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Deployment of carbon capture and storage in the cement industry – Is the European Union up to shape?

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A B S T R A C T

The implementation of Carbon Capture and Storage (CCS) technologies in the cement industry is crucial for achieving near-zero emissions. However, CCS remains capital-intensive, with high operational costs, and faces significant market, investment, and infrastructure coordination barriers. Its deployment also depends on national and regional regulatory frameworks, given the need for CO_2 capture, transport, and storage. This study assesses the European Union's (EU) readiness to implement CCS in the cement sector. Results indicate that the EU-27 cement industry could transition to near-zero emissions within a timeline aligned with EU climate targets, assuming: (i) the EU Emissions Trading System (ETS) price rises in line with projections under the Fit for 55 package, and (ii) sufficient CO_2 storage capacity is made available. The findings underscore the need for complementary policy measures and CCS-specific regulatory frameworks to facilitate deployment. Although early and rapid implementation of CCS could deliver substantial climate benefits, it also poses challenges, including shortages of contractors, expertise, and materials. Moreover, historical investment patterns suggest that the required scale and pace of deployment would be unprecedented. While the EU has laid a strong foundation for the cement industry's transition, CCS deployment potential differs among Member States, depending on the geographic distribution of cement plants and proximity to storage sites. National regulatory variations further complicate deployment. These factors must be addressed to enable a successful shift to near-zero emissions practices in the EU cement industry.

1. Introduction

Emissions associated with industrial processes account for approximately one-third of total global CO_2 emissions (Bashmakov et al., 2022). Yet, despite the urgent need for mitigation, there are currently no full-scale, fully built and operational plants producing iron and steel, cement or chemicals with near-zero emissions anywhere in the world (Bataille et al., 2024). The European Union (EU) has ambitions to reduce territorial greenhouse gas (GHG) emissions to net-zero by Year 2050. The EU *Fit for 55* initiative mandates a reduction of at least 55% in net GHG emissions by Year 2030, as compared with the Year 1990 levels, and aspires climate-neutrality by Year 2050 (European Commission, 2023a). The EU's Emissions Trading System (EU ETS) is the most-important policy instrument to ensure emissions reductions within the region, and it covers around 40% of the EU's total emissions (European Commission, n.d.-b). The recently announced revisions of the EU ETS (The European Parliament and the Council of the European Union, 2023) will increase the pressure on the actors covered by the EU ETS to adapt and decrease their emissions accordingly. Plant operators regulated under the EU ETS have the options to purchase emissions allowances from the market or to abate their emissions. In theory, when the cost of abatement is lower than the price of emissions allowances, firms will opt for emissions reduction strategies. While the details of the legislation have yet to be settled, the communication on the revised EU ETS in the Fit for 55 framework suggests that the free allocation of emissions allowances will reach zero in Year 2034, the downward cap trajectory will be increased, the cap on emissions will be zero in Year 2039, and the Carbon Border Adjustment Mechanism (CBAM) will be phased in, replacing the free allowances, in order to reduce the risk of carbon leakage (European Council, n.d.).

In this work, we focus on the transition of the EU cement industry, which alone accounts for 4% of territorial GHG emissions in the EU

Abbreviations: CCS, Carbon Capture and Storage; CCU, Carbon Capture and Utilisation; CCUS, Carbon Capture Utilisation and Storage.

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(Marmier, 2023). The cement industry is often considered to be a sector for which it is difficult to reduce carbon emissions, given that about two-thirds of its Scope 1 GHG emissions are inherent to the cement-making process (process-related emissions from the calcination of clinker). Various mitigation options are available for decarbonising the cement industry and its related value chains, including: energy efficiency measures; clinker substitution; fuel switching; and Carbon Capture and Storage (CCS) (Favier et al., 2018; Habert et al., 2020; Miller et al., 2018). The first three mitigation measures are more incremental and can only lead to a certain level of emissions reductions, while the latter (CCS) can yield emissions reductions of up to 98% (Brandl et al., 2021). To ensure the transition to a near-zero or net-zero cement industry, a broad portfolio of mitigation options is needed. However, CCS is crucial to ensure strong mitigation of CO_2 emissions within the industry (IPCC, 2023), since CCS can substantially reduce the process emissions. As CCS is already at a high Technology Readiness Level (TRL), we have focused on the large-scale implementation of CCS in the EU cement industry.

CCS implementation in the cement industry has largely been studied from a techno-economic perspective at plant level (see e.g., Zhang et al. (2024) and references therein). The grey and white literature includes analyses of the implementation of various mitigation options, achieved by assessing their current and projected TRLs and technical feasibility over time (CEMBUREAU, 2020; Material Economics, 2019; Scrivener K., Habert G., De Wolf C., 2019). However, CCS deployment faces challenges beyond the purely technical ones, including: regulatory aspects (i.e., future carbon pricing, technology-specific regulation, and adjacent legislation, such as permitting); investment barriers (i.e., difficulties linked to acquiring financing for capital-intensive technologies); and infrastructure and coordination barriers (i.e., deployment of support infrastructure, namely transportation and storage of CO_2) (Barbhuiya et al., 2024; Chiappinelli et al., 2021; Löfgren & Rootzén, 2021; Watari et al., 2023). Various studies have addressed the uncertainties related to future carbon pricing and their effects and implications for the economic feasibility of CCS (see e.g., Jakobsen et al. (2022)). However, the effects of national and technology-specific regulations are not well-understood. Several studies (see for example Bataille et al., 2024; Chiappinelli et al., 2021; Draghi, 2024; Polzin, 2017) have highlighted the insufficient funding mechanisms and the importance of a combination of governmental funding mechanisms and supporting private initiatives to close the gap in the financial demands for the transition and make funding available, since governmental funding mechanisms are limited and in many cases intended for First-of-a-Kind and Flagship projects rather than large-scale implementation, with the result that few projects will be granted these funds. Many studies have assumed that there will be adequate build-out of the supporting infrastructure for transporting and storing CO_2. However, Watari et al. (2023) have highlighted the uncertainties linked to that assumption and the related risk of not reaching climate targets in the event of failure of such a deployment.

To the best of our knowledge, no previous study has explored the combined effects of all the above-mentioned barriers on CCS implementation in the cement industry. This paper explores the challenges associated with the EU cement industry transition to near-zero GHG emissions within the timeframe required by EU climate targets. We examine the implications of the above-mentioned barriers on CCS deployment over time in the EU cement industry through bottom-up modelling, whereby we assess the plant-level costs for CCS implementation, the development with respect to the legislative context across EU Member States, and the availability of and prospects for supporting infrastructure. This study underscores the location-specific challenges that individual cement plants are expected to face.

2. Methodology

In this work, we perform a multi-criteria assessment of decarbonisation pathways for the EU-27 cement industry. The work is based in part on a bottom-up techno-economic assessment of the cost of CCS implementation. The cost of CCS for each individual plant is evaluated in relation to the projected cost of emitting CO_2, given the assumed increase in emissions allowance (EUA) prices. This assessment is used to assess CCS deployment in the EU-27 cement industry over time. We explore how the transition is affected by the national policy landscape across EU Member States and the availability of supporting infrastructure. Section 2.1 describes the bottom-up techno-economic cost assessment through the construction of Marginal Abatement Cost (MAC) curves. Section 2.2 outlines the methodology used to explore the policy context outside of the cement plant boundaries, considering factors that can serve as barriers or enablers to the transition. Section 2.3 describes the method used to estimate historical investments in the EU cement industry. This assessment is then used to evaluate how well-positioned the cement industry is for the transition in different EU Member States, considering the current geopolitical landscape under various scenarios, as described in Section 2.4.

2.1. Marginal abatement cost curves

The abatement cost is calculated for each individual cement plant and includes the following cost components: 1) capital and operational expenditures related to the capture, conditioning and liquefaction of CO_2; 2) inland and off-shore transportation from the cement plant to the storage location; 3) storage of CO_2; and 4) EUA allowance price for unabated emissions. Each of these parameters will be explained in further detail below. The abatement cost is dependent upon when in time the cement plant invests in CCS; some cost components, such as the cost of storing CO_2, may become cheaper by postponing the investment decisions, while other cost components, such as paying for EUA allowances as the price increases over time, will become more expensive. Using the abatement costs for the individual cement plants, we construct a MAC curve[1] that is dependent upon the year in which CCS is implemented.

2.1.1. Capturing CO_2

The first part of the CCS chain is the capture of CO_2 at the cement plant. In this work, we have modelled the cost for CO_2 capture based on the methodology presented in previous studies (Garðarsdóttir et al., 2018; Johnsson et al., 2020). The costs represent the Nth-of-a-kind (NOAK) and are based on post-combustion, amine-based (MEA) absorption, assuming a 90% capture rate. The capital expenditures are based on bottom-up techno-economic cost estimations using the hourly flow rate of CO_2, and we assume in this work that all cement plants have a flue gas CO_2 concentration of 20% (Garðarsdóttir et al., 2018). The CAPEX is annualised assuming an economic lifetime of 25 years and a discount rate of 7.5%. The fixed operational expenditures (OPEX) include the annual maintenance (assumed to be 5% of the CAPEX cost) and labour costs (820 k€/year independent of CC unit size (Johnsson et al., 2020)). The variable OPEX consists of: steam for the capture process, assuming a cost of 20 €/t of steam; electricity for the CO_2 compressors and solvent pumps, assuming an electricity price of 60 €/MWh; cooling water at a cost of 0.02 €/m^3; and MEA make-up cost of 2,000 €/m^3. The cost functions from Garðarsdóttir et al., (2018) have in this work been updated from cost-year 2015 to 2023 using the Chemical Engineering Plant Cost Index.

