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Financing high-cost measures for deep emission cuts in the basic materials industry – Proposal for a value chain transition fund

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A B S T R A C T

There are currently insufficient policy incentives for most producers of basic materials across Europe to invest in low-emissions technologies. This paper explores a novel approach to financing the investments required to accelerate the transition towards zero-emissions practices. To engage non-state actors in this process, and to formalise cross-sectorial collaboration, we explore the establishment of a Value Chain Transition Fund (VCTF). We use the European cement and steel industries as case studies. The VCTF, funded through a premium imposed on basic materials incorporated into end-products, would be used to finance investments in transformative technologies needed to meet emissions cuts along CO_2-intensive supply chains, such as carbon capture on cement and steel plants and hydrogen direct reduction steel production. Our results show that the VCTF ensures that overnight investments and operational expenditures needed for carbon capture in the European cement and steel industries can be recouped in 6–8 and 2–6 years respectively, and for steel produced with hydrogen direct reduction it can be recouped in 3–16 years. The VCTF results in an increase in consumer prices of 0.2%–1.1% in the case of a passenger electric vehicle, and an increase of 0.3%–0.6% in production costs in the case of a high-speed railway, as examples of representative end products.

1. Introduction

The European Union (EU) has ambitions to reduce greenhouse gas (GHG) emissions to net-zero by Year (2050) according to the European Green Deal. Within the Green Deal, the *Fit for 55* initiative mandates a reduction of the EU's net GHG emissions by at least 55% by Year (2030), as compared to the Year 1990 levels, and climate-neutrality by Year (2050) (European Commission, 2023a). Meeting these targets will require ambitious and rapid implementation and investment in measures for deep cuts in GHG emissions (e.g. in infrastructure and technology) across all sectors of the economy, thus creating a substantial demand for materials and services that have little or no climate impacts.

In Year (2022), energy-intensive industries accounted for 22% of the EU's annual emissions (European Commission, 2023b), and the cement and steel industries alone accounted for 9% of the EU's annual Scope 1 CO_2 emissions (Marmier, 2023; Somers, 2022). The steel and cement industries are known to be emissions-intensive and are considered to belong to the "hard-to-abate" or "hard-to-transition" sectors (OECD, 2020) predicted to have residual emissions in Year (2050) (Buck et al., 2022). The average ages of the capital stocks in the European cement and steel industries are progressively increasing (Lei et al., 2023; Rootzén and Johnsson, 2013), and a substantial fraction of the stock will undergo new rounds of re-investment decisions within the next years (Lei et al., 2023; Material Economics, 2019). This implies that there is a need to invest immediately in low-CO_2 technologies to avoid the lock-in effects of carbon-intensive technologies through simply re-furbishing existing stock. However, if the necessary emission reductions are to be met, there is also a need for early decommissioning of fossil fuel installations which will lead to stranded assets, resulting in significant capital losses.

Various mitigation options are available and needed for industry to decarbonise and meet the goal of net-zero emissions (Gajdzik et al., 2023; Habert et al., 2020; Rissman et al., 2020). These include energy efficiency measures, material substitutions, fuel switching, various circular economy and sufficiency measures. Along with these more-incremental measures, transformative technology options that involve complete replacement of existing processes and thus significant investment to enable deep emissions cuts will be needed. These include

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carbon capture and storage (CCS) and direct or indirect electrification (i.e., switching away from using various fuels for high-temperature generation) and are the focus of this work.

Each measure has a different cost structure, in terms of the overall cost and the terms for the distribution of investment costs and operational costs, where incremental measures conventionally imply lower costs compared to transformative technologies. The capital costs involved are typically significant, and the costs related to proceeding from the pilot and demo scales (in the order of tens of millions of €) to the commercial scale (in the order of several hundreds of millions of €) create a substantial risk for the investor. Increased capital and operational expenditures result in higher material production costs. For example, the production cost of low-carbon cement may double (Gardarsdottir et al., 2019; Rootzén and Johnsson, 2016a), thereby exposing these actors to market risks when competing with carbon-intensive materials that have not internalised the carbon costs (Jaffe et al., 2005). Technologies that are categorised as having high technological and market risks, such as CCS, can be particularly difficult to finance (Harring et al., 2021a), and these break-through investments are typically not eligible for conventional project finance, bank debt or venture capital investments (Ghosh and Nanda, 2010; Nemet et al., 2018; Polzin, 2017). Thus, the inability to incentivise and raise the needed up-front capital to finance development and commercialisation is currently one of the most-important barriers to the uptake of alternative, low-CO_2 technologies for applications in basic materials industries. This is the reason why there are various types of state support for de-risking. Yet, equally important are the market barriers that challenge the competitiveness of more expensive low-carbon products (due to higher OPEX) compared to cheaper carbon-intensive alternatives (Bataille, 2020). Thus, the barriers to implementation are influenced not only by the (then annualised) capital expenditures but also by the higher operational costs associated with low-carbon technologies. The barriers to implementing low-emission technologies are therefore related both to the challenge of securing capital for the substantial upfront investment, and the market barriers that threaten the viability and outlet for low-carbon products.

