions for global industry as well as for the industrial sectors of selected regions and countries (e.g. SEPA, 2012; Rootzén and Johnsson, 2013a; IEA, 2013a; Napp et al., 2014). Our results indicate that in the absence of CCS, total annual CO_2 emissions from the Nordic carbon-intensive industries investigated in Year 2050 could amount to approximately 40% of the total Nordic GHG budget. Furthermore, we show how an ambitious deployment of CCS could result in emissions reductions that are in line with the targets for Year 2050. However, the analysis also illustrates how such a large-scale introduction could come at a high cost in terms of energy usage and how the geographical spread of industries that are subject to CO_2 capture requires careful planning of an infrastructure for the transportation and storage of CO_2.

A comparison of the relative contributions of the evaluated abatement measures highlights the importance, especially in the absence of successful deployment of CO_2 capture, of Nordic legislators encouraging the increased use of biomass as a source of renewable carbon in carbon-intensive industry and promoting the use of alternative raw materials in cement manufacturing, to complement the continuing efforts to improve energy efficiency.

Nordic climate policies that target carbon-intensive industries currently rely heavily on the price signal imposed through the EU ETS. However, as long as there is a need to balance competitiveness and environmental effectiveness, there is little chance that the trading system in its current form will deliver a CO_2 price that is sufficiently high to incentivise investments in measures to reduce CO_2 emissions on the scale assumed in our analysis (for estimates of expected abatement costs see e.g NEA, 2010; ECRA, 2012; Kuramochi, 2012; IEAGHG, 2013). Thus, enabling significant reductions in emissions from Nordic carbon-intensive industries in the long term will likely require additional policy interventions. While there is no single end-game strategy for achieving the long-term goals of CO_2 emissions reduction in the Nordic carbon-intensive industry, the discussions presented in this paper suggests several areas in which strategic decisions will need to be made by national legislators and companies.

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