2.1.2. Inland transportation of CO_2

Depending on the location of the cement plant and the available

[1] The MAC curve in this work differs from a MAC curve in the strict sense, which is ordered according to increasing marginal abatement cost. This is because we order the first plants in the cost curve with respect to either the year that they have announced for them to be in operation or the deployment year according to the model results.

infrastructure, different modes can be used to transport the CO_2 from the plant to the harbour. The cost for transporting CO_2 is based on the work of Oeuvray et al. (2024). In the present work, we have allowed for the following inland transportation modes: truck, rail, and barge, all loading containers with CO_2. While using continuous transportation (such as pipelines) could be more economical than discontinuous (container--based) transport at high volumes over long distances, this is not considered in the present work. This since the related cost is complex and highly dependent on the configuration of the pipeline network, and this transportation mode is not cost-competitive in the near and medium term as pointed out by Oeuvray et al. (2024). As the containers are assumed to have a relatively small capacity (up to 50 tonne), the unitary cost (UC) is influenced only by the distance covered and not by the mass flow transported. The *UC* for each transportation mode is, therefore, determined according to the methodology presented by Oeuvray et al., and is expressed as:

$$\mathrm{UC}\left[\frac{€}{\mathrm{t\ km}}\right] = \alpha_1\left[\frac{€}{\mathrm{t\ km}}\right] + \frac{\alpha_2[€\ \mathrm{t}^{-1}]}{\mathrm{d}\ [\mathrm{km}]} \tag{1}$$

where α_1 and α_2 are fitting parameters for each transportation mode according to Table 1, and *d* is the distance covered.

The distance covered from the cement plant to the port is determined using a shortest path analysis to the closest harbour. In this work, the cost of transporting CO_2 is not optimised so as to minimise transportation costs or emissions. However, ship transport is often cheaper than inland transportation. By transporting the CO_2 to the closest harbour rather than to the harbour that entails the shortest total distance (i.e., from plant to storage location), the transportation costs should be lower. Moreover, no additional costs for changing transportation modes during the distance travelled are included in this work, although a maximum of three mode switches is allowed. In cases where the shortest distance could be covered by two different transportation modes on the same stretch, the cheaper transportation option is chosen. The shortest path is modelled using OpenStreetMap data (Geofabrik, n.d.).

2.1.3. Shipping of CO_2

The CO_2 is transported by ship from the harbour to the closest storage location with available capacity. The ships are assumed to have a capacity of 20 ktCO_2, and we assume a fuel consumption of 1.3 t/hour of Heavy Fuel Oil (HFO) and a speed of 26 km/hour. We assume a shipping cost of 0.021 €/t/km in fixed operational costs and annualised capital expenditures. The variable operational expenditures consist of the fuel costs with an assumed HFO price of 270 €/t (Danish Energy Agency, 2021).

2.1.4. Storage of CO_2

As of the time of writing, there are only a few CO_2 storage providers operating in Europe, primarily located in Norway, although numerous additional projects have been announced. The currently announced CO_2 storage capacity will reach approximately 145 MtCO_2 annually in Year 2050 (IOGP, 2023). Table 2 provides an overview of the EU Member States that have currently announced plans to provide CO_2 storage. Early estimates have assessed the costs for CO_2 storage at around 10 €/t (Zero Emissions Platform, 2010). However, to date, storage offers received by actors have been far higher than the above-mentioned costs. Based on some figures from industry, we assume that it costs 60 €/t to store CO_2 in Year 2020, which is in line with the estimates used by Oeuvray et al. (2024) and Beiron & Johnsson (2024). However, we assume that the cost of storage decreases linearly over time to 10 €/tCO_2 in Year 2050.

Table 1
Fitting parameters for the inland transportation modes. Source: Oeuvray et al. (2024).

Transportation mode	α_1	α_2
Container-based truck	0.15	5.58
Container-based train	0.07	28.9
Container-based barge	0.04	33.5

2.1.5. Emissions from transportation and electricity use

The EU ETS database only includes Scope 1 emissions for industrial installations, thus the emissions associated with electricity use are added separately to the decarbonisation pathways investigated in this study. Similarly, emissions associated with land and waterway transportation of CO_2 from the cement plant to the storage location are added.

To estimate the emissions linked to electricity use, we assume an electricity consumption level of 113 kWh/t of cement produced including the CCS unit (IEA Bioenergy, 2021). We determine the emissions related to electricity use for each plant based on the country's electricity mix for Year 2020 (Electricity Maps, n.d.). With regards to future emissions, we assume emissions factors for Year 2030 according to each country's "clean" energy target (Ember, n.d.), and we assume that all of the countries will have no remaining emissions from their electricity production in Year 2050.

The emissions for transporting CO_2 from the cement plant to the storage location are added by making assumptions in relation to the energy consumption level, type of fuel, and related emissions factor for each transportation mode, including transport by truck, train, barge, and ship (see Appendix B).

2.2. Policy context

As previously mentioned, the industrial transition and CCS implementation are heavily dependent upon regulatory factors, which we refer to as the *policy context*. The regulatory aspects include cross-sectoral regulations, i.e., the EU ETS and national CCS-specific policies, and financing strategies. In the following sections, we discuss in greater detail these aspects and their significance for CCS implementation in the EU cement industry.

2.2.1. National CCS policies, strategies and financing

All EU Member States have adopted the CCS Directive, which aims to "ensure that there is no significant risk of CO_2 leakage or damage to health or the environment and to prevent any adverse effects on the security of the transport network or storage sites" (European Commission, 2023b). The European Commission analyses the progress of Member States in implementing the CCS Directive. The application of CCS policies and strategies for CCS implementation varies among the countries. The European Commission analyses the following categories: cross-border co-operation for CO_2 transport; national operational programmes or plans in place to support research, demonstration and deployment of CCS; measures in place to support financially the development for deployment of CCS; and further plans to support the appraisal of CO_2 storage sites, to prepare for the CO_2 transport infrastructure or for the establishment of CO_2 hubs and clusters. Depending on the levels of deployment of these various CCS policies, Member States will differ in their abilities to invest in and implement CCS in their industries. For example, for a landlocked country, cross-border cooperation for CO_2 transport is a necessity for implementing CCS if no national on-shore storage sites are available. Table 2 provides an overview of those countries that have implemented (or plan to implement) the above-mentioned categories of CCS policies and strategies (European Commission, 2023b). Clearly, if the cement plants are planning for CCU rather than CCS then fewer policies for the transportation of CO_2 may be needed, since such transportation will be limited. However, the climate benefit linked to the utilisation of CO_2 depends on the feedstock (i.e., biogenic or fossil), as well as the extent to which the product is re-circulated if at all. Obviously, absolute emissions reductions are crucial to meet climate targets (IPCC, 2023).

As shown in Table 2, only seven EU Member States (and Norway) have implemented three or more of the four CCS policies/strategies.

Table 2
Overview of implementation of general CCS policies and strategies, announced cement CCUS projects, and CO_2 storage locations in the EU Member States plus Norway. Shown are the countries that have implemented or planned (of the four policies/strategies): >2 (green); ≤2 (yellow); and 0 (red).

Country	Announced cement CCUS projects	Cross-border co-operation for CO_2 transport	National operational programmes or plans in place to support research, demonstration and deployment of CCS	Measures/programmes in place to support financially the development or deployment of CCS	Further plans to support the appraisal of CO_2 storage sites, to prepare for CO_2 transport infrastructure or for the establishment of CO_2 hubs and clusters	National CO_2 storage capacity[a]
Austria	1 CCU					No
Belgium	2 CCUS	Yes	Yes	Yes		No
Bulgaria	1 CCS, 1 CCUS					Yes
Czechia					Yes	No
Croatia	1 CCS	Yes				Yes
Denmark	1 CCS	Yes	Yes	Yes	Yes	Yes
Finland			Yes			No
France	2 CCS, 1 CCUS	Yes	Yes	Yes	Yes	Yes
Germany	2 CCUS, 2 CCS, 1 CCU	Yes	Yes	Yes	Yes	No
Greece	2 CCS			Planning	Yes	Yes
Hungary		Yes			Yes	No
Ireland						Yes
Italy						Yes
Latvia		Yes				No
Lithuania		Yes	Yes		Yes	No
Luxembourg						No
Netherlands		Yes	Yes	Yes	Yes	Yes
Norway	1 CCS	Yes	Yes	Yes		Yes
Poland	1 CCS	Yes			Yes	Yes
Portugal			Yes			No
Romania			Yes			Yes
Slovakia						No
Slovenia			Yes	Yes		No
Spain	1 CCUS	Yes	Yes			No
Sweden	1 CCS	Yes	Yes	Planning	Yes	No

[a]This refers to announced CO_2 storage capacity. Several countries have potential for storing CO_2 but have no current plans to do so.

