Managing the costs of CO2 abatement in the cement industry

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Managing the costs of CO_2 abatement in the cement industry

Johan Rootzén* and Filip Johnsson

Department of Energy and Environment, Energy Technology,
Chalmers University of Technology, SE-412 96 Gothenburg, Sweden

Abstract

This paper investigates how costs associated with deep reductions in CO_2 emissions from the cement industry will influence the cost across the entire value chain, from cement production to eventual end-use, in this case, a residential building. The work 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 cement manufacture.

By examining how CO_2 trading and investments in low-carbon kiln systems affect costs and prices further up the supply chain of cement our analysis provides new perspectives on the costs of industry abatement of CO_2 and on the question of who could or should pay the price of such abatement.

The analysis reveals that cost impact decrease substantially at each transformation stage, from limestone to final end-uses. The increase in total production costs for the residential building used as the case study in this work is limited to 1%, even in the cases where the cement price is assumed to be almost doubled.

Keywords: Cement industry; Carbon dioxide; Emission reduction; Costs; Supply chain; Concrete; Construction

*Corresponding author. Tel.: +46 (0) 31 7725251; fax: +46 (0) 31 7723592.
E-mail address: johan.rootzen@chalmers.se (J. Rootzén).

1 Introduction

Cement production represents one of the most energy- and CO_2-intensive industrial processes among all manufacturing industries (IPCC, 2014). Production is typically concentrated into a few large plants, and changes at each single plant can have significant effects on the overall energy usage and CO_2 emission levels of a country or a region. As the pressure to identify workable long-term climate policy strategies has intensified, the body of literature and research concerned with assessing the potential for and costs of reducing CO_2 emissions from carbon-intensive industries has expanded.

The studies in the literature that have focused on the technical potentials for CO_2 emission reductions in the cement industry are generally in agreement that while there remains room for further emission reductions through presently available measures and technologies, reducing CO_2 emissions beyond a certain point will involve significant investments and substantial manufacturing process changes (Moya et al., 2011; Pardo and Moya, 2013; IEA, 2013a; IPCC, 2014, Rootzén and Johnsson, 2015).

Given the large regional differences in climate policies around the world, the commitment to sustaining the competitiveness of domestic industry will continue to limit the room for manoeuvring towards climate policies that target trade-exposed industry sectors. Nevertheless, there is a clear aspiration among European legislators and industries to identify and enforce strategies that would enable significant reductions in CO_2 emissions in the medium term (Year 2030) and long term (Year 2050) (European Commission, 2011a; European Commission, 2014a). In two recent studies, Neuhoff et al. (2014a; 2014b) examined different options for a post-2020 revision of the European Union Emissions Trading System (EU ETS) that, pending a global uniform CO_2 price, could provide effective leakage protection for carbon-intensive industry without undermining investment incentives for low-carbon technologies, such as Carbon Capture and Storage (CCS). One such option, which was identified as being particularly interesting, is to replace the present free allowance allocation approach for trade-exposed sectors with an architecture that combines output-based allocation with the inclusion of consumption of CO_2-intensive commodities in the EU ETS. Consumers of, for example, steel and cement would pay a EU ETS price-related charge regardless of whether these products were produced domestically or imported, and the revenues could be used to support climate actions. Neuhoff et al. (2014b) have argued that the incremental increase in carbon cost facing the final consumer of steel and cement would typically have limited impact on the total cost at the end-user stage, e.g., the increase in price facing a car buyer or a procurer of a building or an infrastructure project.

Previous studies of the costs associated with reducing CO_2 emissions from the cement industry have focused primarily on the impact of cost on primary production and the primary product (see for example, IEAGHG, 2008; Kuramochi et al., 2011; IEAGHG, 2013; IEA, 2013b; Skagestad et al., 2014). The literature provides a few examples of attempts to estimate the price increases facing the final consumer of cement containing products due to CO_2 trading and investments in CO_2 abatement. Skelton et al. (2011) analysed the impact of carbon price on the cost of key construction materials and on construction costs in Australia and suggested that the impact on total costs to a developer would be negligible. Based on a carbon cost of 23 AUD/tCO_2, they estimated that the cost increase for concrete and steel relative to the total construction cost would be ~0.13%–0.23% for concrete and ~0.06%–0.11% for steel, depending on the building type. CEI (2011) has have employed a hybrid computable general equilibrium model (McKibbin and Wilcoxen, 1999) to assess the effects of a carbon price on the Australian building and construction industry. Their results suggest that the flow-through of overall cost increases to the building and construction industry, depending on the carbon price path, would result in an increase of 1.4%–2.0% in the average construction cost (relative to BAU) by Year 2020. Increases in construction material costs are key drivers, e.g., acquisition costs increase for ferrous metals (i.e., steel) by ~3.5%–5.5%, and for mineral products (including cement and concrete) by ~3.5%–5.0%.

While primarily focusing on material substitution and material efficiency as strategies to reduce the CO_2 emissions associated with the production and processing of cement and other basic materials, Gielen (1997), Kram et al. (2001), Sathre and Gustavsson (2007), Nässén et al. (2012) and Allwood et al. (2011) also discuss the impact on costs in end-use sectors of imposing a price on CO_2 emissions from primary production.

This paper aims to provide a better understanding of the effects of passing on the compliance costs of the cement industry to the intermediate and final consumer of the cement-containing product. Our study departs from the earlier literature in that it links more explicitly the impact of carbon cost to the actual material flows and production processes involved in the respective steps of the supply chain, from pyroprocessing in the cement kiln to eventual use in the construction industry.

The paper is organised as follows. In Section 2, we outline the material and value flows involved in the supply chain of cement and describe how the carbon cost impact is assessed at the various stages of the supply chain and the types of limitations imposed. Section 3 presents the results of the analysis. This includes estimates of the cost increases that face the producers of cement, which are dependent upon the choice of cement kiln system and the price of emissions allowances under the EU ETS, as well as estimates of the impacts on production costs and sales prices further down the value chain, i.e., in the concrete and construction industries. The results are summarized and put into context in Section 4. Section 5 then discusses the results and presents our conclusions and some possible implications for policy.

2 Methodology

We provide estimates of the magnitudes of the cost increases that may occur throughout the value chain of cement as the result of CO_2 trading and investments in CO_2 abatement by: (i) mapping the supply chain of cement in a Nordic context; (ii) calculating the production costs for "typical" Nordic cement plants using different assumptions regarding the penetration and cost of low-carbon technologies and with regard to the future price of CO_2 emissions under the EU ETS; and (iii) based on (i) and (ii), we explore how different abatement cost and allowance price paths influence the prices imposed on the intermediate and final consumers of the cement-containing product.

The analysis is based on a description of the Nordic cement industries and estimates of the potentials for existing and emerging measures to reduce CO_2 emissions therein, as described in a previous paper by the authors (Rootzén and Johnsson, 2015). The present study covers cement manufacturing in the four largest Nordic countries of Denmark, Finland, Norway, and Sweden (Iceland is not included).

In the following subsections, we outline the representations of the cement supply chain used in this study, and we present the main assumptions and limitations applied in the subsequent analyses.

2.1 Material flows and value chains

While the material flows involved in the cement supply chain can be traced with good accuracy (see for example, Kapur et al., 2009; Woodward and Duffy, 2011), the questions as to how one can describe the relationships between cost of production and price and how production cost increases are distributed across the product portfolio and passed along the supply chain are not trivial (see for example, Schmidt, 2008 and Neuhoff, 2008). Even in the absence of the risk of carbon leakage, carbon pricing is likely (and indeed is considered desirable) to drive substitution effects throughout the supply chains of carbon-intensive products, such as cement (Neuhoff, 2008). Moreover, previous studies have shown that the various parties in the supply chain, such as retailers, distributors, and subcontractors, may absorb, partly or fully, the price increases. The ability to pass on cost increases may also vary over time and depend on the specific product category and designated end-use sector (Ishinabe, 2011; Laing et al., 2013; Laing et al., 2014).

As a first approximation in this work, we assume that all production costs are passed on to the products and that costs are distributed evenly across the product portfolio. Thus, the price of 1 tonne of cement is equivalent to the average total production costs, irrespective of the specific cement type. Furthermore, as a first estimate, we assume that industry pass-through of cost is complete, in other words that the intermediate and final consumers of the cement-containing products bear the full costs of CO_2 trading and investments in CO_2 abatement.

2.1.1 *Cement*

The supply chain for cement, from limestone to final cement-containing product, involves multiple transformation steps and actors. Figure 1 outlines the key material flows considered in the present work. This representation is based on data for the Nordic cement and concrete markets, as provided in Table 1.

Table 1. Material flows and key actors in the supply chain for cement and concrete.

			Source(s)
	No. of plants	Capacity (Mt cement/year)	
Cement Production			
DK – Aalborg Portland (Cementir Holdings)	1	3.0	Aalborg Portland, 2013
FI – Finnsementii (CRH Group)	2	1.5	Finnsementti, 2013
NO – Norcem (HeidelbergCement)	2	1.9	HeidelbergCement, 2014
SE – Cementa (HeidelbergCement)	3	3.0	HeidelbergCement, 2014
Total		*9.4*	
	Seaborne imports (Mt cement/year)	Seaborne exports (Mt cement/year)	
Imports/Exports			Ligthart, 2011; ICR, 2014
DK	0.2	0.65	
FI	0.4	0	
NO	0.3	0.4	
SE	0.3	1.5	
Total	*1.2*	*2.55*	
	Total concrete production[a] (10^6 m^3/year)	RMC production (10^6 m^3/year)	
Concrete production			ERMCO, 2014
DK	4.1	2.1	
FI	4.2	2.8	
NO	5	3.3	
SE	5	3.7	
Total	18.3	11.9	
Share of production (%)			Jónsson 2005; ERMCO, 2014
Ready-Mix Concrete (RMC),	55		
Precast Elements (PCE)	25		
Precast Concrete Product (PCP)	20		
	Share of total concrete production (%)		
Final end-use			Gielen, 1997; Andersson et al., 2013
Civil engineering	40		
Non-residential buildings	37		
Residential buildings	23		

[a] Average annual production of concrete, including ready-mixed, site-mixed, and precast concrete. The density of the concrete varies depending on, e.g., the concrete mix design. The density of "normal" concrete is 2.4 t/m^3 and the density of lightweight concrete is 1.75 t/m^3.