The European Emissions Trading System (EU ETS) is the main policy instrument in the EU for controlling GHG emissions from cement and steel production and other industries with large point sources of emissions. The price of emission allowances has varied in the range of 60–100 €/tCO_2 between January 2022 and January 2024 (Ember, 2024). While future EU ETS allowances prices are not known, a study has estimated that the allowance price will increase up to 130 €/tCO_2 in the early 2030's and thereafter remain relatively stable until the 2040's, followed by a steep increase (Enerdata, 2023). Stede et al., (2021) argue that continued free allocations of emissions allowances in the fourth trading period (2021–2030) will continue to mute the carbon price signal for many energy-intensive industries, thereby limiting the EU ETS ability to incentivise the transformative technological shifts necessary to achieve ambitious decarbonisation goals. However, free allowances are planned to be phased out by Year (2034), as the Carbon Border Adjustment Mechanism (CBAM) is phased in to avoid carbon leakage (International Carbon Action Partnership, 2023). The overall cap set by the EU ETS will be reduced at a rate of 4.3% per year, and the last emissions allowance will be issued in Year (2039) (European Parliament, 2023). Yet, the ongoing unpredictability and risk due to political uncertainties with respect to the future development of the carbon price could mean that firms do not invest or under-invest in low-carbon technologies (Chiappinelli et al., 2021; Richstein and Neuhoff, 2022). The EU ETS will not be fully effective until the free allocation of emissions allowances has been phased out, which may mean that the incentives will arrive too late in relation to the planning processes and investment decisions that need to occur within the coming decade. However, industrial installations included in the EU ETS also receive an incentive to transition to low-emission technologies and benefit from selling excessive allowances on the market. Yet, it is a fact that the current transformative projects have challenges in scaling up. In fact, they typically seek governmental funding for the first plants (e.g., from national support schemes and the EU innovation fund, see for example (European Commission, 2024a.; Heidelberg Materials, 2024; Hybrit, 2024)). Thus, even though the EU ETS has been operational for many years we have yet to see any large-scale deployment of low-emission technologies in the carbon-intensive industries. In addition, the EU ETS may be modified for political reasons, to limit its effects in case some Member States exhibit what they consider to be too-high carbon prices.

As part of climate policy governmental support plays an important role in contributing to the development and scaling up of technologies that can contribute to the transition of the harder-to-abate sectors (Nilsson et al., 2021). Thus, there is a need to support the up-scaling of new technologies and the de-risking of projects, as well as by contributing to developing markets for low-carbon products. Several funding mechanisms exist within the EU and in individual Member States, some of which are directed towards supporting technological transformations in energy- and emissions-intensive industries (e.g., the EU Innovation Fund, the EU's Just Transition Fund, the programme for Environment and Climate Action (LIFE)). The EU Innovation Fund would make 40 billion € available from 2020 to 2030 at a carbon price of 75 € per tonne CO2, the EU Just Transition Fund has a budget of 19.32 billion € from 2021 to 2027, and LIFE has 5.43 billion € in the same time period. Additionally, individual Member States have their own initiatives and funding mechanisms, and in Year (2022) an average of 10.2% of the Member States total government budget allocations for R&D, equalling 12 billion €, were allocated specifically to industrial production and technology (Eurostat, 2023). Member States also provide State aid to Important Projects of Common European Interest (IPCEI) (European Commission, 2024c.). However, many of these initiatives are narrowly focused — such as on demonstration, First-of-a-kind, and flagship projects, or addressing inequalities between member states — and are not designed to support the widespread scaling and deployment of low-emission technologies. Draghi (2024) shows that the decarbonisation of chemicals, basic metals, non-metallic minerals and paper is projected to cost 500 billion € over the next 15 years, and the EU's 2040 Climate Target Plan estimates the investment needs for the steel sector to 100 billion € during the period 2031–2040 (European Commission, 2024b.). As a result, there is a gap in effectively financing this broader transition, particularly in securing the necessary upfront investments both at the plant level and across the entire industry, especially since these funding mechanisms are limited and allocated across multiple sectors. In summary, the existing support programs fall short of addressing the comprehensive scale-up required for a successful transition.