Meanwhile, six EU Member States have implemented none of these policies/strategies. Table 2 also shows the planned CCUS (i.e., CCS and CCU) projects for cement plants in the EU-27 and Norway. One can imagine that the announced CCUS projects will be located in countries where some of these policies/strategies are implemented; from Table 2, it is evident that 19 out of 21 CCUS projects are located in such countries. However, of the other three projects, one is located in Austria and is a CCU project with utilisation at an adjacent plastics plant, and the other two projects (one CCS and one CCUS) are located in Bulgaria, which indeed has some national on-shore CO_2 storage location that is planned to be used by the CCS project.

2.2.2. EUA price

The EUA price will heavily influence the production cost of cement as the prices increase and the free allocation of emissions allowances is phased out. In this work, we include a 'high' and a 'low' EUA price estimate (see Fig. 1), to explore how these affect CCS implementation in the cement industry. The 'high' EUA price curve is based on projections gathered by Beiron & Johnsson (2024), in which the EUA price is 80 €/tCO_2 in Year 2024 and increases exponentially by 9% each year. This results in an allowance price of 150 €/tCO_2 in Year 2030 and 400 €/tCO_2 in the 2040s, which is comparable to other published estimates of future CO_2 prices (see e.g. Enerdata, 2023; GMK Center, 2023; Simon, 2023). The 'low' EUA price trajectory follows the same curvature as the 'high' EUA price trajectory, albeit at a slower exponential increase rate of 3%. This slower growth leads to a price of approximately 100€/tCO_2 in the 2030s and 200€/tCO_2 by 2050. These CO_2 price trajectories illustrate a broad range of possible outcomes and are used to explore how political uncertainties could influence the pace and direction of the transition.

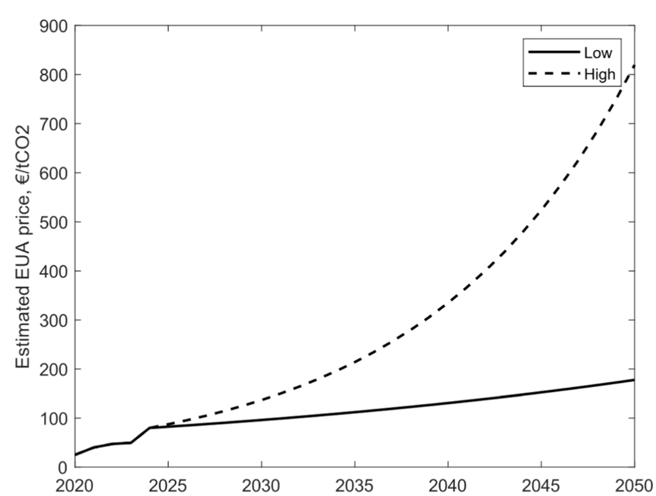

Fig. 1. EUA price curves used in this work. The prices shown for Year 2020 to Year 2023 reflect the average market prices (Statista, n.d.).

2.3. Historical and future investments

We have used historical investment levels as a reference point when estimating the magnitude of future investment needs in the cement industry, providing context for assessing the financial requirements of a low-carbon transition. To assess historical investments in the EU cement industry, we construct a timeline of estimated investments based on plant-level data. The analysis relies on the Chalmers Industry Database (Rootzén & Johnsson, 2015) which includes, among other things, individual cement plants, their installed clinker capacity, and their operating starting year. For some plants, the starting year is unknown; therefore, while they are accounted for separately, they are not included in the year-by-year investment timeline. While investment costs have varied over time, a rough estimate of historical investments is obtained by assuming a fixed overnight investment cost of 240 € per tonne of clinker capacity adjusted to cost year 2023 using CEPCI (Obrist et al., 2021) for all plants, independent of their starting year. The total historical investment costs for each year are then calculated by multiplying the installed capacity of plants operating in that year by the assumed investment cost per tonne clinker capacity, as:

$$I_t = OC_i \cdot PC_{i,t} \tag{2}$$

where *I* refer to the yearly historical investment in year *t, OC* refers to the overnight investment cost per unit of clinker production capacity (i.e. here assumed to 240 € per tonne of clinker capacity), and *PC* is the annual production clinker capacity installed for each year. To validate the overall scale of historical investments, we compare the estimated order of magnitude of historical cement production and emissions with data from Andrew (2024) although the database may not capture all plants that were built and decommissioned during the 20th century. Similarly to the historical investment estimate, future investments in CCS are calculated using a fixed overnight investment cost of 512 € per tonne CO_2 captured (cost year 2023), based on the average of estimates reported in literature (Anantharaman et al., 2016; Gerbelová et al., 2017; IEAGHG, 2013; Liang & Li, 2012).

2.4. Scenario analysis

Table 3 presents a schematic overview of the parameters that define the scenarios used in this work to explore the transition in the EU cement industry. The scenarios are varied based on the following parameters: First-of-a-kind (FOAK) vs Nth-of-a-kind (NOAK) costs comparing 100% and 200% contingency costs related to NOAK costs; different CO_2 price curve projections (Fig. 1); time penalty for when very few or no CCS-specific policies and strategies exist in the form of time delays in CCS implementation, hereinafter referred to as *Default year implementation*; and a scenario in which Member States that do not have the potential to store captured CO_2 nationally and that are landlocked will in one way or another be dependent upon other Member States to transport and store their CO_2. In the *National storage or bilateral agreement* scenario, Member States will not be allowed to transport and store CO_2 if:

1) they do not have announced plans for national storage capacity;
2) they are landlocked and thus dependent upon other Member States to transport and store their CO_2; and
3) they do not have any bilateral agreements for the transportation of CO_2 (see Table 2).

The modelling of CCS implementation in the cement industries of the EU-27 countries will be described in further detail in the following sections.

2.4.1. Pathways for decarbonisation

In this work, we utilise the abatement cost for each individual cement plant to decide on when investing in CCS is economically beneficial compared to purchasing emissions allowances under the EU ETS (*cf.* Fig. 1). By comparing the cement production costs with and without CCS, we identify when in time it is beneficial for each plant to invest in CCS or to pay for the emissions allowances, according to Eq. (3):

$$C_{Ref} \geq C_{CCS} \tag{3}$$

where C_{Ref} is the production cost of cement without CCS, including a reference cement production cost of 51.5 €/t of cement (IEAGHG, 2013) and additional costs for purchasing emissions allowances dependent on

Table 3
Schematic overview of the parameters that define the scenarios investigated in this work, with each row representing a scenario.

Scenario name	FOAK vs NOAK	CO_2 price	Sufficient CCS policies	CO2 storage
1. Ambitious mitigation	**NOAK** / 100% / 200%	low / **high**	no / **yes**	**Anywhere** / National or bilateral agreement
2. Contingency 100%	NOAK / **100%** / 200%	low / **high**	no / **yes**	**Anywhere** / National or bilateral agreement
3. Contingency 200%	NOAK / 100% / **200%**	low / **high**	no / **yes**	**Anywhere** / National or bilateral agreement
4. Low CO_2 price	**NOAK** / 100% / 200%	**low** / high	no / **yes**	**Anywhere** / National or bilateral agreement
5. Default year implementation	**NOAK** / 100% / 200%	low / **high**	**no** / yes	**Anywhere** / National or bilateral agreement
6. National storage only or bilateral agreements	**NOAK** / 100% / 200%	low / **high**	no / **yes**	Anywhere / **National or bilateral agreement**
7. Combined	**NOAK** / 100% / 200%	**low** / high	**no** / yes	**Anywhere** / National or bilateral agreement

the year-specific EUA price and the levels of free allocations of emissions allowances. The term C_{CCS} refers to the production cost of cement with CCS and includes, in addition to the reference cement production cost, the capital and operational expenditures of the carbon capture unit, the inland and off-shore transportation and storage of CO_2, and the purchasing of emissions allowances for unabated emissions that are not covered by the free allocation, as expressed by Eq. (4):

$$C_{CCS} = CAPEX_s + OPEX_s^{var} + OPEX_s^{fix} + C_{transport} + C_{storage} + C_{allowances} \quad (4)$$

The cost for emissions allowances is based on an assumed CO_2 price profile and an estimation of the free allocation of emissions allowances to each individual cement plant. Real data on emissions and retrieved free emissions allowances have been collected to update the Chalmers Industry Database (Rootzén & Johnsson, 2015). The already allocated free emissions allowances for the period of 2020–2022 are accounted for in the European Union Transaction Log (EUTL) (European Commission, n.d.-a), in addition to the projected free allowances up until Year 2025. For Years 2024 and 2025, the projected emissions allowances for each installation and the projections of the corresponding emissions for each plant are made using a constant emissions factor for that plant based on previous years. In this work, we have assumed that there will be a constant demand for cement. Obviously, the future cement demand is unknown and there are projections of stabilization, increases (Marmier, 2023) and decreases in demand (Material Economics, 2019; Scrivener K., Habert G., De Wolf C., 2019) in the EU-27 countries. Therefore, we chose to assume a constant demand, as making a reliable projection is not possible.