Between 5% and 10% of total clinker production from Nordic cement manufacturers is currently white clinker, with the remainder being grey clinker. While some of the clinker is sold directly from the cement plants (often the case on the Danish cement market (Nielsen and

Glavind, 2007)), the majority of clinker is mixed and ground on-site. The European cement standard defines 27 cement compositions categorised into five different cement types, Cement I–V (CEM I–V) (Cembureau, 2012). Portland-composite cements (CEM II) with a clinker content of 65%–94%, typically slag or fly ash cements, currently dominate the Nordic cement market. Portland cement CEM I (>95% clinker) is used in applications with high demands regarding performance and durability (i.e., for civil engineering structures), whereas white cement is used in designs that have strict aesthetic requirements. All but one of the Nordic cement plants are located on a waterfront, and the majority of the finished clinker and cement is transported by ship and sold via a network of terminals. Despite regional trade and the presence of a few independent importers, the Nordic cement manufacturers typically dominate their respective home markets. While the proportion of cement production exported internationally has increased, the market remains largely regional in nature.

The cement is used almost exclusively to produce concrete and mortars. Thus, most of the finished cement is sold to concrete producers and contractors in the construction industry. The Nordic cement producers are, as subsidiaries to larger building materials groups, vertically integrated into the concrete manufacturing industry, i.e., Norcem (NO) and Cementa (SE) are subsidiaries of the HeidelbergCement Group, Aalborg Portland Cement (DK) is subsidiary of Cemntir Holdings, and Finnsemmenti (FI) is a subsidiary of the CRH group (ICR, 2014). Similarly, the large Nordic firms of contractors, through subsidiaries, are major actors in the Nordic market for concrete (SOU, 2000; SOU, 2002). Thus, aside from a number of independent concrete manufacturers (e.g., Cemex, Thomas Concrete, and Ruskon Betoni), a dozen building materials and contractor firms together enjoy strong positions in the Nordic markets for both cement and concrete.

The concrete may be mixed on-site, ready-mixed or produced in a plant for precast concrete products. Following Jónsson (2005), concrete is in the present work divided into three classes: Ready-Mix Concrete (RMC); Precast Elements (PCE): and Precast Concrete Product (PCP). While there exists a wide variety of concrete mix designs, cement (~15%), aggregates, and water are the main components. RMC, i.e., wet concrete mixed at an RMC plant and typically delivered by truck to the construction site, is available in a range of specifications depending on the application. PCE include reinforced and pre-stressed concrete structural elements and frames manufactured in dedicated precast concrete production plants before delivery to the construction site (e.g., slabs, roofs, walls, facades and columns). PCP includes precast concrete products other than structural elements (e.g., pipes, blocks, bricks and tiles).

Based on the previous studies of Gielen (1997), Kapur et al. (2009), and Andersson et al. (2013), the concrete (and cement) end-use markets are divided into three main sectors and nine subsectors; civil engineering (including transport infrastructure, hydraulic works, and other infrastructure); non-residential buildings (including public, commercial and other buildings); and, residential buildings (including multi-dwelling houses, single detached houses and other residential buildings).

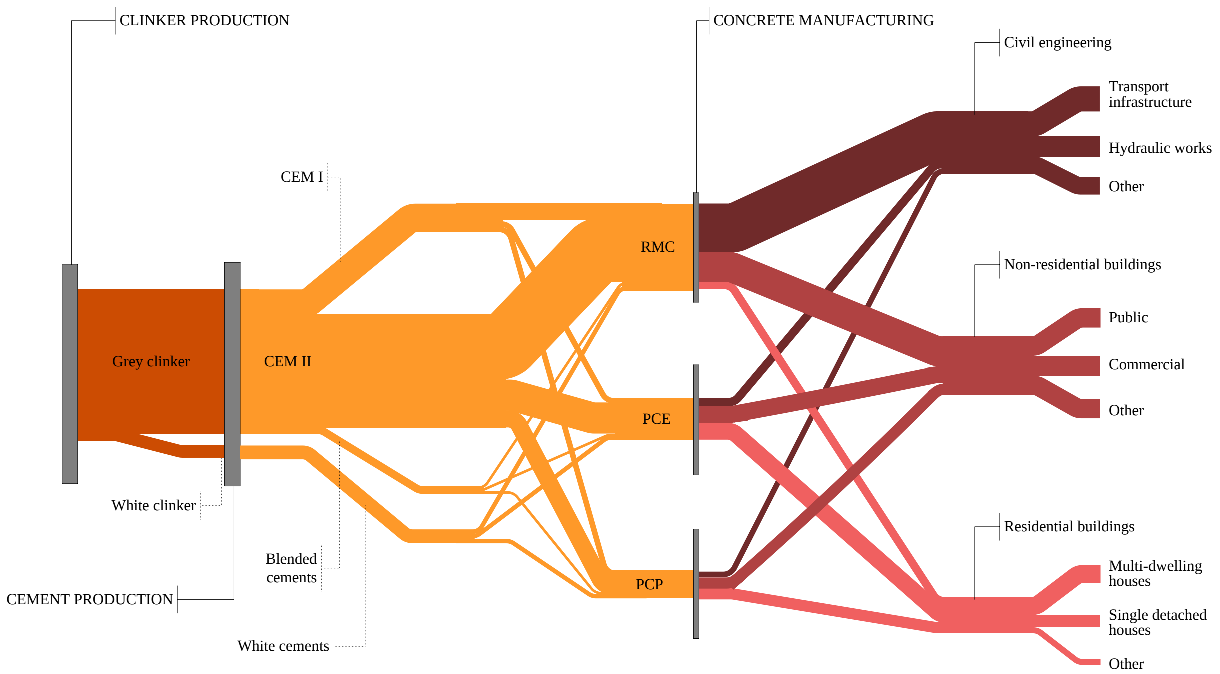

Figure 1. Material flows in the supply chain of cement – from clinker burning to final end-use. The width of each line gives an approximation of the share (% by weight) of the total annual cement clinker production in the Nordic countries going in to the respective concrete class and final end-use sector.

2.2 The pathway from upstream costs to downstream prices

The derived descriptions of the material flows involved in the supply chain for cement provide an overview of the systems under consideration and highlight some of the complexity involved. However, since the analysis relies on historical data, the descriptions provided are static snapshots of the flows and interlinkages. Furthermore, as already noted, the value flow does not necessarily correlate to the physical flow of material.

To limit the scope of the analysis so as to make it manageable, when assessing how increasing production costs in the cement industry affect costs and prices further up the value chain, we limit the subsequent analysis to a specific supply thread (Sturgeon, 2001) in the flow from basic material to final uses. For this purpose, the cement supply chain is defined by the following steps: (1) the production of cement in a 'typical' Nordic cement plant; (2) further refinement in a RMC factory; and (3) final use in the construction of a four-storey apartment building.

To illustrate the effects of changes in the reference conditions in the three stages of this particular supply chain, two periods were defined, Period 0 and Period 1. Various options were considered for the respective periods.

- For Period 0 (P0), the options were:
  (1) cement is produced in a hypothetical 'average' Nordic cement plant (C0) with performance data for the kiln system, i.e., energy use, fuel mix, and other characteristics relevant to the production costs, which are chosen to reflect current (Year 2010) conditions in the Nordic cement industry. The price of emissions allowances under the EU ETS (EUA) is assumed to remain in the range of 10–40 €/tCO_2;
  (2) the RMC factory produces 'conventional' building concrete with a cement content set at 340 kg/m^3 concrete; and
  (3) the RMC is used as structural building material for the construction of a four-storey apartment building with either a concrete (heavy) frame or a wood (light) frame.

- In Period 1 (P1), the following options were applied:
  (1) the existing kiln system can be replaced with one of the following: a new state-of-the-art kiln system (C1); a kiln system equipped for post-combustion CO_2 capture (C2); or a kiln system that is adapted for full oxy-combustion (CO_2 capture applied to both the precalciner and the cement kiln) and CO_2 capture (C3). The cement production costs reflect the characteristics of the respective kiln systems. The market price for CO_2 allowances is assumed to remain in the range of 40–100 €/tCO_2;
  (2) the RMC factory produces 'conventional' building concrete, as above, or 'low-cement' building concrete with a cement content set at 180 kg/m^3 concrete; and
  (3) as above, the use of RMC in the construction of a four-storey apartment building (heavy or light frame) marks the end of the supply thread.

The description of the performance of the 'average' or 'typical' Nordic cement plant (C0), which is used as the reference throughout the analysis, is based on data taken from Rootzén and Johnsson (2015). Table 2 outlines the key assumptions and options considered in the three stages of the supply thread in the respective periods. Figure 2 gives an overview of the cases that have been considered.

Table 2. Summary of the key assumptions and options considered.

	Period 0	Period 1
General		
CO_2 price range[a]:	10–40 €/tCO_2 (0)[b]	40–100 €/tCO_2
Cement supply chain		
(1) Cement manufacturing	Existing average kiln (C0)	New BAT kiln system (C1) Kiln system with post-combustion CO_2 capture (C2) Kiln system with oxy-combustion and CO_2 capture (C2)
(2) Concrete fabrication	'Conventional' concrete (RMC1)	'Conventional' concrete (RMC1) 'Low-cement' concrete (RMC2)
(3) Construction	Concrete frame (HF) Wood frame (LF)	Concrete frame (HF) Wood frame (LF)

[a] The CO_2 price range in Period 0 corresponds to the price range expected for emissions allowances under the EU ETS (EUA) for the period up to Year 2030 (European Commission, 2014a). Correspondingly, the price range in Period 1 corresponds to the estimated development of the carbon price in the period 2030–2050 (European Commission, 2011a).
[b] In the reference case, used in the following assessments, the carbon cost is set to zero.