However, a number of alternative policies and private initiatives have also been initiated to lay the foundation for developing markets for low-carbon products. The EU has imposed additional requirements on companies to report on these topics through voluntary initiatives, such as the GHG Protocol's three-scope framework (Greenhouse Gas Protocol, 2023a), and through the mandatory EU Corporate Sustainability Reporting Directive (CSRD) (European Commission, 2024). These initiatives build on the notion that consumers prefer to purchase products from firms that are engaged in carbon emissions reduction activities (Abdallah et al., 2010a), and that there is a significant willingness to pay for climate change mitigation among the public (e.g., Alberini et al. (2018)).

The literature dealing with new complementary policy options aimed at enabling the low-carbon transition of the basic materials industry has grown in recent years. Production-oriented instruments include project-based 'carbon contracts for difference' (CCfD), which are subsidy agreements between regulators and firms where the regulator commits to compensate the firm for the difference between the carbon price and a strike price, which ideally reflects the carbon price required to make a low-carbon production investment economically viable

(Richstein, 2017; Sartor and Bataille, 2019). Consumption-oriented instruments involve the imposition of consumption charges on carbon-intensive materials (Pollitt et al., 2020), which would be a way to ensure that the CO_2-cost associated with primary production is reflected in the end-uses for which the materials are destined.

Several possible support mechanisms and policy requirements that address cost- and risk-sharing of the investment have also been proposed. These include: governmental risk sharing and state funding during the early phases of the development and implementation of new technologies (Mazzucato and Rodrik, 2023), for example the reversed auctioning system for negative emissions operating in Sweden (Swedish Energy Agency, 2021), the EU Innovation Fund (European Commission, 2023c), and the US Inflation Reduction Act (Internal Revenue Service, 2022); the use of sustainable procurement requirements as a tool to create niche markets and to guarantee a market outlet (i.e., green lead markets, see e.g., Agora Industry (2024)) for low-carbon cement and steel (obviously low-carbon products must first be available on the market before they can be procured) (Åhman et al., 2023; Chegut et al., 2014; Kadefors et al., 2019; Simcoe and Toffel, 2014; Uppenberg et al., 2015); innovative business models that create and capture value for the actors involved in the production, refinement, and use of materials, such as steel and cement (Chesbrough, 2010; Teece, 2010); and the issuance of Green Bonds, i.e., loans that are only approved for what is considered as "green projects" (Åhman et al., 2022; Chiappinelli et al., 2021; Monk and Perkins, 2020). To share more broadly the risks, there have been suggestions of: public-private partnerships as a climate finance policy with the function of de-risking and reducing the market uncertainties in relation to investments (Bhandary et al., 2021); trans-national decarbonisation clubs (Åhman et al., 2022; Hermwille et al., 2022); and co-operative arrangements, i.e., to deal with technological risks related to co-ordination between actors (Harring et al., 2021a). These can have more or less governmental involvement depending on their specific purposes.

From the above, we observe that while the current policy regime that targets the energy- and emissions-intensive industries has significantly improved in recent years (with the revisions of the EU ETS, initiatives in individual EU Member States, and the introduction of the US IRA), it remains unclear as to whether the current policy mix induces long-term confidence and provides the incentives required for the investments in low-emission technologies that must occur within the next few years if climate targets are to be met. Even though there are policy instruments (such as CCfD) that aim at addressing the risk of investment in capital-intensive technologies, the question remains as to what extent such instruments can aid in the broad upscaling of low-emission technologies rather than only First-of-a-kind and flagship projects. At the same time, it can be difficult to raise funding for mitigation projects, since governmental and EU funding sources are limited and often specialized toward demonstration or First-of-a-kind projects, and private investors may deem the market and technological risks to be too high. Producers not granted such agreements or funding through governmental programs (which will be granted the few rather than the many), are exposed to and have to carry all of the risks of the required investment, while trusting that policy instruments will provide the incentives required to cover the investments and the increased operating costs of the low-carbon materials.