From Year 2025 onwards, the free allocation of emissions allowances is planned to be phased out according to the European Commission's *Fit for 55* initiative (European Union, n.d.). The phase-out rate is used in this work to estimate the future free allocation of emissions allowances until the phase-out process is completed in Year 2034 (European Union, n.d.). The total cap on emissions allowances will be phased out by Year 2039 (as compared with Year 2050 before the *Fit for 55* reformation), and since the ETS is a market-based instrument that includes many different industries, the price of allowances will depend on the supply of allowances on the market (regulated by the EU) and on the demand for allowances from the industries. Since the present work focuses exclusively on the cement industry, we have used the estimations given in Fig. 1, i.e., both a high and a low EUA price estimate. With the current set-up of the EU ETS, it should not be possible to purchase emissions allowances after the complete phasing out of the cap on allowances in the system, i.e., after Year 2040. However, in this work, this has been modelled as a rapidly increasing EUA price after Year 2040 (for the high EUA price profile). Even if all the cement plants were to invest in CCS there would still be residual emissions, as it is not currently possible to capture 100% of all emissions. Currently, the EU ETS does not allow for any compensatory measures through carbon removal (CDR) or similar that could act to mitigate this issue.

2.4.2. Treatment of plants with announced CCUS investment decisions

To date, 21 CCUS projects have been announced at cement plants in 12 different EU-27 Member States and Norway (see Table 2). These plans are included when constructing the decarbonisation pathways in this work. These cement plants will not base their investment decisions on when CCS becomes economically beneficial (as is the case for the other cement plants modelled in this work); instead, they will invest as already planned. For the CCUS projects that have yet to specify their deployment time-lines, it has been assumed that these plants will be operational by the Year 2030. Some of the planned projects distinguish between whether they are planning to implement CCS or CCU, whereas others do not specify and are referred to as 'CCUS' in Table 2. It is important to note that long-term reductions in emissions can only be achieved through storing the CO_2, while the climate benefit of utilising the CO_2 depends on the feedstock used and whether or not the product is recirculated. However, in this work, we assume that CCU projects also provide emissions reductions, even though the specific usage of the CO_2 is unknown.

2.4.3. FOAK vs NOAK costs

Nth-of-a-kind (NOAK) cost estimates are commonly used in techno-economic studies of carbon capture technologies because estimations of First-of-a-kind (FOAK) cost data are limited (Gerbelová et al., 2017; van der Spek et al., 2019). Many high-cost investments become more expensive than first projected (Flyvbjerg, 2014; Kumar et al., n.d.; Spek et al., 2017). Thus, it is important to examine not only NOAK costs but also FOAK costs, to avoid creating misconceptions about the expected cost performance of CCS. In this work, we assume that FOAK projects can be 100% or even 200% more expensive than NOAK projects, based on examples from Beiron & Johnsson (2024). For many technologies, cost reductions are expected as learning occurs from the first to subsequent projects. This has been clearly demonstrated in the case of granular technologies such as solar photovoltaics. In contrast, carbon capture is often characterized as a lumpy technology – one that involves large, indivisible capital investments rather than incremental or modular deployment. Lumpy technologies tend to offer more limited opportunities for experiential learning, resulting in slower learning rates (Choi & Jae, 2023). Additionally, learning rate assumptions for CCS remain highly uncertain, as cost reductions are often influenced more by site-specific constraints, project-specific customisation, and national contexts that limit knowledge transfer across projects (Lohwasser & Madlener, 2013; Roshan Kumar, 2024). In our scenarios, we do not account for cost reductions due to learning between projects. Instead, the FOAK cost premiums of 100% or 200% are applied as fixed mark-ups over NOAK costs and are assumed to remain constant over time (referred to as 100% contingency respectively 200% contingency) in the scenario analysis.

2.4.4. Identifying challenged regions for CCS implementation

Based on the decarbonisation pathways, we identify regions in which cement plants may encounter greater challenges in relation to implementing CCS, involving factors such as infrastructure, regulatory environment, and techno-economic conditions. Regions are defined according to the Nomenclature of Territorial Units for Statics (NUTS) geocode standard. To estimate when CCS is implemented in each NUTS region, we calculate a weighted average (based on emissions) per region, which allows us to determine the average regional timing of CCS adoption.

3. Results

Figure 2 shows the MAC curve for CCS implementation for each cement plant for the Ambitious mitigation scenario (Fig. 2a) and the Low CO_2 price scenario (Fig. 2b), using the NOAK costs, as defined in Eq. (4). The plants are ordered by the year of CCS implementation, as indicated by the vertical lines, either as determined by the model or as announced. Within each year, plants are further ordered by increasing cost. As shown in Fig. 2, the capture cost is higher the smaller the emissions source. The figure shows that the entire carbon capture and storage chain must be considered when evaluating the profitability of projects, since the inland transportation cost can be a significant expense. Some plants are located at ports, which means that they will have an insignificant inland transportation cost, so they will have a lower full-chain cost and earlier CCS implementation. The inland transportation cost could, for some plants, be reduced below the values shown in this work if, for example, pipelines and clustering were to be used, since pipelines are more cost-competitive compared with other transportation options at high emissions volumes over long distances.

The already announced projects (the bars in faded colour in Fig. 2) are in almost all cases early movers, and if they are realised according to plan it will mean that investments are made before they are actually

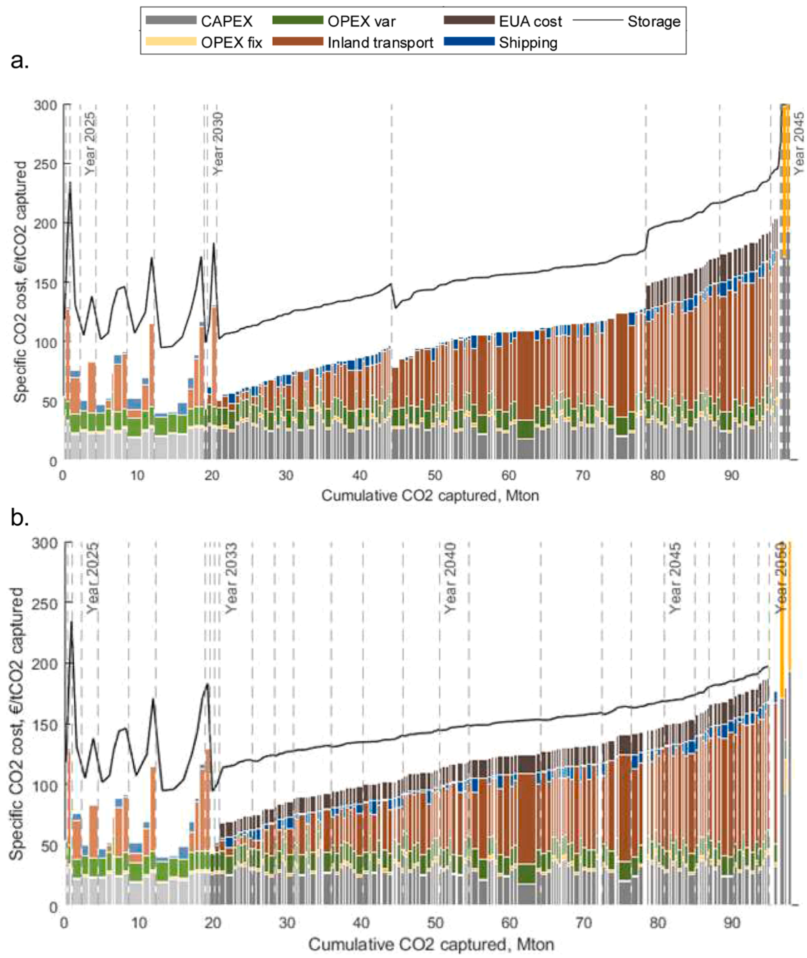

Fig. 2. Marginal Abatement Costs based on Nth-of-a-kind CCS cost for each cement plant in the EU for the a) Ambitious mitigation scenario, and b) Low CO_2-price scenario, calculated according to Eq. (4). Thus, the units are in order according to increased costs except for the plants which have announced a target year for CCS implementation which are then arranged in the order of announced implementation (from left to right). For plants that are implementing CCS during the same year, the bars are arranged according to increasing cost, including costs for capture, conditioning, transport, storage, and costs for purchasing emissions allowances for remaining emissions. The inland transportation corresponds to Eq. (1). The width of each bar describes the magnitude of each plant's emissions, and the faded colours indicate the already announced plants.

profitable based on the EU ETS prices assumed in this work (Fig. 1). Fig. 2 also shows that the projects announced as early movers are not necessarily the projects with the lowest costs when looking at either capture costs on their own or full-chain costs including transportation and storage. Nevertheless, it is worth noting that 9 out of 21 announced projects have received EU Innovation Fund support – ranging from 12–27 €/tCO_2 captured over a 10-year period – which helps to partially alleviate the cost burden faced by these early movers.