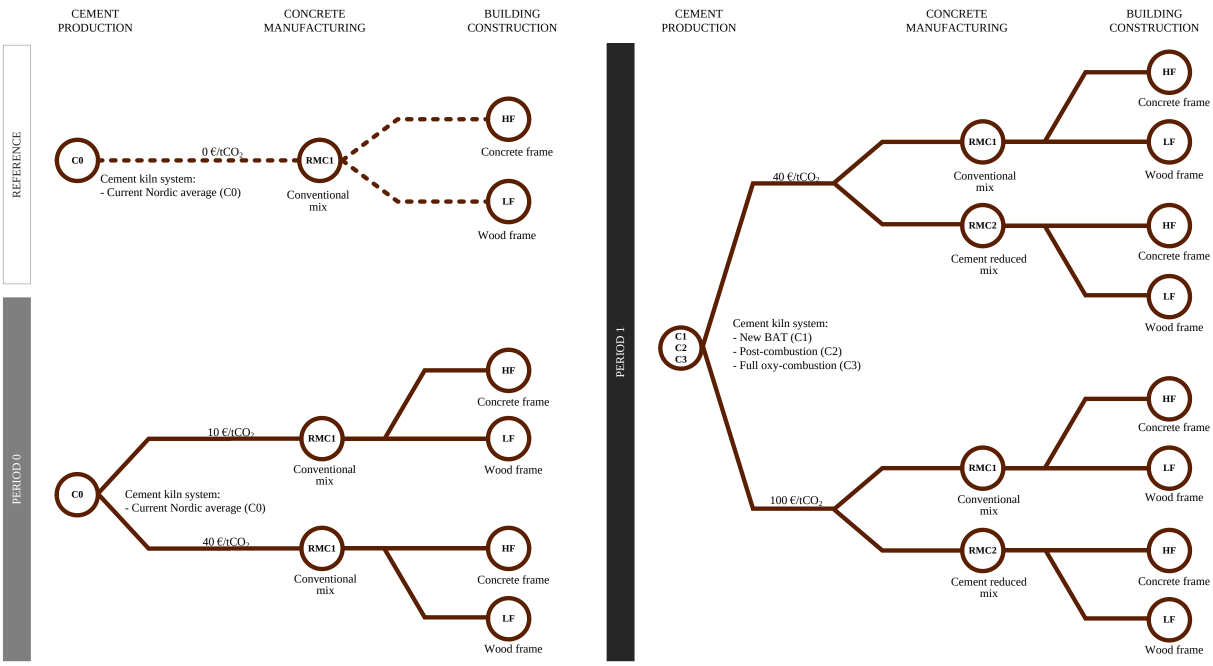

Figure 2. Overview of the analysed cases in the supply chain for cement. The problem statement can be simplified as: (1) one cement plant, which perseveres with the existing kiln system (C0) in Period 0 and upgrades to one of three kiln systems in Period 1 (C1–C3), supplying cement to (2) a single RMC manufacturer that offers one product (RMC1) in Period 0 and two products (RMC1 or RMC 2) in Period 1 to a building contractor who chooses between two types of building frame (HF or LF). Given the market prices of 10–40 €/tCO_2 in Period 0 and 40–100 €/tCO_2 in Period 1, what is the magnitude of the cost increases facing the building contractor?

2.2.1 Production costs and carbon cost impact – from limestone to cement

The unit selling price (€/t cement) required to cover the production costs, including the carbon costs, is calculated as the sum of the average total production cost, the cost involved in delivering the cement to a cement terminal, and an assumed expected operating profit. The break-even cost includes all costs but excludes the expected operating profit. All cost estimates were adjusted to Year 2010 Euro (€). Table 3 lists the general assumptions applied. The same assumptions were applied in both periods (P0 and P1) and for the three kiln systems considered (C0–C3).

Table 3. General assumptions applied to the 'average' Nordic cement plant. The same assumptions were applied in both periods (P0 and P1) and for all the kiln systems (technological options) considered (C0–C3).

	Period 0 and Period 1
The average Nordic cement plant	
Production capacity	1.5 Mt cement/year
Average capacity utilisation rate	90%
Clinker-to-cement ratio	0.8
Discount rate	8%
Economic life (years)	25
Technical lifetime (years)	50
Fuel mix[a] (energy-based %)	
Coal	50
Petcoke	22
Fuel oil	<1
Alternative fuel	15
Biomass	11
Average transportation costs	
Delivery to cement terminal	10 €/t cement
Average profit per unit sold[b]	10 €/t

[a] Estimated current (2010) fuel mix taken from Rootzén and Johnsson, 2015. Refers to the fuel used in the cement kiln/precalciner and does not include the fuel used to cover thermal energy requirements for capture solvent regeneration.
[b] Assumed expected pre-tax profits before interest repayments.

The average total cement production costs, *TC*, for each of the kiln systems *i* considered in respective period *t* are calculated as:

$$TC_{i,t} = VC_{i,t} + FC_{i,t} + CC_{i,t} + C_{CO_2 i,t} \quad (1)$$

where *VC* is the variable operating cost, *FC* is the fixed operating cost, *CC* is the annualised capital cost, and C_{CO_2} is the carbon cost. Table 4 gives the breakdown of the production costs, excluding carbon costs, for the hypothetical average Nordic cement plant (C0). Performance data for the kiln system, i.e., energy use, and the fuel mix were taken from Rootzén and Johnsson, 2015. Production costs can vary significantly between individual cement plants due to varying local conditions, and over time, due to fluctuating input costs. Nevertheless, the cost model gives an overview and a measure of the relative weights of the various input factors.

Table 4. Breakdown of production costs in an average Nordic cement plant (C0) for Period 0.

	Unit cost (€)	Unit	Requirement per tonne cement[a]	Cost (€/t cement)
Variable operational costs				26.2
Raw material[b]				9.2
- *Limestone*	3	t	1.4	4.2
- *Other raw materials*	25	t	0.2	5.0
Fuel[c]				7.4
- *Coal*	2.6	GJ	1.5	3.8
- *Pet coke*	2.1	GJ	0.6	1.3
- *Fuel oil*	10.0	GJ	<0.1	0.3
- *Alternative fuels*	0.8	GJ	0.4	0.3
- *Biomass*	5.0	GJ	0.3	1.6
Electricity[d]				9.6
- *Electricity*	0.08	kWh	120	9.6
Fixed operational costs[e]				27.3
Labour	35	hrs	0.35	12.3
Maintenance				10.0
Other overhead costs				5.0
Capital cost[f]				5.0
Average total production cost				58.4

[a] Raw material requirement and energy use (per tonne cement) chosen to represent current average or typical use levels in Nordic production of grey cement clinker (Rootzén and Johnsson, 2015).
[b] Raw material costs from Moya et al., 2010, IEAGHG, 2008, and IEAGHG, 2013.
[c] Fuel costs for coal (IEA, 2013a), pet coke (Roskill, 2013; Energy Argus, 2014), fuel oil (European Commission, 2014b), alternative fuels ~15%–30% of the coal price (IEAGHG, 2013), and biomass (SEA, 2013). Fuel requirements per unit of cement based on an assumed thermal energy use of 3650 MJ/t cement, taken from Rootzén and Johnsson, 2015.
[d] Electricity prices for industrial consumers from Eurostat, 2014.
[e] Fixed operational costs for labour (USDOL, 2013), and labour input (hrs/t cement), which includes both direct and indirect labour, maintenance, and other overhead costs (Harder, 2010; Moya et al., 2010; IEAGHG, 2008; IEAGHG, 2013; Boyer and Ponssard, 2013).
[f] Estimates of capital expenditures and depreciation from European Commission, 2006 and Boyer and Ponssard, 2013.

Table 5 lists the production costs, excluding carbon costs, for the kiln systems considered for Period 1: a new state-of-the-art kiln system (C1); a kiln system equipped for post-combustion capture of CO_2 using chemical absorption with monoethanolamine (C2); and a kiln system adapted for full oxy-combustion and CO_2 capture (C3). The production capacity and capacity utilisation are assumed to be the same as for Period 0 (see Table C3). Similarly, the unit costs of raw materials, fuels, and electricity are the same as those applied for the existing kiln (C0) in Period 0. The performance data, including the added energy requirements in cases where

CO_2 capture is applied, i.e., thermal energy requirements for capture solvent regeneration (C2) and electricity required for air separation (C3) for the respective kiln system, were taken from IEAGHG (2013) and Rootzén and Johnsson (2015). Estimated fixed operational costs and capital costs were taken from IEAGHG (2013) and scaled to meet the production capacity of the average Nordic cement plant. The investment costs, and the resulting capital costs, associated with replacing the kiln system of the existing average Nordic cement plant are assumed to be the same as if investing in a corresponding greenfield plant. Since practical experiences of applications of CO_2 capture in the cement industry, with a few exceptions (GCCSI, 2014), are still largely lacking, the cost estimates are associated with significant uncertainties. With an assumed CO_2 avoidance rate of 90% relative to C1 for both kiln systems in which CO_2 capture is applied, the CO_2 avoidance costs would be approximately 75 €/tCO_2 for the kiln system with post-combustion capture (C2) and 45 €/tCO_2 for the kiln system adapted for oxy-combustion and CO_2 capture (C3). Both estimates are within the range of the estimates of the CO_2 avoidance costs for the cement industry found in the literature, which vary from 25 to 110 €/tCO_2, depending on the capture option considered and on the assumptions made with respect to the different cost items involved (see for example, IEAGHG, 2008; Kuramochi et al., 2011; IEAGHG, 2013; IEA, 2013b; Skagestad et al., 2014).

Table 5. Indicative production costs in the Nordic cement industry for Period 1.

Kiln system	New BAT[a]	Post-combustion[b]	Full oxy-combustion[c]
	C1	C2	C3
Variable operational costs (€/t cement)	23	30	35
Fixed operational costs (€/t cement)	22	35	30
Capital costs (€/t cement)	15	35	20
Average total production costs (€/t cement)	60	100	85

[a] Fuel requirements per unit of cement based on an assumed thermal energy use in the cement kiln/precalciner of 3025 MJ/t cement, taken from Rootzén and Johnsson, 2015.
[b] Capital costs include the costs of investing in a natural gas-fired Combined Cycle Gas Turbine (CCGT) to supply steam for capture solvent regeneration (IEAGHG, 2013). The energy penalty associated with CO_2 capture (2400 MJ/cement) is also reflected in higher fuel expenditures. Surplus electricity is sold to the grid.
[c] Increased variable costs are primarily the result of increased electricity use for oxygen production. Electricity is assumed to be imported from the grid.

Finally, the carbon cost, C_{CO_2}, is calculated as the sum of the cost of purchasing emissions allowances and, where applicable, the costs of transporting and storing the captured CO_2. Table 6 presents the carbon costs for each of the kiln systems considered, given the market price for CO_2 allowances, within the respective periods.

In the reference case, the carbon cost is set at zero. Thus, in the reference case, the unit selling price, $P_{Cem,Ref}$ (€/t cement), equals the production cost in the existing average Nordic cement plant (C0) (as listed in Table 4) plus the transport costs and the assumed expected operating profit (Table 3).

Accordingly, for all other cases, the added costs relative to the reference include: the cost of buying emissions allowances (C0-C3); the added costs associated with investing (and operating) a new low-carbon kiln system (C1–C3); and, in the cases where CCS is applied, the cost of transporting and storing the captured CO_2. The actual costs of transporting and storing CO_2 will depend on the distance to a suitable storage site, the mode of transport, and the possibility to co-ordinate with other major CO_2 emitters. The cost estimate used in the present work is chosen to reflect average Nordic conditions and is based on estimates of the costs associated with transport and storage in the Baltic Sea region (Kjärstad and Nilsson, 2014) and the Skagerrak and North Sea Region (Skagestad et al, 2014).

Table 6. Aggregate carbon costs for Periods 0 and 1.