This article addresses critical gaps in financing and implementing low-emission technologies in basic materials industries: 1) Financial friction (Armitage et al., 2024), including insufficient governmental funding mechanisms for the large-scale transition needed since such support is often aimed at financing First-of-a-kind or flagship projects, thus failing to raise necessary upfront capital from the private sector for capital-intensive technologies deemed to have high market and technological risks, 2) Market barriers (Chiappinelli et al., 2021; Löfgren and Rootzén, 2021), that affect the competitiveness of more expensive low-carbon products, with increased capital and operational expenditures, compared to cheaper carbon-intensive alternatives, 3) Risk Allocation (Harring et al., 2021b), where producers face significant risks in investment, while depending on policy instruments to offset both capital and operational costs, which may not be adequately covered on a broad-enough scale. This paper proposes and explores the Value Chain Transition Fund (VCTF), a novel, private, bottom-up financing approach independent of governmental intervention. The VCTF is an addition to the current instruments and mechanisms in place that would allow industry to be frontrunners in the transition to near-zero or net-zero emissions in the materials sector within the coming decades. We will in this paper explore the implications for such a fund, how it could be designed and how it could be used to finance the transition in the EU-27 cement and steel industries.

The paper is organized as follows. In Section 2, we present the theoretical framework of the proposed VCTF. In Section 3, we describe the scope and method of this study. In Section 4, we present our results from applying the VCTF to typical cement and steel value chains.

2. The case for a value chain transition fund

Over the last few years, several incumbent firms in both the cement and steel industries have announced the building of demonstration plants for low- or zero-CO_2 processes (IEA, 2020; Vogl et al., 2021). Indeed, there are plenty of signs of a strong and growing awareness among industrial stakeholders of their roles in tackling sustainability challenges and in reducing the climate impacts of production processes and products[2] (Abdallah et al., 2010b; Alberini et al., 2018; European Commission, 2024; Greenhouse Gas Protocol, 2023b). The VCTF builds on the concepts of the supply and value chain and the assumption that it is possible to establish collective action of the actors along the supply chain while maintaining competitiveness between companies. The rationale for the VCTF is built on three basic premises.

The first premise is that a significant share of the steel and cement that is produced ends up being used in the construction and automotive industry (see Fig. 1).

The second premise is that the actors involved in these supply chains[3] act in a mutually dependent manner in the climate transition and cannot achieve the goal of net-zero emissions on their own (Stevens, 1990). If such mutual dependency does not occur, it can lead to coordination failures, as widespread adoption of climate-mitigation technologies often requires simultaneous investments across the supply chain (Armitage et al., 2024). The primary producer relies on the users to adopt the less-emissions-intensive but more-costly product, while the users rely on the primary producer to take on the investment in low- or zero-emissions production capacity to reduce embedded emissions.

The third premise is that most of the GHG emissions arise up-stream in the value chain,[4] while most of the value is realized down-stream. As an example, (Clift and Wright, 2000) have shown how primary resource industries give rise to environmental impacts that are disproportionate to the associated added value. This also means that when a carbon price is introduced the carbon price signal is unevenly distributed along the value chain, i.e., between different companies along the supply chain. This is certainly the case in the building and construction industry and the automotive industry, where the embedded CO_2 emissions are mainly concentrated in the production of the basic materials (cement and steel),

[2] E.g., the Clean Energy Ministerial Industrial Deep Decarbonisation Initiative (UNIDO, 2023); First Movers Coalition (First Movers Coalition, 2023); and the Climate Group Initiative (Climate Group, 2023).

[3] Here, supply chains refer to the networks (typically, cross-sectoral) that facilitate the sourcing and primary production of materials, as well as the further processing and assembly and delivery of products or services to the consumer (see, for example (Stevens, 1990)).

[4] Here, value chain refers to the value creation and the margin which can be obtained from a certain supply chain business (see original work by Porter (1985); and Mentzer et al. (2001), as well as references therein).