In addition, Fig. 2a shows that in the Ambitious mitigation scenario, most plants do not have an EUA cost in their CCS deployment year, as they receive free allowances covering their remaining emissions after CCS deployment. However, by Year 2033, 97% of these free allowances have been phased out. As a result, the remaining emissions – 10% of total plant emissions after CCS deployment – are no longer fully covered, and plants begin paying for this portion (shown in brown). This CO_2 cost thus reflects the cost of emitting this remaining share at the time of CCS deployment, which is generally lower than in later years due to the upward CO_2 price trajectory. Thus, the modelling gives that the laggard plants postpone implementing CCS until a point at which the carbon price signal is much stronger, i.e., when the free allocation has decreased and the CO_2 price is higher than the costs of CCS deployment. Thus, the free allocation does not cover their remaining 10% of emissions, so they need to purchase EUAs (see the abatement costs for the right-most part of the graph in Fig. 2). It should be noted that the modelling assumes

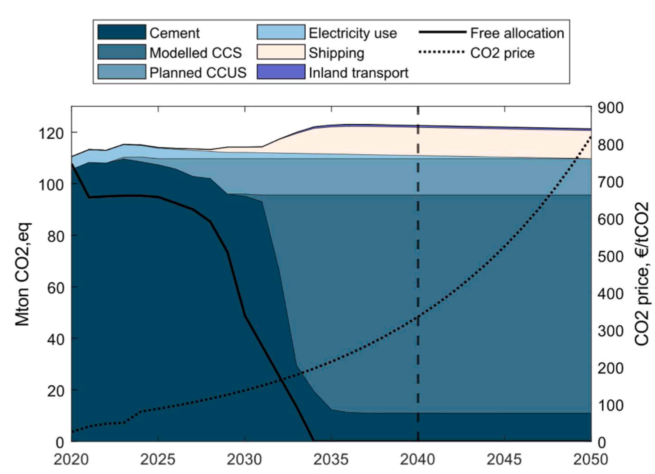

Fig. 3. Transition pathway for the EU cement industry. The vertical line indicates the year when the total cap on emissions will be zero in the EU ETS, according to current policies (EU *Fitfor55 package*).

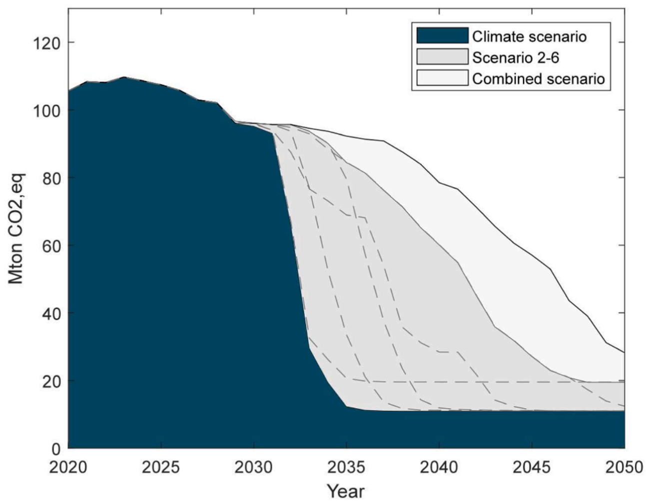

Fig. 4. Remaining emissions over time for the Ambitious mitigation scenario (blue), the range for the 100% contingency, 200% contingency, Low CO_2 price, Default year implementation, and National storage only or bilateral agreements scenarios (medium grey), and for the combined scenario of Low CO_2 price and Default year implementation (light grey).

that all actors are required to pay eventually for emissions allowances to cover the remaining 10% of their emissions due to the phasing out of free allocations of emissions allowances. However, this requirement does not apply at the time of CCS implementation, as illustrated in Fig. 2a. In the Low CO_2 price scenario, as shown in Fig. 2b, the plants deploy CCS later in time, when almost all also pay for their remaining 10% of emissions.

Figure 3 shows the decarbonisation of the EU cement industry over time as obtained from the modelling, for the Ambitious mitigation scenario, as the price of emissions allowances rises. As in Fig. 2, the already announced CCUS projects are shown separately, since their implementation is not simulated but their implementation year is fixed as per the announcement. The emissions and free allocation of emissions allowances are for the period of 2020–2023 based on real data from the EU ETS database (European Commission, n.d.-a). For Years 2024 and 2025, the figure is based on projected emissions allowances for each installation. Fig. 3 shows that all industries implement carbon capture technologies and phase out their emissions by Year 2035. This is a consequence of the phasing out of the free allocations of emissions allowances, which strengthens the CO_2 price signal for cement producers while the CO_2 price increases rapidly. This modelling results obviously reflect a very rapid phase-out rate, which may pose significant practical challenges as well as challenges to raise the necessary capital for the investments required.

Figure 4 shows the range of decarbonisation pathways obtained from the modelling for the Ambitious mitigation scenario (blue), scenarios two to six (grey), and the Combined scenario (light grey). The industry's ability to invest in carbon capture is delayed by 3 and 5 years in the Contingency scenarios, and 15 years in the Low CO_2 Price scenario compared to the Ambitious mitigation scenario. The latter scenario achieves near-zero emissions only in the early 2050s, representing a significant delay in the transition. This delay occurs because purchasing emissions allowances remains less costly over a longer period than investing in CCS in these scenarios. This highlights the critical role of high EUA price levels in the EU ETS in providing a strong enough carbon price signal to producers, ensuring rapid CCS implementation. While the Low CO_2 Price scenario achieves emissions reductions comparable to the Ambitious mitigation scenario by 2050, it does not fully reach the same level. Moreover, the cement industry only reduces its emissions by 57% in 2040, despite the EU ETS no longer permitting emissions beyond that year. Similarly, the Default Year Implementation scenario reaches near-zero emissions levels in mid-2040's which underlines the importance of strong policies and bi-lateral agreements for inland countries to

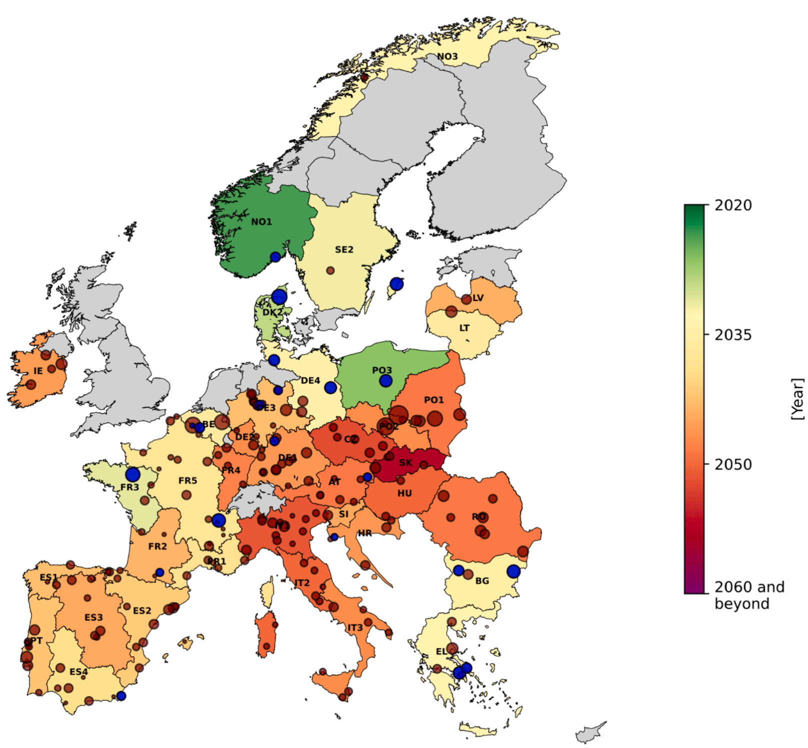

Fig. 5. Map showing when in time the cement plants implement CCS in the Combined scenario. The blue and red circles indicate the locations of the cement plants, with their sizes being proportional to their reported emissions in Year 2022. The location of the announced CCUS projects is indicated in blue, and the modelled CCS projects are indicated in red. Countries and regions not included in the analysis, either due to not having any cement plants or not being in the EU, are marked in grey.

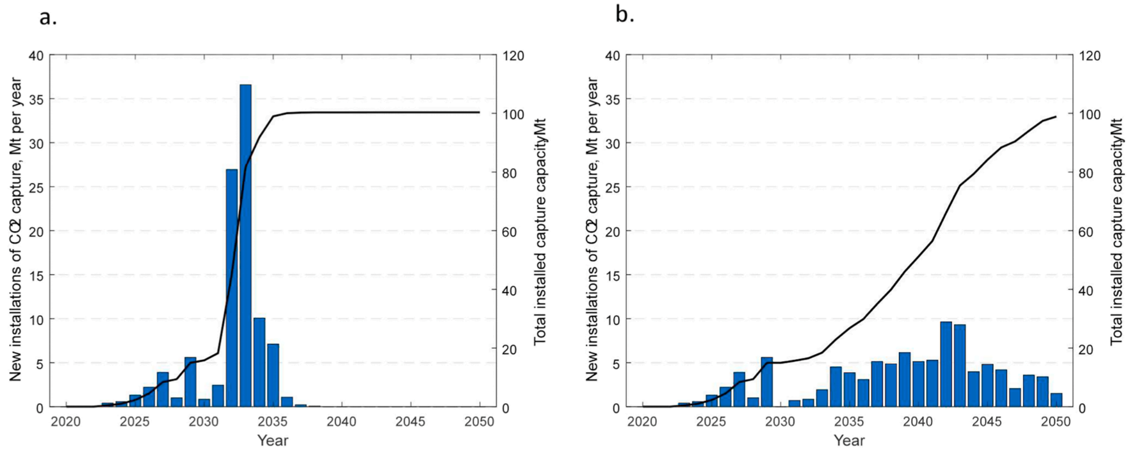

Fig. 6. Deployment of CCS capacity sorted by year. a) Ambitious mitigation scenario; b) the Low CO_2 price scenario.

transport and store CO_2.