	Period 0	Period 1		
Kiln system	Current average C0	New BAT C1	Post-combustion C2	Full oxy-combustion C3
Carbon costs				
Specific emissions[a] (tCO_2/t cement)	0.7	0.6	0.06	0.06
Captured CO_2[b] (tCO_2/t cement)	-	-	0.7	0.6
Allowance price (€/tCO_2)				
- High	40	100	100	100
- Low	10	40	40	40
Free allocation of allowances	Yes (0%–100%)	No	No	No
Transport and storage costs[c] (€/t CO_2)	-	-	25	25
Total carbon cost (€/t cement)				
- High	28	60	24	21
- Low	7(0)	24	20	17

[a] Includes both the combustion-related CO_2 emissions and the CO_2 emissions arising from the calcination of limestone. In C2 and C3, the specific emissions refer to all CO_2 emissions released from the kiln system after capture.
[b] For C2, the amount of CO_2 captured includes the share of the CO_2 emissions from the CCGT related to the generation of steam for capture solvent regeneration.
[c] Transport cost of ~15–20 €/tCO_2 and storage cost of ~7 €/tCO_2 (Kjärstad and Nilsson, 2014; Skagestad et al, 2014).

2.2.2 From cement to concrete

Markets for RMC are typically spatially confined, and the input costs and delivery prices may vary considerably across markets in different regions (Syverson, 2008, Ballebye-Okholm et al., 2009). Nevertheless, the costs for materials and transportation account for the majority of the costs in RMC manufacturing (Olivarri, 2011; CIS, 2015). Table 7 outlines the assumed cost structure of the Nordic RMC industry used as the basis for assessing the impact of increased cement costs on RMC manufacturing costs. The unit price for concrete (€/m^3 concrete) is calculated as the sum of the raw material costs, the conversion costs (i.e., all manufacturing costs other than direct material costs), the delivery costs, and an assumed operating profit.

Table 7. Assumed cost structure of the Nordic ready-mixed concrete industry.

	Period 0 and Period 1
Ready-mixed concrete manufacturing[a]	
Share of total break-even cost (%)	
Variable costs	
- Raw materials	50
- Delivery costs[b]	20
- Plant costs	5
Fixed costs	25
Average profit per unit delivered[c]	15 €/m^3 concrete

[a] Cost structure based on data for the RMC industry in North America (Olivarri, 2011; CIS, 2015).
[b] Including driver wages and fuel cost.
[c] Pre-tax profit before interest repayments.

Table 8 lists the unit costs (€/kg) of the raw materials used in RMC manufacturing and the raw material consumption per unit produced (kg/m^3) of the two considered types of concrete. The ‘conventional’ concrete mix design (RMC1) was chosen as representative of the type of RMC currently used in building construction (e.g., for *in situ* casting of the foundation slab and building frame) in the Nordic market (Stripple, 2013). The extent to which alternative cementitious binders are used at the present time is dependent upon local availability and national price standards, and market acceptance (Nielsen and Glavind, 2007; Proske et al., 2013). While the use of alternative binders remains limited in most Nordic countries, with Denmark being the exception (Nielsen and Glavind, 2007), the trend is towards increased use of alternatives to cement clinker (Cembureau, 2012). To capture the impact on manufacturing costs of the introduction of RMC with reduced content of cement clinker, a low-cement concrete mix design (RMC2) was also considered. RMC1 is available in both periods (P0 and P1) and RMC2 is assumed to be introduced at-scale in Period 1. The cost of materials (€/m^3) is calculated based on the concrete mix design as:

$$M_k = \sum (q_{j,k} \times u_j) + q_{c,k} \times u_c \tag{2}$$

where q_{jk} is the quantity of material j in concrete mix design k, u_j is the unit cost of material j, q_{ck} is the quantity of cement in concrete mix design k, and u_c is the unit cost of cement. The unit cost of cement equals the unit selling price of cement, which (as described in the previous subsection) depends on the kiln system considered and the assumed price for CO_2 allowances.

The reference price of concrete, $P_{RMC,Ref}$ (€/m^3), is estimated from the case in which the material cost is equivalent to the total costs of the raw materials involved in manufacturing 1 m^3 of RMC1 with the unit cost of cement being equal to $P_{Cem,Ref}$. The break-even cost of concrete includes all costs except for the expected operating profit. The convergence costs and delivery costs, taken together, are assumed to be equal to the material costs in the reference case (*cf.* Table 8) and are kept constant in all the other cases.

Table 8. Concrete raw material costs and mix designs.

	Unit cost[a] (€/kg)	P0 and P1	P1
		Concrete mix design	
		RMC1 Conventional[b] (kg/m^3)	RMC2 Low-cement[c] (kg/m^3)
Raw material costs			
- Building cement[d] (CEM II)	0.07–0.14	340	180
- Alternative binder[e]	0.08	-	250
- Crushed aggregates	0.02	950	900
- Pit run sand	0.02	900	900
- Water		190	140
- Admixtures	1.5	2	3
Density (kg/m^3 concrete)		2382	2373

[a] The unit costs of cement reflect the estimates of the cement production cost, as described in Section 2.2.1, with all other raw material prices being assumed to remain constant.
[b] Representative 'conventional' concrete mix design used for casting *in situ* of concrete (Stripple, 2013).
[c] Concretes with reduced water and cement contents (Proske et al., 2013).
[d] Comprises 80% cement clinker and 20% fly ash.
[e] The costs of alternative binders, i.e., fly ash or granulated blast furnace slag, are assumed to be in line with the current average selling price of cement. Where supplementary cementing materials can be sourced locally costs are generally lower.

2.2.3 From concrete to building construction

Table 9 outlines the characteristics and costs of the residential building project used as a reference in this work. The same building project has been the subject of several previous investigations (Persson, 1998; Gustavsson et al., 2006; Sathre and Gustavsson, 2007; Nässén et al., 2012; Dodoo et al., 2014), which means that disaggregated data are available for material use and the various components of the building production cost. These previous studies also include a comparison of two functionally equivalent versions of the same building, i.e., having either a concrete or a wooden frame. This also allows for comparisons of the impacts of increased cement and concrete costs on the construction costs depending on the choice of building frame structure, i.e., heavy frame (concrete) or light frame (wood).

In Table 9, presents five distinct cost categories: total production costs; building construction costs; material costs; structural material costs; and concrete costs, where the latter represents subsets of the former categories. Following Sathre and Gustavsson (2007), the current (Year 2010) production and construction costs are estimated based on the costs at the time of construction (Persson, 1998) and adjusted in accordance with the construction price index for multi-dwelling buildings in Sweden (SCB, 2012).

Table 9. Characteristics and costs of the reference residential building project.

	Heavy frame building	Light frame building
General		
Frame type	Concrete	Wood
Number of storeys	4	4
Gross floor area (m^2)	1120	1071
Residential floor area[a] (m^2)	928	928
Overall costs		
Total production costs[b] (€/m^2)	2710	2620
Building construction costs[c] (€/m^2)	1380	1320
Material costs		
Total material cost[d] (€/m^2), of which	450	430
- Structural building materials (%)	50	50
- Other materials[e] (%)	50	50

[a] Usable floor area arranged for accommodation, i.e., excluding common areas and the area occupied by walls. All costs are expressed per square meter of residential floor area.
[b] Including direct and indirect construction costs and overheads, e.g., land procurement and parcelling, planning and design, and other contractor costs.
[c] Direct construction costs, i.e., excluding connection charges and other indirect and overhead costs.
[d] Excluding materials for plumbing, electrical installations, and ventilation.
[e] Including windows, doors, appliances, and interior materials (carpentry, wallpaper, ceramic tiles, paints, varnishes, floor products).

Table 10 shows the unit costs (€/t) of the materials used and the amounts of material used (kg/m^2) in the respective versions of the building (heavy or light frame). Structural materials refer to materials used in the construction of the foundation, frame structure, and building envelope. The total costs (€) associated with acquiring the structural materials in the respective versions of the building are calculated as follows:

$$S_n = A_n \times \left(\sum (q_{mn} \times u_m) + q_{rn} \times u_r\right) \quad (3)$$

where A_n is the residential floor area, q_{mn} is the quantity of material m in version n of the building, u_m is the unit cost of material m, q_{rn} is the quantity of RMC used in version n, and u_r is the unit cost of RMC. The unit cost of RMC equals the unit selling price of RMC, which depends on the type of RMC considered (RMC1 or RMC2), which in turn depends on the estimated unit selling price of cement.

Table 10. Structural building materials used in the construction of the reference residential building project.

	Unit cost[a] (€/t)	P0 and P1	
		Frame type	
		Concrete (kg/m^2)	Wood (kg/m^2)
Building materials			
- Concrete[b]	60–70	1460	240
- Macadam	16	340	340
- Lumber[c]	860	36	64
- Plasterboard	370	27	96
- Steel[d]	850	27	17
- Mortar	390	24	26
- Plywood	850	21	19
- Particle board	390	19	19
- Insulation	2130	11	23
- Other materials[e]	-	25	25
Total		1990	870

[a] The unit costs for all materials, except the concrete, are taken from Svensk Byggtjänst, 2015. A quantity discount of 25% of the list price is assumed for all the materials.
[b] The unit costs of concrete depends on the estimates of the cement production cost, as described in Section 2.2.2.
[c] Of which approximately 75% is construction wood (470 €/t) and 25% glued laminated timber (2000 €/t).
[d] Of which approximately half is reinforcement steel (680 €/t) and half galvanised steel plate (1000 €/t).
[e] Including windows, doors, appliances and interior materials (carpentry, wallpaper, ceramic tiles, paints, varnishes, floor products).

Table 11 shows the amounts of concrete (m^3) and cement (t) used in the construction of the reference residential buildings, taking into account the choice of building frame structure: heavy frame (concrete) or light frame (wood).

Table 11. Concrete and cement used in the construction of the reference residential buildings.

	P0 and P1	
	Frame type	
	Concrete	Wood
Concrete and mortars		
- Ready mixed concrete (m^3)	570	95
Cement in RMC (t)	*190*	*30*
- Mortars (t)	23	25
Cement in mortars (t)	*3*	*4*
Total cement[a] (t)	195	35

[a] If low-cement concrete (RMC2) is used the total cement content is reduced to approximately 105 t for the concrete frame building and 20 t for the wood frame building.

3 Results and Discussion

3.1 Cement manufacturing

The results obtained in the present project for the cement industry reveal that compliance costs, i.e., the combined effects of internal abatement cost and the cost of buying emissions allowances, have significant impacts on the break-even production costs, and, ultimately, on the selling price of cement.