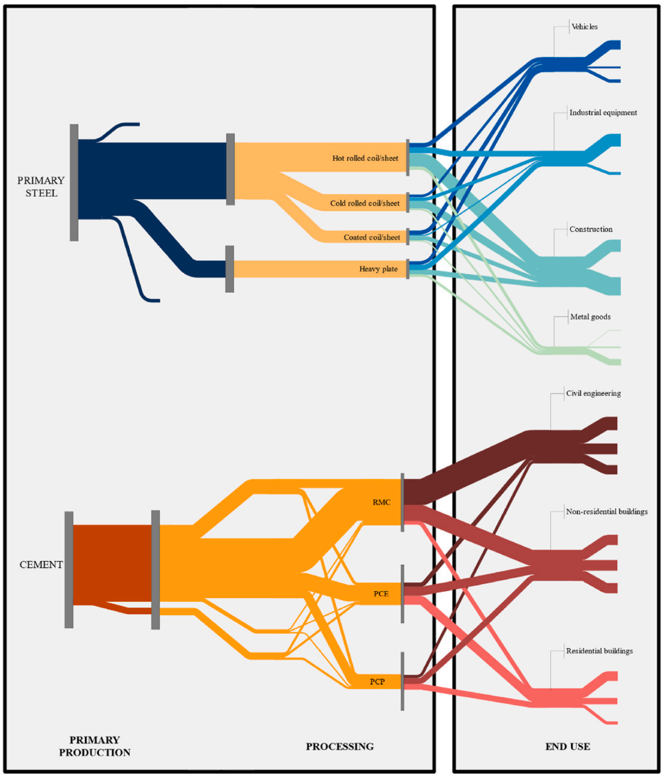

Fig. 1. The supply chains from basic materials production to end-use in the building and construction and automotive industries, for steel and cement. The supply chain involves: (i) *Primary production*, i.e., steel- and cement-producers; (ii) *Processing*: firms involved in the design and manufacturing of construction steel, e.g., steel sheets, beams and bars (most often done at the same site as (i)), and firms involved in concrete manufacturing; (iii) *End-use*: actors involved in construction and construction planning; building and/or infrastructure procurers; public and private tenants and end-users of road infrastructure; and vehicle manufacturers.

i.e., at the very beginning of the value chain, where the pricing of emissions is through the EU ETS system (*polluter pays principle*). Previous works by the authors and others (Skelton and Allwood, 2013; Allwood et al., 2011a; Hörbe Emanuelsson and Johnsson, 2023; Rootzén and Johnsson, 2016a, 2016c) have revealed that investing in new low-CO_2 steel-making and cement-making processes – in spite of the fact that these processes are associated with high up-front investments – has only a marginal effect on the overall costs, and thereby the price facing the end-users of steel- and cement-containing products. This could be regarded either as a "barrier", since the carbon price signal is too weak to induce the car producer to shift to using less material or to using a less-CO_2-intensive material, or as a means to induce the car buyer to choose a car that contains less steel. However, it could also represent an opportunity, since a steel-maker who is producing fossil-free but more-expensive steel could pass on that cost. Thus, the car manufacturer would only have to add a relatively small premium of around +1% (Rootzén and Johnsson, 2016b) onto the final retail price for a car built with fossil-free steel (iron and steel making currently account for more than 50% of the mass and embedded carbon emission of an average car (see e.g. Rootzén and Johnsson (2016b)). This is of course assuming that the passing on of the cost increase to the end-product could be done in a transparent way that would not result in other additions along the value chain.

The above-mentioned calls for a cross-sectoral analysis and the involvement and co-operation of different companies and actors. The conditions for such cross-sectoral involvement should be favourable because, as indicated above, there is presently good consensus among the different market actors regarding the need to meet climate targets,[5] and Ramboll, 2024 show that nearly half of global companies are ready to pay a premium for lower emission steel and concrete. Reducing global GHG emissions is a collective action problem, i.e., the costs of contributing are concentrated to the individual actor, while the benefits are shared (for a general discussion on the pre-conditions for large-sale collective action, see Jagers et al., 2019). Different authors, such as (Ostrom, 2010), have claimed that such problems must be addressed at multiple scales and levels, i.e., following a poly-centric approach. Taken together the above-mentioned three premises highlight how no single actor along the value chain can address the challenges involved in decarbonizing steel and cement and how multiple actors along the value chain need to cooperate.

We propose a VCTF that will gather a critical mass of actors involved in the supply and value chains of the steel and cement industries. The three aims of this VCTF are:

1. To share the financial risk related to the high, up-front investments required to transform key CO_2-intensive production processes in industry;
2. To create a bottom-up system in which the value of low-carbon processes is internalised in the end-product; and
3. To create funding for projects that enable deep emissions cuts but that are associated with high technological and market risks.

With the VCTF, supply chain actors have the opportunity to become actively involved in creating a bottom-up initiative towards enabling investments in the production of low-carbon materials. The VCTF would spread the risk, make private capital accessible, and reduce the need for public funds. Since the long-term policy landscape remains unclear it would also be a way to hedge against changes in the climate policy. Fig. 2 shows the general principles with regards to the physical and monetary flows and interactions amongst the actors involved in the supply chain actor formation and other enabling actors, such as banks and governmental bodies, when applying the VCTF. The basic material producers issue a certificate to which is attached a specific premium, the cost of which is passed on to the consumers of the end-products.

We propose that the set-up and operation of the VCTF will contain the following principal steps with the aim of establishing a collective action within the supply chain. While these principals represent the key steps, the precise details of the VCTF's formation must be developed in consultation with experts from the financial world.