However, in the National Storage Only and Combined scenarios, near-zero emissions are not achieved even by 2050, falling far short of the reductions required to meet climate targets. In the National Storage Only and Bilateral Agreement scenarios, the industry never reaches its full decarbonisation potential – defined in this work as a 90% reduction in Scope 1 emissions – but instead achieves only an 80% reduction. This shortfall occurs because not all projects can store CO_2, as cross-border transport is restricted due to the lack of bilateral agreements and the absence of national CO_2 storage sites. Additionally, transporting CO_2 to storage locations generates further emissions, underscoring the need for the shipping sector to decarbonise in parallel to ensure a sufficiently robust reduction in overall CO_2 emissions. For more detailed results for the respective scenarios please refer to Appendix C.

Figure 5 shows a map of when in time the cement plants, on average, in each region will implement CCS in the Combined scenario. This outcome reflects a combination of the following factors: inland transportation (i.e., the distance and available infrastructure, which dictate the transportation mode); off-shore shipping to the storage location; national policy implementation; and the phase-out of free allocations within the EU ETS. These results identify the regions that could face an earlier or later transition based on this multi-criteria analysis. The colour coding corresponds to a weighted average for the year in which CCS implementation occurs for each region. For instance, in the case of region FR5, which encompasses a large area, there is a broad span in the actual year of CCS implementation around the average value shown in the map.

Figure 6 shows the deployed capacity per year for the Ambitious mitigation scenario (Fig. 6a) and the Low CO_2 price scenario (Fig. 6b), which are the scenarios with the fastest and second slowest deployment rates for CCS investments, respectively. Fig. 6a shows that around 100 Mt of CCS capacity are installed in only 4 years, whereas Fig. 6b shows that in the Low CO_2 price scenario less than 10 Mt of CCS capacity (apart from Year 2041) is installed annually. The key question, however, is whether these CCS deployment rates are at all feasible. To assess this, we examine historical investment patterns in the EU cement industry.

Figure 7 shows the estimated historical investments in the EU cement industry from Year 1850 to 2020, and the corresponding future investments in CCS from Year 2020 to 2050, as projected in the modelling. The future CCS investments for the Ambitious mitigation scenario are shown in light blue, those for the Low CO_2 Price scenario in yellow, and areas where the two overlap are shown in green. The results show that the yearly future investments for CCS for the Ambitious mitigation scenario far exceeds the historical investments into the industry. However, while the yearly investments in the Low CO_2 price scenario also exceed historical levels, they remain within a similar range. Historically made investments would in this case make up 67B€, over 170 years, while the future investments needed in CCS would add up to almost all historical investments made of 52B€, but across 15 and 25 Years respectively for the Ambitious mitigation and Low CO_2 price scenario. On the other hand, the GDP of EU countries have tripled from 5 858B€ in Year 1975 to 16 193B€ in Year 2022, suggesting that a lot more funds are available today, where the EU cement transition would require only 0.32% of the EU GDP in Year 2022, compared to 0.89% in Year 1975.

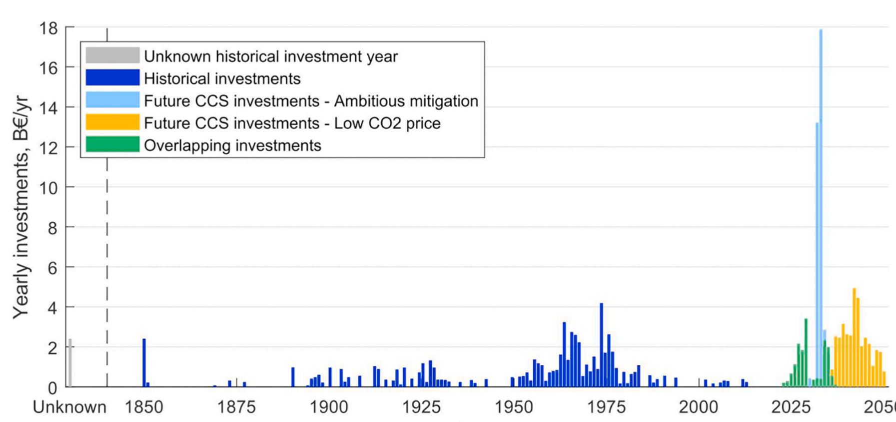

Fig. 7. Historical investments made in the EU cement industry compared with future CCS investments according to the modelling for the Ambitious mitigation and Low CO_2 price scenarios. All costs are expressed in €2023. The 'unknown' bar to the left shows investments made in cement plants with unknown investment year.

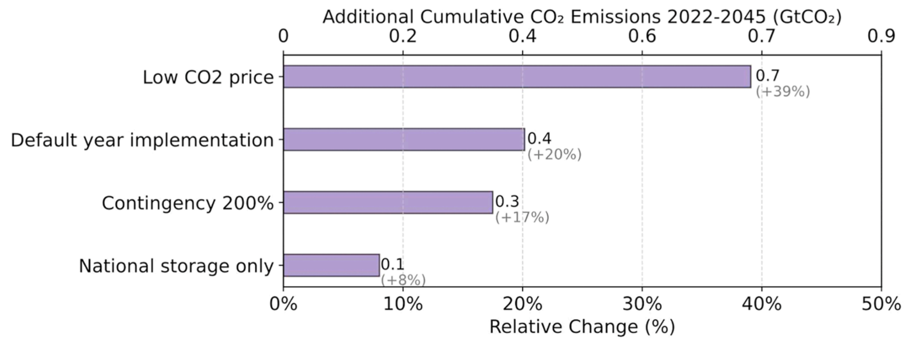

Fig. 8. Estimated additional cumulative CO_2 emissions for the period 2022–2045 relative to the Ambitious mitigation scenario (which results in 1.8 Gt of cumulative CO_2 emissions over the period), when varying the CO_2 price, default year of CCS implementation, contingency, and CO_2 storage availability, respectively.

Yet, there may still be challenges to raise the required capital in the cement sector and there may also be other barriers such as related to skills supply for carrying out the projects.

Although the Low CO_2 price scenario reflects investment levels more consistent with historical investment trends, the delayed transition it entails results in significantly higher cumulative emissions up until Year 2050 compared to the Ambitious mitigation scenario. The Ambitious mitigation scenario would save 1045 million tonnes of cumulative CO_2 emissions compared to the Combined scenario up until Year 2050, while the Low CO_2 price scenario would only save 317 million tonnes of CO_2 emissions compared to the Combined scenario and reach near-zero emissions around 21 years later than the Ambitious mitigation scenario. Fig. 8 illustrates the sensitivity of the cumulative CO_2 emissions to key input parameters – namely CO_2 price trajectories, timing of policy implementation, capture costs, and national storage availability – relative to the Ambitious mitigation scenario. Among the parameters tested, the CO_2 price shows the strongest influence: in the Low CO_2 price scenario, cumulative emissions are 39% higher than in the Ambitious mitigation scenario. Delaying policy implementation in the Default year implementation scenario increases emissions by 20%, while a tripling of capture costs raises emissions by 17%. These results underscore how both economic and policy choices can significantly delay or reduce the climate benefits of CCS.

Figure 9 shows the already announced plans of storage providers concerning CO_2 storage capacity over time in the EU-27 countries, as well as the available storage capacity remaining after cement plants have stored their captured CO_2 as modelled in this work. The total announced storage capacity available in Year 2050 is 141 $MtCO_2$ per year. It should be noted that this does not necessarily represent capacity but rather an estimated potential, since the capacity cannot be known until the drilling and operation of the well are established. For simplicity, we will continue to refer to this as *capacity*. As shown, the total storage capacity increases rapidly between Year 2025 and Year 2030, primarily due to the aspirations of storage providers to start with smaller capacities and expand them over time. For some storage providers, the announced planned capacity may increase by as much as 15-fold from one year to the next, raising questions about the likelihood that such expansions can be realised. Fig. 9 shows that all cement plants that would want to store CO_2 each year are capable of doing so, in that sufficient storage capacity is planned for the cement industry to complete the transition according to the simulation performed in this work, if no competition with other sectors is included.

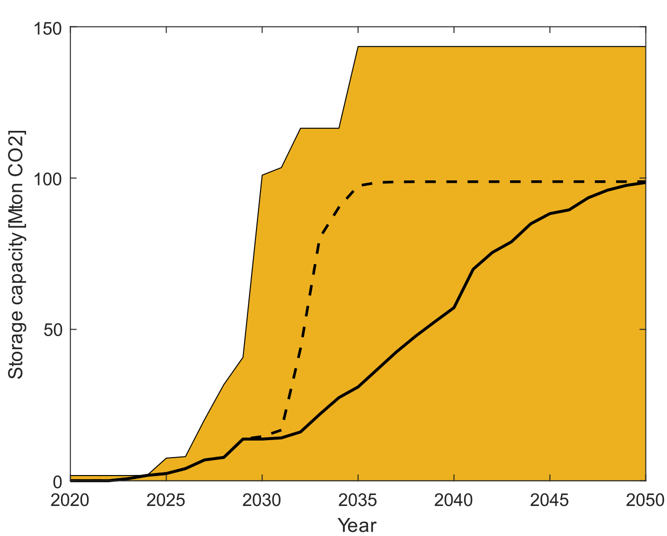

Fig. 9. Storage capacity (yellow), and used storage capacity required by the cement plants for the Ambitious mitigation scenario (dashed line), and for the Low CO_2 price scenario (solid line).