Table 12 list the total break-even production costs of an average Nordic cement plant with different cement kiln systems given different future developments of the carbon price under the EU ETS. Current average production costs are used as a reference. Since the capital costs are low, the total production costs with the existing conventional kiln system remain below the alternative kiln systems, as long as the carbon price remains low (<40 €/tCO_2). At a carbon price of approximately 40 €/tCO_2, the total production cost with a new 'state-of-the-art' kiln system that has lower levels of specific emissions becomes lower than that for the existing conventional kiln system. With a high price for carbon of 100 €/tCO_2, the kiln system adapted for oxy-combustion with CO_2 capture becomes competitive. In Period 0 (P0), when the carbon price is assumed to be in the range of 10–40 €/tCO_2, the production costs increases by10%–40%. In Period 1 (P1), with a carbon price of 40–100 €/tCO_2, the production costs increase by approximately 40%–90% without CCS and 65%–95% with the introduction of kiln systems that are equipped for CCS. The selling price (including profit) in Period 0 would be in in the range of 80–105 €/t cement. Correspondingly, the unit selling price in Period 1 would be in the range of 80–140 €/t cement.

Table 12. Relative and absolute cost increases under different assumptions regarding future technological developments. The current average production cost (excluding carbon costs) is set as reference (68 €/t cement).

	P0[a]	P1[b]		
Kiln system	Current average C0	New BAT C1	Post-combustion C2	Full oxy-combustion C3
Total break-even cost of cement				
Excluding carbon costs (€/t cement)	68	71	110	95
- Absolute increase (€/t cement)	0	2	42	27
- Relative increase (%)	0	3	61	39
With low carbon price (€/t cement)	75	95	130	112
- Absolute increase (€/t cement)	7	26	61	44
- Relative increase (%)	10	38	90	65
With high carbon price (€/t cement)	96	131	134	116
- Absolute increase (€/t cement)	28	62	65	48
- Relative increase (%)	41	91	95	70

[a] In Period 0, the high and low carbon prices are set at 10 €/tCO_2 and 40 €/tCO_2, respectively (see Table 6).
[b] In Period 1, the high and low carbon prices are set at 40 €/tCO_2 and 100 €/tCO_2, respectively (see Table 6). The carbon cost includes, where applicable, the cost associated with transporting and storing captured CO_2 (25 €/t CO_2).

Figure 3 the shows the cement production costs (€/t cement), divided into cost categories, under the different assumptions made regarding the evolution of the carbon price, as well as the choice of cement kiln system (C0–C1). The basic production cost depends on the input cost, which encompasses raw materials, energy, labour, and capital. The estimated break-even cost for cement production includes also the cost involved in delivering the cement to a cement terminal, the cost of purchasing emissions allowances and, where applicable, the costs of transporting and storing captured CO_2. It is clear from both Table 12 and Figure 3 that the price range expected for emissions allowances under the EU ETS for the period up to Year 2030 (see Table 2), 10–40 €/t CO_2, will not be sufficiently high incentivise investments in CCS.

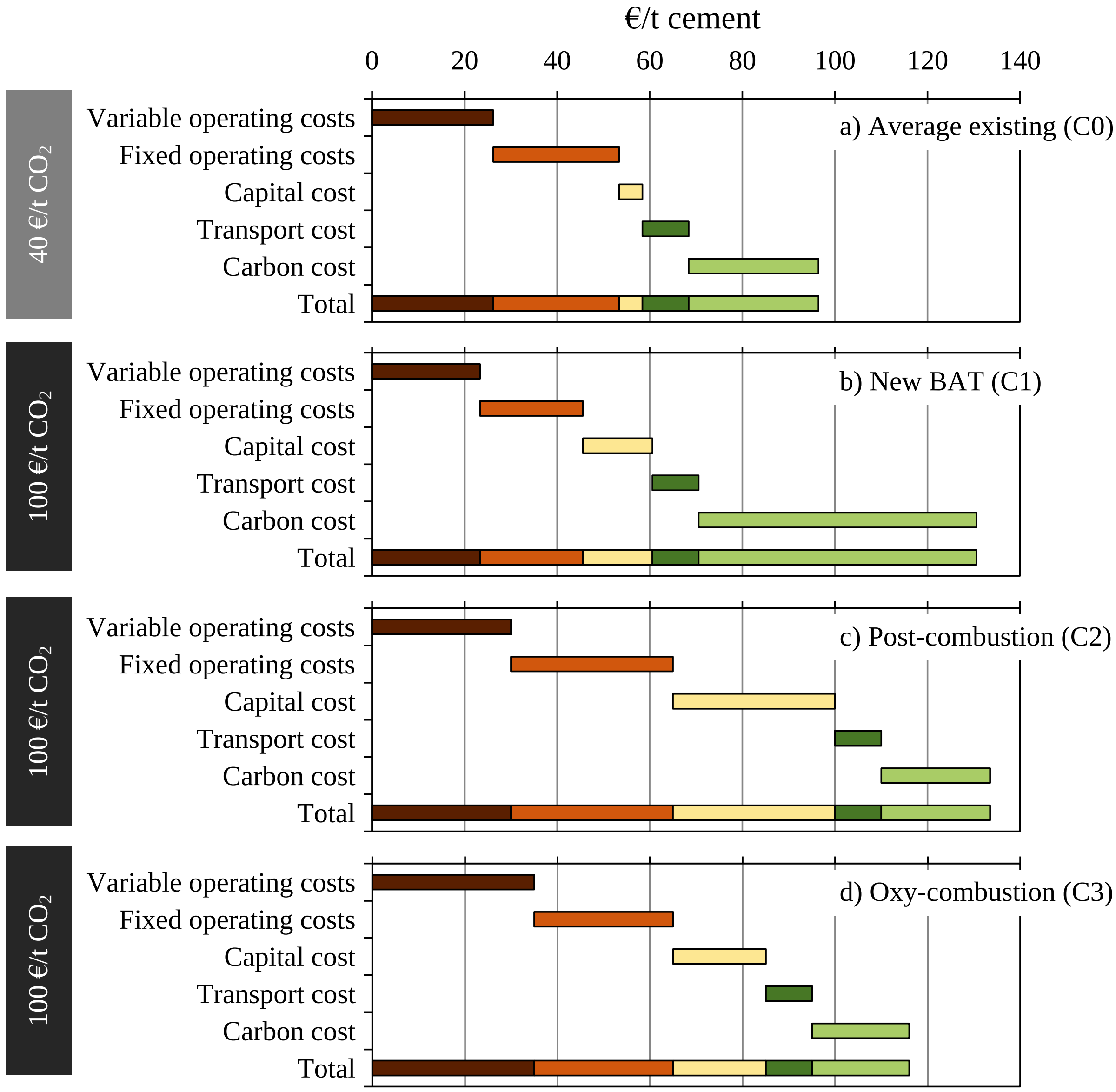

Figure 3. Break-even costs for cement production (€/t cement) for a Nordic cement plant in Periods 0 and 1 under different assumptions with regards to the development of the carbon price, as well as the choice of cement kiln system (C0–C1). a) Estimated manufacturing costs in a hypothetical average Nordic cement plant, including carbon costs (40 €/tCO_2) and excluding free emissions allowances. b) Average production costs for a new Nordic cement plant with a conventional "state-of-the-art" cement kiln system (New BAT), including carbon costs (100 €/tCO_2). c) Production costs for a cement plant with a new kiln system equipped for post-combustion capture of CO_2, including carbon costs (100 €/tCO_2 for all unabated emissions plus 25 €/tCO_2 for transport and storage). d) Average total production costs for a cement plant with a new kiln system adapted for oxy-combustion and CO_2 capture, including carbon costs (100 €/tCO_2 for all unabated emissions plus 25 €/tCO_2 for transport and storage).

Figure 4 shows the break-down by type of cost of the estimated compliance cost for each respective kiln system (C0–C3). It is evident from these graphs that the introduction of CCS will not be profitable unless the cost of emitting CO_2 becomes significantly higher than it is today. In addition, and perhaps more importantly, the graphs show how, in addition to the added production costs, the cost of transporting and storing CO_2 affects the overall costs in the cases where CCS is applied.

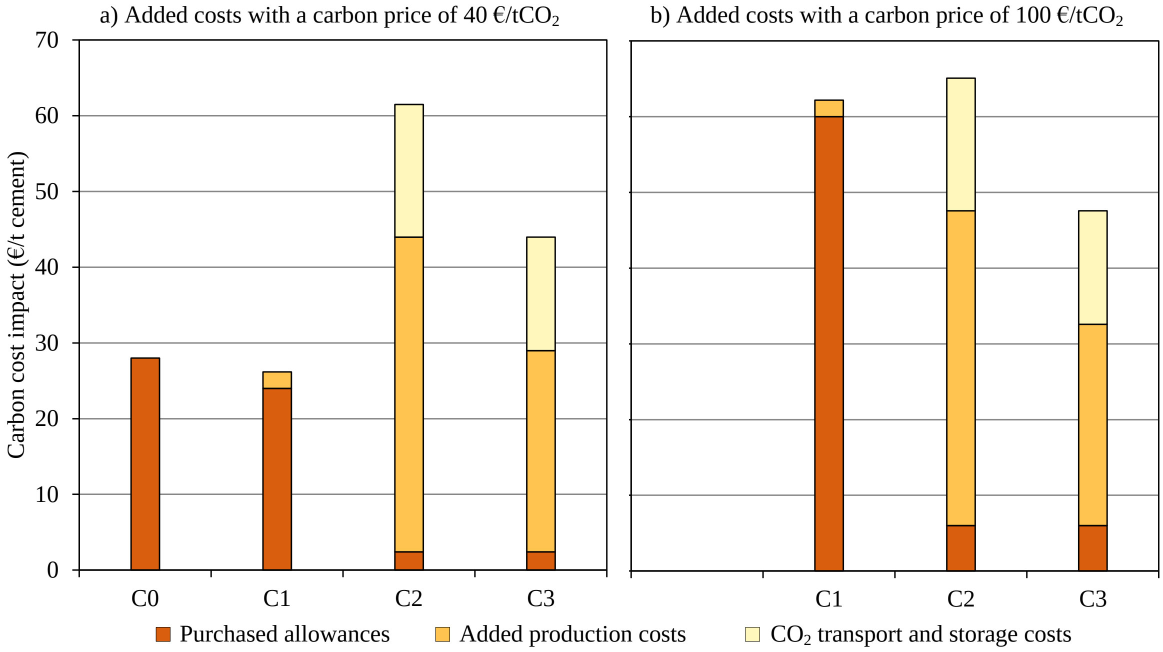

Figure 4. The full carbon cost impact on cement production, including the cost of buying emissions allowances (C0–C3), the added costs associated with investing and operating a new low-carbon kiln system (C1–C3), and, in the cases where CCS is applied, the cost of transporting and storing the captured CO_2.