- **Formation of Supply-chain actors.** The aim of this step is to bring together many of the relevant stakeholders, including the industries that are involved in the production of basic materials (e.g., cement and steel), intermediary industries (e.g., processing and manufacturing companies), and those involved in the production/construction of the end-products (e.g., public and private procurers, contractors, suppliers, vehicle manufacturers), and then to agree on the design and financing of the VCTF. Thus, there needs to be a basis for an agreement as to the premium that should be placed on low-carbon products to finance the VCTF. This step has similarities with the concept of climate clubs, i.e., to be within the group of actors should be attractive enough to be regarded as a competitive advantage (and possibly associated with a certain label or

[5] Examples of cross-sectoral coalitions for deep decarbonisation: First Movers Coalition, Mission Possible Partnership, Responsible Steel, Low-Carbon Emitting Technology Initiative, Climate Group, Concrete Sustainability Council, and others. Here are some examples of companies with emission targets: Volvo Cars have a target of net zero emissions by Year (2040), including Scope 1–3 emissions (Volvo Cars, n.d.); Polestar has the target to offer a climate neutral car by Year (2030) (Polestar, 2024); and Scania aims to reduce 50% of their industrial and commercial CO_2 emissions by Year (2025) (Scania Group, n.d.).

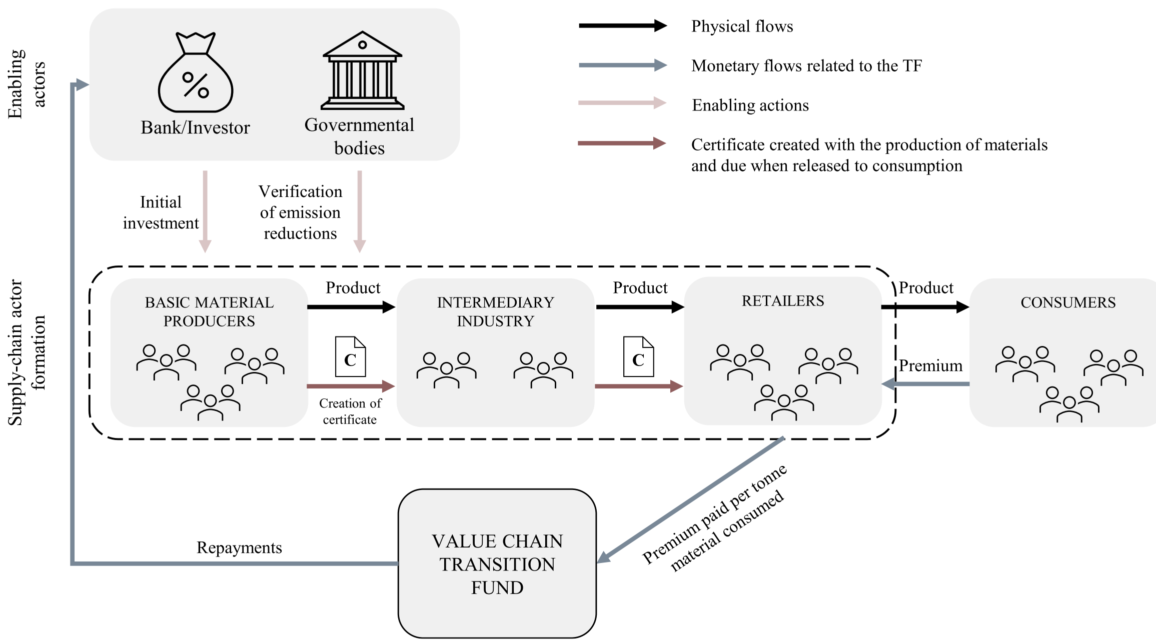

Fig. 2. Principal flows and interactions between actors along the supply chain when the VCTF is applied.

certificate). Using the value chain of cement and steel as examples, the fee could be assessed in proportion to the difference in cost between a carbon-intensive material and a low-carbon material.

- **Agreement.** A negotiation between the parties on the structure of the agreement will be conducted. A prerequisite for a functioning system, built on collective commitments, is that the actors involved agree on the overall goal of the fund including agreements on how to share the risks and benefits associated with involvement, and mechanisms that ensure accountability and transparency (Bastos Lima et al., 2021; Jagers et al., 2019) and that mechanisms are put in place that safeguards against anti-competitive practices (e.g. cartels and price-fixing).
- **Establishment of the VCTF.** The premium is used to build up the fund as a Special Purpose Vehicle (SPV), i.e., a legal entity created with the objective of transforming the basic materials industry to carbon neutrality. Thus, there is a need to establish a legal and regulatory structure for the fund that will allow the premiums to be handled in a secure and efficient way. This will probably be done through a bank or other financial institution.