4. Discussion

The Ambitious mitigation scenario in this study reveals that, if the EUA prices increase rapidly and storage providers fulfil their commitments as announced, the EU cement industry has the potential to achieve near-zero GHG emissions within a timeframe that aligns with EU climate targets. However, as this work shows, there are numerous potential barriers to this transition. This work demonstrates the importance of increasing EUA prices, implementing strategic CCS policy measures (especially for countries with plants located inland without national storage possibilities), and making known the real CCS cost to succeed with large-scale CCS implementation. As expected, the findings suggest that cement plants that are situated in proximity to ports or in areas with a well-developed transport infrastructure for cost-effective inland CO_2 transportation are more likely to transition to CCS technologies at an earlier stage than those in less-advantageous locations. Conversely, the results indicate that even if regions meet these requirements, the transition to CCS may be delayed in the absence of proactive, CCS-specific regulatory measures. This emphasises the importance of also implementing other supply-side mitigation measures that face fewer challenges with respect to implementation, as well as demand-side strategies for reducing cement consumption, so as to ensure a timely transition.

It is often believed that the largest emitters are those that would realise CCS first, since these plants often have the lowest specific capture costs due to economy of scale. However, this is not necessarily the case, as shown in this work. First, the costs for the entire CCS chain must be taken into account, i.e., from capture to storage, since the transportation costs can represent a significant share of the total CCS-chain cost. Second, all plants receive the same level of free allocations, i.e., 0.693 allowances per tonne of clinker in the third phase of the EU ETS according to the benchmark value for grey clinker. Since different plants have different energy efficiencies and, thus, emit different amounts of CO_2 per tonne of cement produced, they will pay different amounts for allowances per tonne of cement produced. Thus, the plants will have different incentives regarding when to implement CCS, i.e., the more-inefficient plants will have greater incentives to implement CCS earlier, since their cement production costs without CCS will increase more rapidly due to increasing EUA prices. This inefficiency principle in relation to the ETS results in the "dips" in the MAC curve shown in Figure 2. Third, the finding that some plants have announced that they will be early movers shows that companies may react to and invest in decarbonisation options for reasons other than simply costs. If they adhere to their time plans, these announced CCS projects will implement CCS before being economically incentivised by the EU ETS. However, any unused freely allocated emissions allowances could be sold on the market, generating a profit and covering some of the loss caused by the increased costs linked to the CCS investment.

In this work, we assume that CCS can be deployed as soon as the modelling finds it to be cost-effective (less costly than emitting). However, in reality, the planning for CCS must start several years prior to the actual investment and construction of the unit. The planning stage, locating a storage site, and securing the necessary permits can take many years to complete. Thus, the stages at which the planning and permitting processes are for the announced early mover projects, as well as the future average planning and permitting times, are not known. Thus, while the stages of planning and permitting for early mover projects remain uncertain, and the average duration of these processes in future projects is also unknown, the slower CCS uptake observed in the Low CO_2 price scenario may implicitly reflect delays associated with planning and permitting.

In addition, the present study shows that for rapidly increasing CO_2 prices, the EU cement industry must transition at a rapid pace in order to avoid paying high EUA prices, as for example in the Ambitious mitigation scenario where approximately 100 Mt of CCS capacity is installed in under 4 years. However, the feasibility of deploying such a large CCS capacity within a short period remains uncertain, as it depends on the availability of expertise, contractors, materials, and components. In contrast, the Low CO_2 Price scenario features a more gradual and consistent deployment, occurring at levels that seem more attainable. This perspective is reinforced when comparing the required future CCS investments with historical investments in the cement industry, where the Ambitious mitigation scenario's projected investments far exceed past levels. It is important to note, however, that the historical investment data used in this work are not exhaustive, as reinvestments are not included. While investment feasibility is a key consideration, it is also crucial to assess these deployment trajectories in the context of climate policy. The EU Fit for 55 initiative sets climate targets for achieving net-zero GHG emissions by a specific year but does not define a strict carbon budget. This means that compliance with the initiative does not necessarily align with Paris Agreement-compatible carbon budgets, as the total emissions will depend on the timing of decarbonization efforts. A delayed phase-out, such as in the Low CO_2 Price scenario, ultimately results in a greater cumulative use of the remaining carbon budget.

It is important to note that the mitigation measures included in this work only bring the industry to near-zero emissions, rather than achieving zero emissions. We have assumed a capture rate of 90%, which implies that even if all the cement plants apply carbon capture technologies, 10% of the total emissions from the industry will remain. This fact must be aligned with the aim and design of the EU ETS, since the cap on emissions will eventually reach zero and what will happen thereafter with residual emissions is unknown. Simultaneously, higher capture rates are driven by the impending cap on emissions, set to reach zero by Year 2040 under the EU ETS, as well as by the high EUA prices, which incentivise investments in higher capture rates in order to avoid the cost of purchasing emissions allowances. While higher capture rates are technically feasible (such as 95%–98%), it is unclear under what conditions such measures would be economically feasible, given that these higher rates would substantially increase the cost of capture. Thus, if higher capture rates were implemented the emissions from the cement industry could be brought closer to zero. Residual emissions (i.e., emissions that are deemed to be unavoidable or too expensive to abate) must be addressed in the EU ETS as the cap reaches near zero-levels, by for example, allowing for CDR with highly durable storage (see for example, Fridahl et al., 2023; Rickels et al., 2022; Zetterberg et al., 2021).

As previously mentioned, CCS is only one of several options for mitigating emissions in the cement industry. While CCS is currently the main option to mitigate the emissions from cement production, fuel switching from fossil to renewable and alternative fuels are also an important aspect of the transition of the transition of the energy related part of the emissions. Additionally, when considering the full value chain – including the use of cement in the construction sector – the role of CCS must be assessed in relation to other mitigation strategies. Multiple studies have shown that achieving near-zero emissions in the construction sector requires a combination of CCS, material efficiency, material substitution, energy efficiency measures, and electricity sector decarbonisation (Habert et al., 2020; Karlsson et al., 2021; Scrivener K., Habert G., De Wolf C., 2019). In addition, concrete carbonation can offset a small share of production-related CO_2 emissions over time – 6% over 64 years in the case of a concrete building as suggested by Van Roijen et al. (2024) – but this long timescale is misaligned with the EU's 2050 climate targets, where near-term reductions are needed. Furthermore, the absence of established IPCC guidelines for reporting carbonation complicates its inclusion in national emissions inventories. Therefore, the assumed effect of carbonation is considered outside the scope of this work.

As previously mentioned, the European Commission has proposed in the Net-Zero Industry Act that the EU should develop at least 50 Mt of CO_2 storage capacity by Year 2030, increasing to around 280 Mt by Year 2040 (European Commission, 2024). Although the target for Year 2030 seems reachable with the announcements made to date, the currently announced storage projects account for only about 50% of the target for Year 2040. The total storage capacity will reach approximately 145 $MtCO_2$ annually in Year 2050 (IOGP, 2023), i.e., less than Year 2040 target. Thus, additional projects must be proposed and developed if the target is to be reached. It is important to note that even though storage providers have announced the development of some capacity this is more of a potential capacity rather than actual capacity. The actual capacity of a well can only be estimated and cannot be fully determined before the operation of the well, due to many uncertainties (Xiao et al., 2024). Therefore, it is currently unclear as to how much storage capacity will be provided within the EU-27. In addition, there are still many uncertainties regarding the storage of CO_2. In addition to those already mentioned above, there are the effects of impurities in the CO_2 and whether the industry can meet those conditions set by the storage providers. The European Commission also explicitly states that this capacity should be developed within the EU, which excludes much of the potential capacity in the North Sea owned by the United Kingdom.

Our results show that the cement industry alone will require around 70% of the announced storage capacity in the EU from Year 2040 onwards. The cement industry is one of the industries that has a high demand for CO_2 storage capacity, as CCS is the main option for deep decarbonisation of CO_2 emissions. However, there will be other industries competing for this storage capacity, and the question is whether the planned capacity is sufficient or if strong competition will mean that only the actors with the highest willingness to pay will be able to store CO_2. Cement is a relatively low-cost product, which implies that investing in CCS will have a relatively strong impact on the production cost, e.g., 100%–200% for cement compared to, for example, 40%–60% for steel production (Hörbe Emanuelsson et al., 2025; Witecka et al., 2024). This implies that other industries producing high-priced products might be more willing to pay for the available storage capacity in case of competition, since the costs for CCS will be more diluted for those products and, thereby, will have a lower relative price impact for consumers. Yet, since the cost of cement (in concrete) in the building and construction sector is a small part of the final product (e.g., a building), the additional cost of CCS cement will have a low impact on the final end-product (for example, Hörbe Emanuelsson & Johnsson, 2023; Rootzén & Johnsson, 2017). It should also be noted that there are projects on electrifying the cement production (e.g., using plasma burners) which, if successful, would eliminate the energy-based emissions while the need for CCS would be limited to the process emissions (see e.g., Quevedo Parra & Romano (2023)).