3.2 Concrete manufacturing

Figure 5 shows the impact on RMC manufacturing costs (absolute and relative) of increases in the price of cement. The increase in cement price, in turn, depends on the choice of kiln system and the cost of emitting CO_2, as given above. Estimates are made for the manufacturing cost of two concrete mix designs, 'conventional' concrete (RMC1) and low-cement concrete (RMC2). The results suggest that the manufacturing cost increase is appreciable. The absolute increases in break-even costs for concrete production, in the cases with the largest increases in cement price, are in line with or slightly higher than the profit margin suggested for that RMC industry (15 €/m^3 concrete).

As can be seen in Figure 6, cement cost fractions of the raw material costs and total production costs (including delivery costs) are considerably lower for a RMC manufacturer that produces low-cement concrete. Therefore, a shift towards low-cement concrete production would reduce the vulnerability of the RMC manufacturer to cement price increases. However, the impact on total manufacturing costs will depend on the costs of alternative binders. Returning to Figure 5a, the estimates of the break-even cost of production for RMC2 are only marginally lower than those for RMC1. In these cases, the cost of supplementary cementing materials is assumed to be in line with the current average selling price of cement.

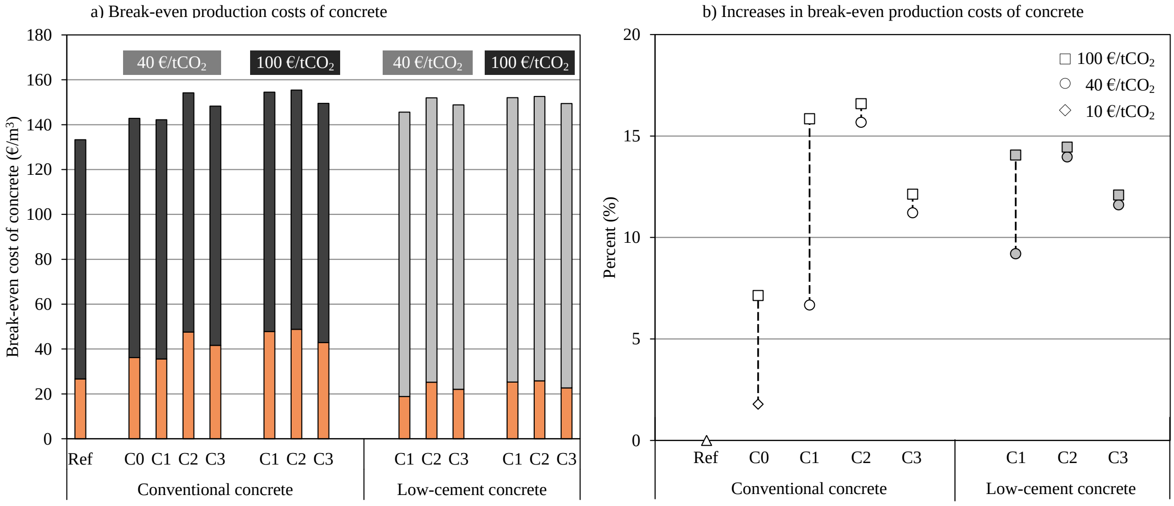

Figure 5. a) Break-even costs for concrete production (€/m^3) for a Nordic RMC manufacturer. The shares of total production costs that are attributable to cement are in orange. b) Relative increases in the break-even costs for concrete production for a Nordic RMC manufacturer. The current average costs for cement (excluding carbon costs) and concrete production are used as references.

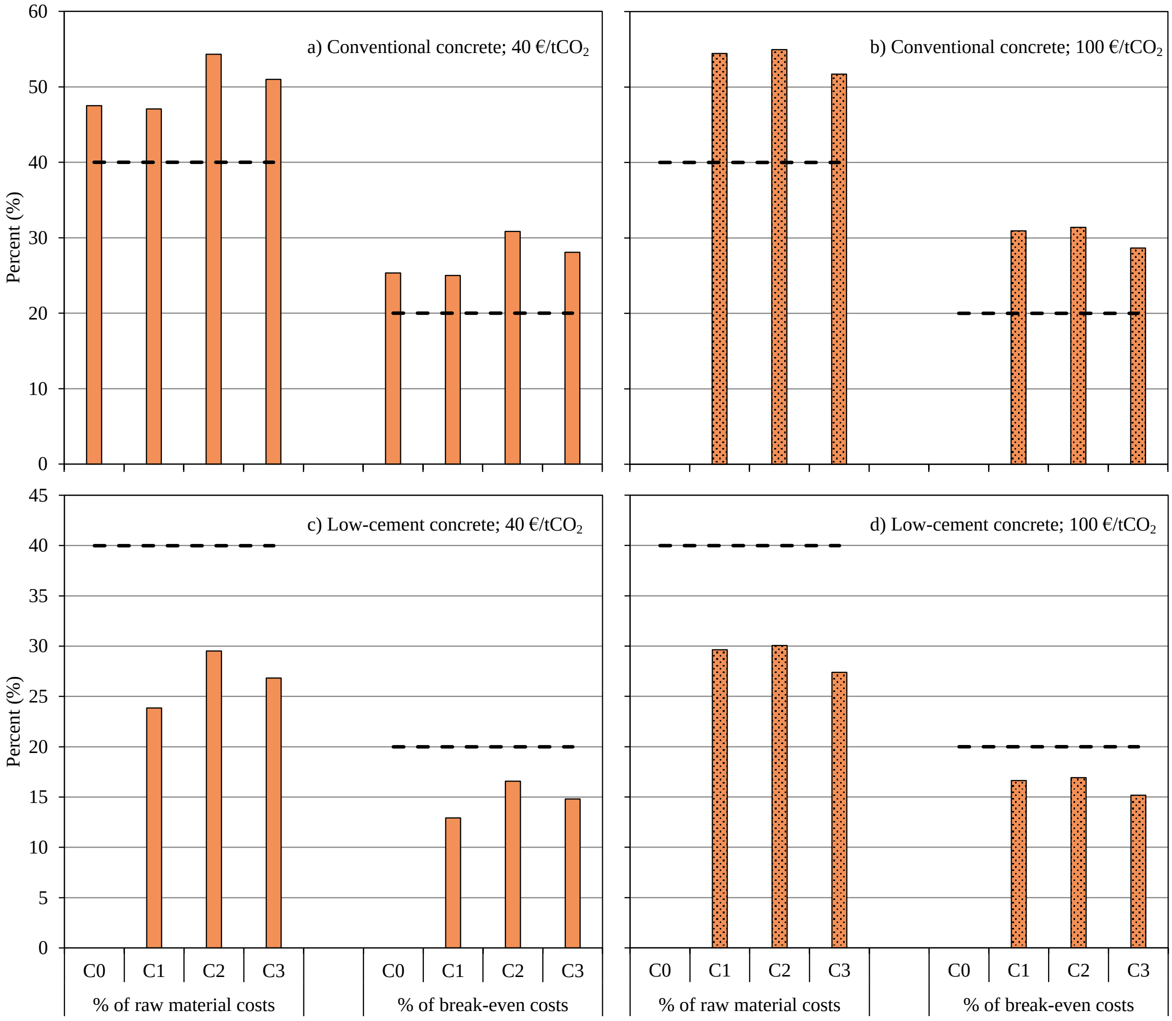

Figure 6. Cement shares of the total concrete production costs and cement shares of the raw material costs depending on: the origin of the cement (kiln systems C0–C3); the price of carbon emitted from the cement production process (40 or 100 €/tCO_2); and the concrete mix design (conventional or low-cement concrete). The black dashed lines correspond to the cement shares of the raw material costs and the total production costs of concrete in the reference case (i.e., with cement produced in C0 and the allowance price set to zero).

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3.3 Construction

Figures 7 and 8 show the impacts on construction costs of increases in the price of cement given the type of concrete used (RMC1 or RMC2), the price of alternative binders used to replace cement in the RMC industry, and the choice of building frame structure in the reference residential building project (concrete or wood). It is clear from these results that while contractors' RMC acquisition costs would increase markedly in the majority of the assessed cases, the cost increase would be minor relative to the overall construction costs, and therefore, the increase in total project costs would be negligible. Since the cost of concrete represent only a small fraction of the total building production costs, the impact on the total construction cost, even in cases where the cement price is assumed to almost double (*cf.* Figure 7d), would be limited to an increase of less than 1%. Given that the cost of alternative binders can be kept low, the cost impact would be further alleviated if the trend towards increased use of alternatives to cement clinker in the RMC manufacturing continues (*cf.* Figure 7, b-c and e-f). The largest cost increase, estimated for the case in which 'conventional' concrete is used (RMC1) with cement produced in a kiln system with post-combustion capture (C2) and with an emission allowance price of 100 €/tCO_2, would be approximately 12600 €, which corresponds to a cost increase of 13.5 € per square meter of residential floor area. Figure 8b reveals that for a wooden building frame structure, wherein concrete accounts for a smaller proportion of the overall cost, the cost impact is further reduced.