The fund should be able to issue bond emissions based on the cash-flow from VCTF premiums. State guarantees could be used to guarantee these bond emissions, for example issued by the European Investment Bank (EIB) or any national entity such as the Swedish Export Credit Agency (SEK) or National Debt Office.

- **Distributions from the VCTF.** The fund will be distributing support to its beneficiaries in the form of amortizing loans with attractive terms and conditions. The loan structure will likely have a more positive effect on the assessed risk by the bond investors as well as allow for more support to be distributed as a whole. The loans will be used to support investments in transformative technologies, such as CCS and hydrogen-based steel-making. The investment support must be allocated in a competitive manner (similar to the reversed auctioning system for negative emissions in Sweden or the CCfD in Germany) and used to finance a certain share of the investments to lower the level of risk for the investor. The exact share will depend on market conditions and the strength of the policy measures in place, such as those on the prices of emissions allowances within the EU ETS system. Projects that can benefit from the VCTF may be selected by means of procurement, to ensure competition with respect to how the projects are executed. This is to avoid excessive costs, as may be the case in early projects when participants try to minimise their risk exposure (by having high margins). Before the fund is established, a detailed governance structure must be in place regulating which general criteria to apply for the lending, who will decide on the actual lending and what the risk and compliance structure would look like, but such considerations are beyond the scope of this work. To design this, as well as administrative and operational procedures of the fund, will require cooperation with established financial institutions.
- **Development of VCTF premium.** As conventional products are replaced by VCTF products (e.g., low-carbon cement and steel) over time and a market for these products is created, the VCTF premium can be lowered. Similarly, if the VCTF fee is based on the difference between the production cost of conventional and low-carbon materials, the fee will decrease over time as the EU ETS price increases and free allocation of emissions allowances are phased out, thus increasing the production costs of carbon-intensive materials. The level of the premium will decide the number of years required for the investments to be recouped as well as what will be the cost increase for the end-consumers. The VCTF is a way to overcome market barriers and level the playing field between low-carbon and carbon-intensive materials through the issuance of certificates and by integrating a premium price concept into low-carbon product sales. The premium must be separated from the basic material price to avoid market violations.
- **Repayment.** In this case, entities that receive support from the VCTF will repay part of or the entirety of the investment support to the VCTF once a market for low-carbon products has been established. This will, over time, increase the monetary levels in the VCTF, thereby enabling an even quicker transition.

It must be stressed that these are the principal steps, and the exact financial design of the fund must be scrutinised in greater detail by financial actors together with the relevant authorities. In addition to the above steps, there will be a need for monitoring and evaluation of the projects that are financed (or partially financed) by the VCTF, with respect to the levels of emissions reductions and the experiences with the mitigation technologies. Thus, it can be of importance to involve governmental bodies or other third-party actors for the verification of emissions reductions.

3. Methodology

3.1. Overnight investment needs and operational expenditures

We assessed the overnight investment needs for CCS and hydrogen-based steel production in a European context, to derive an indication of the magnitude of investments needed for the cement and steel industries. Thus, the range of investments represents the 'overnight' types of costs, thereby non-annualised and only including pure capital expenditures, without any additional costs or margins. The investment only applies to transformative technologies (i.e., CCS for the cement industry and CCS and H-DR for the steel industry), and no other incremental investments are needed to achieve net-zero (or near-zero) emissions. Thus, our analysis focused on direct investments in full-scale production capacity. Obviously, other investments in incremental measures will be needed directly in the cement and steel industries, as well as supporting measures such as expanding fossil-free electricity production and transmission, and expanding the infrastructure to transport and/or store hydrogen and CO_2. It is possible that the investments in these supporting measures will surpass the direct investments in the steel and cement industries (Mission Possible Partnership, 2022). Thus, even though investments in supporting measures are outside of the industrial plant boundaries, industries will have to pay for these services depending on the choices and set-ups of abatement options. As examples of this: a plant owner will have to pay for the service of transporting and storing CO_2 when using CCS; the plant owner might have to pay for the service of transporting hydrogen depending on whether or not it is produced within the plant; and depending on the development of the electricity system, a plant owner might have increased or decreased electricity costs. The costs for the transportation and storage of CO_2 and the different set-ups for producing hydrogen have been included in the cost estimates in this work. However, the investment needs presented in this work are not exhaustive, instead providing an estimate of the magnitude of the overnight investments needed for the purpose of VCTF-evaluation of CCS and H-DR in the EU cement and steel industries.