5. Conclusions

Carbon Capture and Storage (CCS) is a crucial mitigation measure for deep decarbonisation of the cement industry owing to the high levels of emissions inherent to the process. The implementation of CCS faces several challenges, and the large-scale deployment of CCS technologies is highly dependent upon the build-out of supporting infrastructure, i.e., CO_2 transport and storage, and CCS-specific regulatory measures. This work shows that the cement industry in the EU-27 countries could transition to near-zero emissions on a time-line that is compatible with EU climate targets, under the assumptions that: (i) the EUA price will increase in line with estimates from the evaluation of the *Fit for 55* initiative; and (ii) CO_2 storage providers ensure the necessary capacity. However, this work also illustrates the importance of having a CCS technology-specific regulatory framework, such as for the transportation of CO_2, to enable the transition. We also highlight that the cement industry alone will require a substantial fraction (around 70%) of the already announced CO_2 storage capacity in the EU, which implies that little capacity will be available for other sectors and that competition over storage will occur between the sectors that envision CCS as mitigation measure (if no additional capacity is to be planned). Moreover, while the early and rapid implementation of CCS in the cement industry is beneficial from a climate perspective, accelerated deployment rates may present practical challenges with respect to raising the sufficient capital, shortages of contractors, skills supply, and materials. Additionally, historical investment patterns in the industry suggest that scaling up at such a rapid pace would be unprecedented, further highlighting the feasibility concerns of achieving these deployment rates. Lastly, the already announced CCS plans, herein referred to as *early movers*, show that costs are not the only determinant of CCS implementation. Assuming that they will implement according to the announced plans, this means that the early movers must build CCS before it is economically incentivised by the EU ETS. To summarize, the EU provides a strong foundation for the cement industry's transition, but the potential for CCS deployment varies between Member States due to the geographical locations of cement plants, which affect transport and storage possibilities for CO_2. Additionally, Member States have differing CCS-specific regulatory frameworks, and these factors must not be overlooked to ensure a successful shift to near-zero emission practices.

CRediT authorship contribution statement

Anna Hörbe Emanuelsson: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Johan Rootzén:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Filip Johnsson:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Filip Johnsson reports financial support was provided by Horizon Europe. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Overview of key model inputs

The model is implemented in MATLAB. The capital expenditures are annualized using a lifetime of 20 years and a discount rate of 8%.

Summary of most-important model assumptions and input.

Cost assumptions	
Capture cost (CAPEX)	$5400\cdot\mathbf{Fluegasflow}^{0.65} + 7004.6\cdot\mathbf{CO_2\ flow}^{0.5243}$ k€[a]
Capture cost (OPEX)	Fixed OPEX includes costs for maintenance of 4% of CAPEX, labour costs of 0.66M€/yr for operators and 0.16M€/yr for engineers. Variable OPEX includes costs for steam at 12€/t steam.
Inland transportation costs	Inland transportation costs including container-based trucks, train and barge are calculated accordingly: $\mathrm{UC}\left[\frac{€}{\mathrm{t\ km}}\right] = \alpha_1\left[\frac{€}{\mathrm{t\ km}}\right] + \frac{\alpha_2\left[€\ \mathrm{t}^{-1}\right]}{\mathrm{d\ [km]}}$ For details on α_1 and α_2 refer to Table 1.
Shipping transportation costs	Assumed to 0.21 €/tonne-km transported CO_2. The distance has then been calculated from each cement plant to the closest storage location.
Storage cost	Ranging from 60€/tCO_2 in Year 2020 and decreasing linearly to 10€/tCO_2 in Year 2050
Scenario assumptions	
FOAK vs NOAK costs	FOAK cost premiums of 100% or 200% (100-200% contingency) are applied as fixed mark-ups over NOAK costs and are assumed to remain constant over time.
Time delays due to lacking CCS specific policies	5 years for countries marked in'Yellow' in Table 2 (i.e., Czechia, Croatia, Finland, Greece, Hungary, Latvia, Poland, Portugal, Romania, Slovenia, and Spain). 10 years for countries marked in 'Red' in Table 2 (i.e., Bulgaria, Ireland, Italy, Luxembourg, and Slovakia).
High and low CO_2 price trajectories	High: $\mathbf{P}_{CO2,y} = \mathbf{P}_{2024}\cdot 1.09^{y}$ Low: $\mathbf{P}_{CO2,y} = \mathbf{P}_{2024}\cdot 1.03^{y}$ where y is the specific year.

[a]The cost is then adjusted from cost Year 2015 to 2023 using CEPCI. For more details on cost calculations, please refer to (Garðarsdóttir et al., 2018).

Appendix B. Emission factors per transportation mode

Table A1

Table A1 shows the assumed emission factors per transportation mode.

Transportation mode	Emission Factor	Unit	Reference
Truck	0.057	$kgCO_2$/ tonne-km	(Ragon & Rodríguez, 2021)
Rail	Assuming that all trains run on electricity and have an electricity demand of 0.05 kWh/tonne-km, along with a yearly electricity emission factor for each country		
Barge	0.050868	gCO2/tonne-km	(European Commission, 2020)
Ship	44	gCO2/tonne-km	(Istrate et al., 2022)

Appendix C. Detailed transition pathways per scenario

Figure C.1

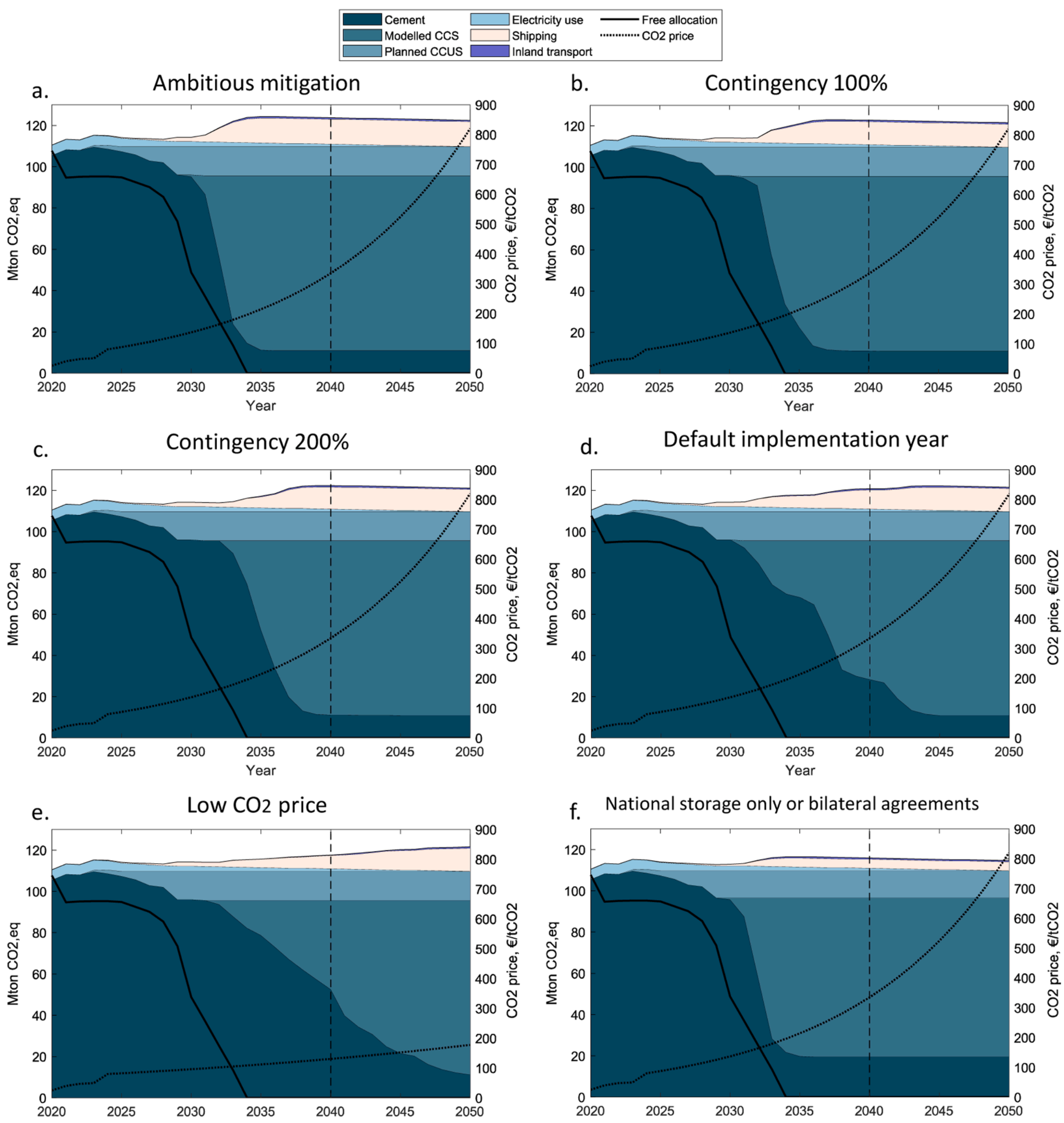

Fig. C.1. Transition pathways for the scenarios investigated in this work: a) Ambitious mitigation scenario (also shown in Fig. 3); b) 100% contingency; c) 200% contingency; d) Default year implementation; e) Low CO_2 price; and f) National storage only or bilateral agreement.

Data availability

Data will be made available on request.

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