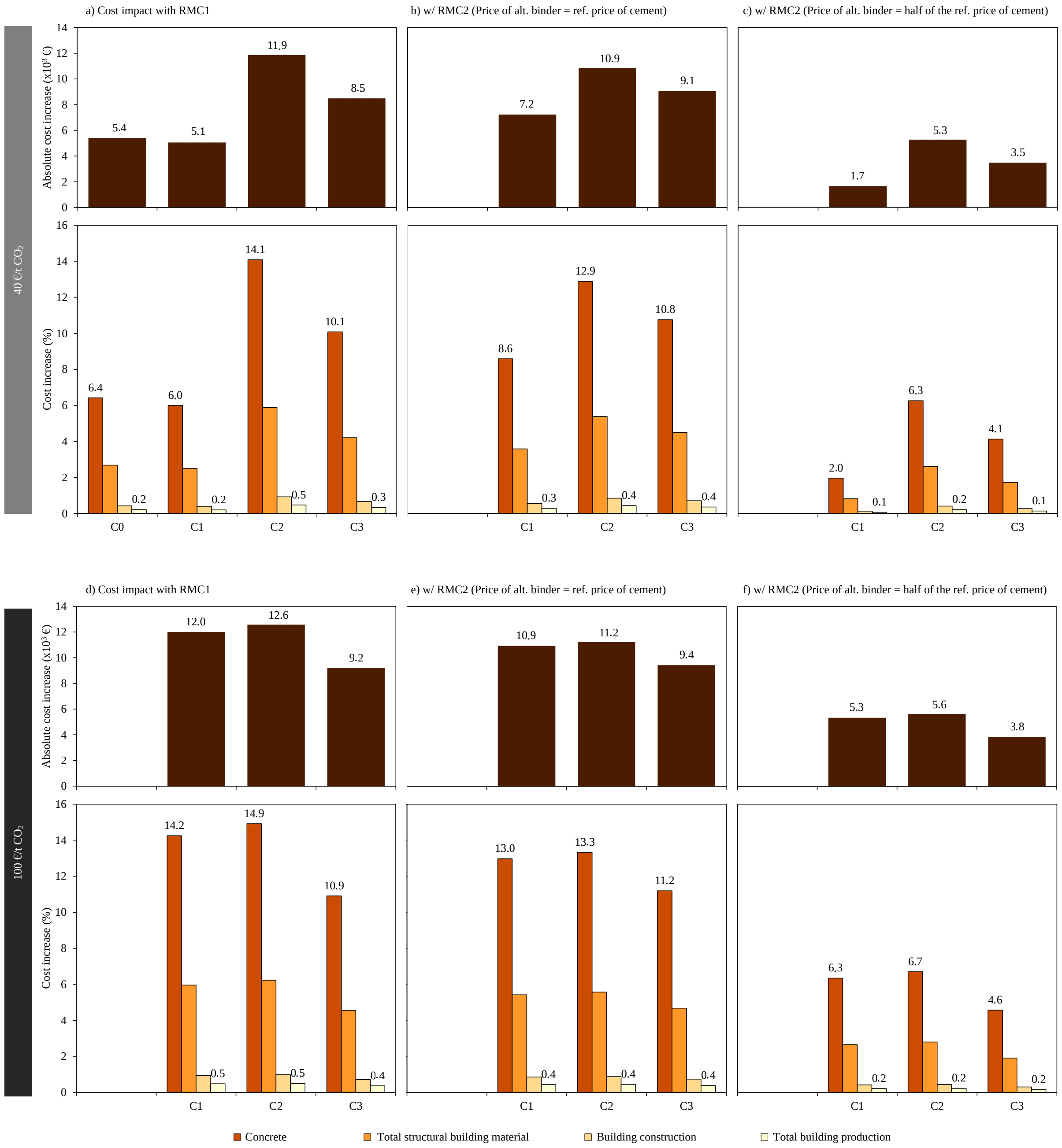

Figure 7. Increases in the costs for material, construction and total production cost of an apartment building with a concrete frame owing to increased cement/concrete prices. The charts (a–f) show the absolute cost increases (above) and the relative cost increases (below). The cement price increase, in turn, is driven by internal abatement costs, i.e., investments in BAT and CCS kiln systems (C1–C3), and the purchasing of emissions allowances at 40 €/tCO_2 (a–c) or 100 €/tCO_2 (d–f) in the cement industry.

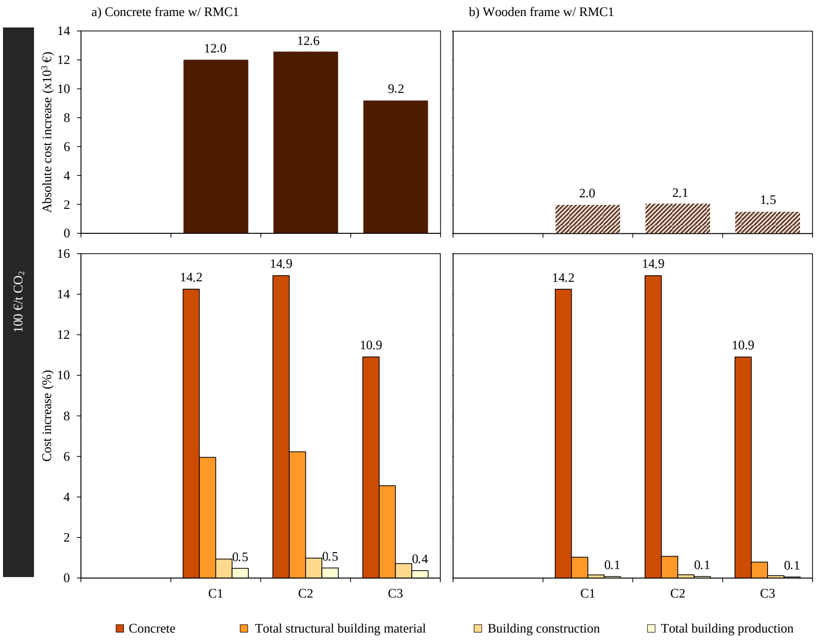

Figure 8. Comparison of the absolute and relative cost impacts on the costs of buildings with concrete or wooden frames, with 'conventional' concrete (RMC1), and with the cement producer paying 100 €/tCO_2 for emissions allowances.

4 Summary and Perspectives

The partial analyses described above show how the cost impact of CO_2 trading and investments in low-carbon kiln systems in the cement industry are significantly reduced throughout the supply chain for cement. Figure 9 gives an overview of the magnitudes of the impacts given full cost pass-through throughout the flow of cement, from the cement plant (1), to use as a binder in the RMC industry (2–3), to eventual use as a constituent of concrete, in the construction of the residential building used as the case study in this work (4–7).

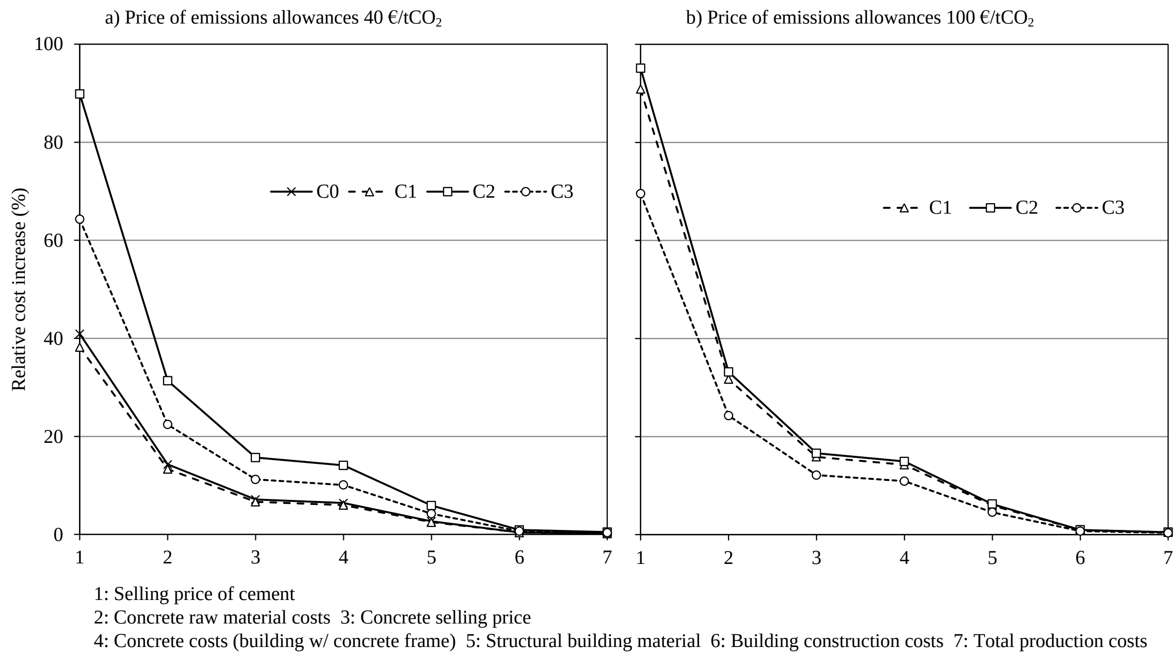

Figure 9. Cost impacts along the supply chain of cement depending on the origin of the cement (kiln systems C0–C3) and the price of emissions allowances for the cement producer (40 or 100 €/tCO_2). The current average production cost (excluding carbon costs) is set as reference (68 €/t cement).

As these estimates are based on a simplified representation of the material and value flows involved and since they apply to only a limited sector of the market, the results may not be directly applicable to other parts of the market for cement and concrete. As shown in Table 13, the costs of concrete and cement as shares of the total building construction costs are in our case in the lower range of the costs for other building and civil engineering projects. However, while every building project is unique and while the conditions in the cement, concrete, and construction industries may vary considerably even within a restricted geographical area, e.g., the Nordic region, our analysis suggests that passing on some or all of the compliance costs of the cement industry would entail only a small increase in the total cost of the final construction project. However, the issue of how such a cost could be passed on to the end of the value chain in a transparent way is not straightforward.

Table 13. Estimates of the costs of cement and concrete as shares of the total construction costs in typical building and civil engineering projects. Comparison based on data from Statistics Sweden and The Swedish Construction Federation (SCF, 2011).

	Reference case[a]	Multi-dwelling houses (*in situ* casting of concrete frame)	Multi-dwelling houses (prefabricated concrete frame)	Single detached house (wood frame)	Industrial building (prefabricated concrete frame)	Industrial building (Steel frame)	Concrete bridge
Share of constructions costs (%)							
- RMC	6.6	7.3	1.9	1.9	5.6	5.6	14.4
- PCE			19.0		14.6		
- PCP		2.6	2.8	1.7	0.1	0.1	
Concrete, total	6.6	9.8	23.7	3.6	20.3	5.7	14.4
Cement[b]	1.2	1.6	2.4	0.5	2.4	1.0	2.7

[a] Concrete and cement costs as shares of the building construction costs for the concrete-frame version of the reference residential building, with the prices for cement and concrete at the reference levels, $P_{RMC,Ref}$ and $P_{RMC,Ref}$, respectively.
[b] Cement cost is assumed to account for 20% of the selling price of RMC and 10% of the selling prices of PCE and PCP.

As already pointed out, since practical experiences remain limited, appraisals of the costs associated with the introduction of CCS for industrial applications remain uncertain. Figure 10 shows the impacts of changes in input variables on the break-even costs for the production of cement and concrete. It is noteworthy that changes in the CO_2 avoidance rate have a significant impact on production costs. The only way to bring certainty to the real costs of the different parts of the CCS chain is to test the different options available for capture, transport, and storage.

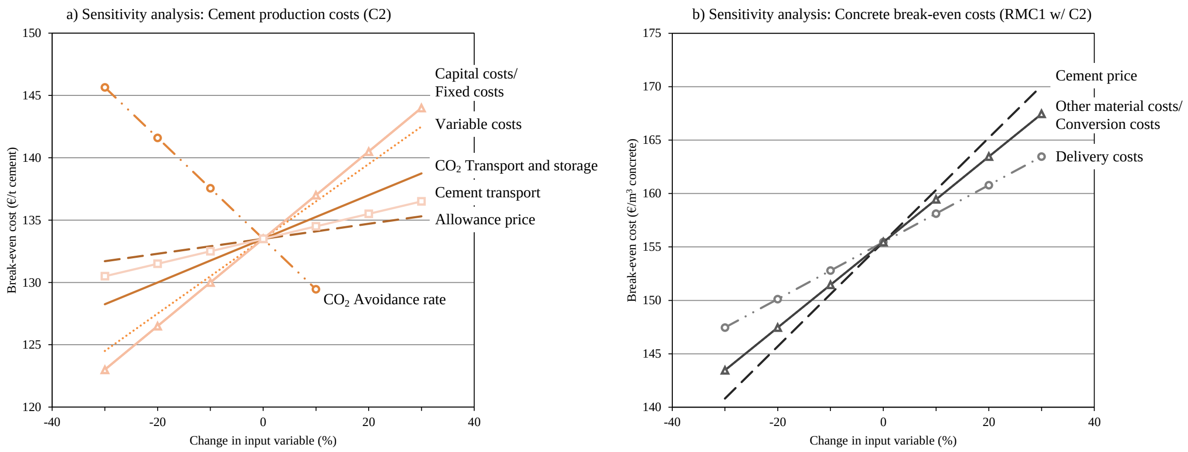

Figure 10. Sensitivity analysis showing the effects of changes in input variables on cement productions costs and concrete manufacturing costs. The basic break-even cost for producing cement is estimated based on an allowance price of 100 €/tCO_2. a) Cement produced in a kiln system with post-combustion capture of CO_2 (C2). b) Manufacturing of 'conventional' ready-mixed concrete.

To ensure a level playing field, any policy measure designed to pass on the compliance costs of the cement industry to its customers would require that a similar measure be applied to competing CO_2-intensive materials (Neuhoff et al, 2014a). To explore how this would affect the cost structure of the reference residential building project, we estimated the amounts of CO_2 embodied in key structural materials in the concrete-frame version of the building (Table 14). Figure 11 shows how the cost for materials and the overall construction cost would be affected if the costs of carbon were to be reflected in the price of the structural building materials. Again, this illustrates that imposing a price tag on the CO_2 embedded in construction materials, even with a high price for CO_2, is likely to have limited effects on the cost structure and overall project costs in the construction industry.

Table 14. Specific emissions from the primary production of building materials originating from industries included in the EU ETS and estimates of the amounts of CO_2 embodied in the materials used in the construction of the reference residential building.

		Direct emissions from primary production[a] (tCO_2/t material)	Concrete frame Embodied CO_2 (tCO_2)
Building materials			
	Structural materials		
-	Cement in Concrete (RMC1) and Mortars	0.7	135
-	Plasterboard	0.131	3
-	Steel[b]	0.714	18
-	Insulation[c]	0.544	5
	Other materials		
-	Glass	0.453	2
-	Plastics (PVC)	0.085	<1
-	Ceramic tiles	0.192	<1
Total			166

[a] Specific emissions from cement production correspond to the average emissions from the Nordic cement industry (*cf.* Table 6). Specific emissions from the manufacturing of all other materials are assumed to be equal to the benchmark value for the respective industry (European Commission, 2011b).
[b] Assuming 50/50 ratio for virgin/recycled steel.
[c] Assuming 50/50 ratio for fibreglass/mineral wool.

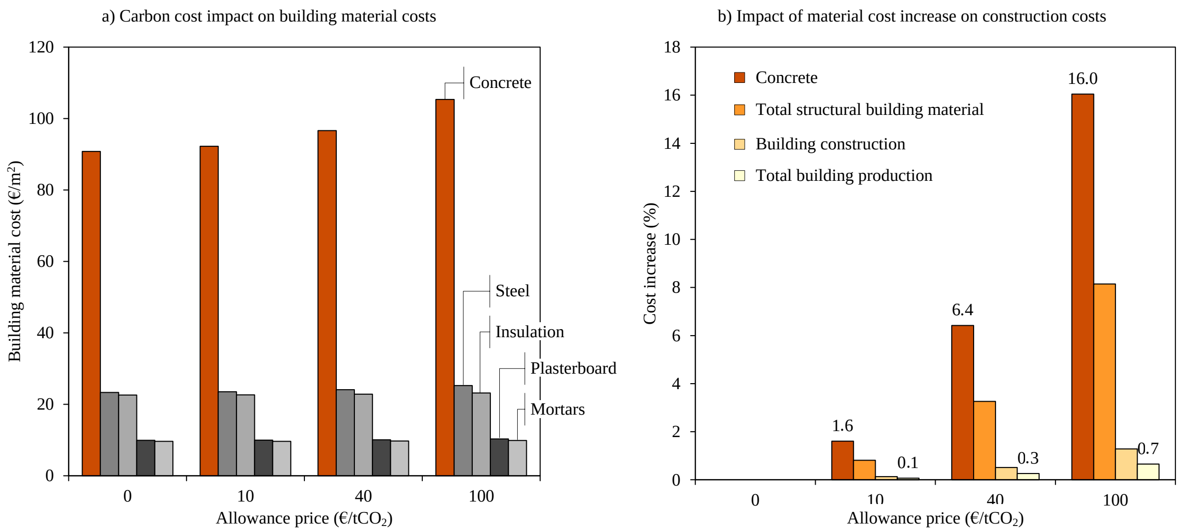

Figure 11. Carbon cost impacts on the costs for selected structural building material and on the overall costs for construction and production. a) Impacts on the costs of selected structural building materials of pricing levels of CO_2 emissions (0–100 €/tCO_2) originating from the primary production of the respective material. b) Impacts on the costs for materials and construction and on the total production cost of the reference building project with a concrete frame attributed to increased prices for materials.

The current average costs for production and construction have served as reference values when assessing the relative increases in costs associated with investing and operating new low-carbon kiln systems and with buying emissions allowances in the cement industry. To complete the picture, we add a complementary perspective on the values at stake in the respective parts of supply chain for cement. We do so by comparing the cost increases with the Gross Value Added (GVA) in the respective sector, as suggested by Sato et al. (2013) and Neuhoff (2008). Figure 12 presents the values at stake in the Swedish cement, RMC, and construction industries given different assumptions with respect to the choice of kiln system and the pricing of emissions allowances in the primary production of cement. Again, while the potential value at stake is high in the cement industry and significant in the RMC industry, even at moderate CO_2 price levels, the cost increases relative to GVA in the construction industry are calculated as <1% in the cases without CCS (C0 and C1) and <2% in the cases with CCS (C2 and C3).

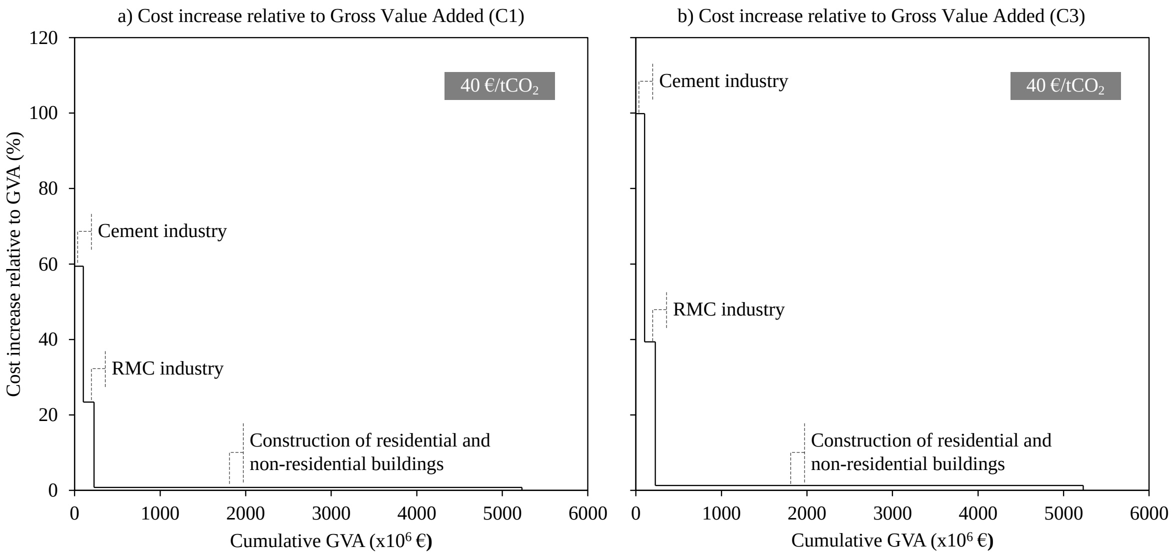

Figure 12. Cost increase relative to Gross Value Added (GVA) along the value chain of cement. Current average production costs (excluding carbon costs) are set as reference (68 €/t cement and 133 €/m^3 concrete). The data used were (source): annual cement production (HeidelbergCement, 2014); RMC production data (ERMCO, 2014); investments in construction (BI, 2011); and GVA (SCB, 2015). a) Impact of introducing a new BAT kiln system (C1) including carbon costs and emissions allowance price of 40 €/tCO_2. b) Cost increase if introducing kiln system with oxy-combustion and CO_2 capture (C3).

5 Conclusions and Policy implications

Returning to the original set of questions that drove the present research, we find that:

As expected, the cost impact on the primary product (in this case, cement) of introducing high-abatement, high-cost measures such as CCS will be substantial and far higher than any near-term projection of allowance prices under the EU ETS. Thus, the price range expected for emissions allowances under the EU ETS for the period up to Year 2030 (European Commission, 2014a) will not suffice to drive the development of the technologies and infrastructures required.

In contrast to previous studies that focused primarily on the cost impact of CO_2 pricing on the primary production and primary product, we examine how cost increases in the cement industry affect costs throughout the cement supply chain. After all, cement is an intermediate product and as such, is of little use on its own. Our estimates of the magnitude of the cost increases that may occur at various stages of the supply chain of cement reveal that the impact of carbon pricing on cement diminishes substantially for each transformation stage, from pyroprocessing of limestone to the final end-uses.

While our analysis relies on a rather stylised representation of the material and value flows involved, it is clear that since cement and concrete typically account for a limited proportion of the total cost of most construction and civil engineering projects, a policy scheme designed to allocate more of the costs of CO_2 abatement to the end-users (of cement) would neither (significantly) alter the cost structure nor (dramatically) increase overall project costs.

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Based on the present study and in the context of weak carbon pricing under the EU ETS, a policy scheme that would 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. We believe that the suggestion put forward by Neuhoff et al. (2014a; 2014b) to include the consumption of cement and other CO_2-intensive commodities in the EU ETS and to use raised revenues to fund climate actions warrants serious consideration in the context of policymaking. Bennett and Heidung (2014) have discussed how the roles of legislators will change as technological advances are made, and they argue that public involvement in the early phases is crucial to securing the necessary technological progress in a timely manner. If designed as non-discriminatory instruments, procurement requirements that guarantee an outlet for low-carbon concrete, as well as taxes that target resource- and carbon-intensive materials hold significant promise (Bahn-Walkowiak et al., 2012; Eckerman at al., 2012; Wilting and Hanemaaijer, 2014). In the longer run, it is conceivable that the ability to offer low-carbon concrete structures will become a competitive advantage, which in itself would justify the slightly higher construction costs.

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