The magnitudes of the overnight investments were evaluated by assessing the roadmaps given in the literature for decarbonisation of the EU cement and steel industries, which are listed in Table 1 together with their key assumptions. The roadmaps show how the cement and steel sectors could decarbonise over time to meet climate targets using both incremental and transformative mitigation options. Each roadmap includes a certain share of the transformative technology options needed under different scenarios, and these are in focus in the present work (i.e., CCS and indirect electrification of the steel-making process using newly built H-DR technology, together with green hydrogen produced via electrolysis). The levels of deployment of CCS and H-DR in each roadmap are obviously dependent upon which other mitigation options are included in the roadmap. However, as previously mentioned, the costs for mitigation options other than CCS and H-DR have not been included in this work.

The roadmaps in Table 1 vary in nature, whereby 2 out of 6 and 5 out of 9 studies evaluate decarbonisation towards the goal of net-zero emissions or climate neutrality for the cement and steel industries, respectively, in Year (2050). The remaining roadmaps assume certain CO_2 reduction savings, 65%–95%, compared to the Year 1990 levels. In such cases, the over-arching goal of the EU being climate-neutral in Year (2050) will depend heavily on the levels of emissions reductions and carbon removals achieved in other sectors. However, in cases where emissions reductions are limited, industries might need to compensate for residual emissions, though this aspect is not included in our analysis. The authors of the roadmaps range from single-industry actors to private partnerships, to public authorities such as the European Commission, to research institutes. Only roadmaps with a sufficient level of detail required for the analysis in this work are included in Table 1. Furthermore, only roadmaps that analyse the EU are selected, thereby excluding national and global roadmaps.

The overnight investment needs and additional operational expenditures were estimated by assuming a range of overnight investment costs and operational expenditures for each transformative technology (i.e., CCS for cement and CCS and H-DR for steel) according to the literature (Table 2). All costs were adjusted to cost Year 2020 using the Chemical Engineering Plant Cost Index (CEPCI).

In this work, CCS was assumed to be used as an end-of-pipe type of solution in the form of a retro-fitted, post-combustion, amine-based carbon capture technology based on already existing assets. The assumed investment costs for CCS were in the ranges of 100–325 €/t steel capacity (Ho et al., 2013; IEAGHG, 2013b, 2018; Tsupari et al., 2013) and 120–420 €/t cement capacity (Anantharaman et al., 2016; Gerbelová et al., 2017; IEAGHG, 2013a; Liang and Li, 2012). The operational expenditures for post-combustion CCS reported in the literature were in the ranges of 35–90 € (Ho et al., 2013; Hughes and Zoelle, 2022; IEAGHG, 2013b, 2018; Tsupari et al., 2013) and 20–32 € (Anantharaman et al., 2016; Gerbelová et al., 2017; IEAGHG, 2013a; Liang and Li, 2012) per tonne of material production capacity for the steel and cement industries, respectively, excluding the costs for the transportation and storage of CO_2. These values correspond to capture rates of at least 89%, although for the steel industry, CCS is only installed for 35%–75% of the total plant emissions. It should be noted that the actual cost for implementing CCS could exceed the costs reported in literature data. For example, Beiron and Johnsson (2024) show that the specific CO_2 cost (€/tCO_2) for a cement CCS project in Norway is 100%–200% higher than originally planned for. The costs for transportation and storage of CO_2 have been added to the OPEX, assuming a range of 35–50 €/tCO_2 (Global CCS Institute, 2021; IOGP, 2019). This has been added to the OPEX by assuming a capture rate of 90% for cement with an assumed emissions intensity of 0.7 tCO_2 per tonne of cement, and an overall capture rate of 35%–75% for steel with an assumed emissions intensity of 1.8 tCO_2/t primary steel.

The cost range for CCS deployment depends on factors such as the technology set-up, plant size, geographical and site-specific conditions, the availability of excess heat supplying the capture process, emissions volumes, and the CO_2 concentrations in the flue gases, as well as whether the installation is assumed to be the 1st or Nth of its kind. Moreover, the cost estimates for technologies can vary significantly depending on the cost assumptions for the equipment, the level of detail in the work, and whether it is an early stage or mature cost estimate (Roshan Kumar et al., 2024; Spek et al., 2017). All of these factors contribute to the rather broad range of cost assumptions shown for CCS in Table 2.

The investment cost for the H-DR was assumed to be in the range of 575–905 €/t steel capacity[6] (Fischedick et al., 2014; Mission Possible Partnership, 2022; Vogl et al., 2018; Wörtler et al., 2013). This range depends on factors such as whether the green hydrogen is produced on-site or off-site (meaning that the investment cost of the electrolyser is included or not), and whether the electrolyser is over-dimensioned to be able to produce hydrogen during low electricity price hours and store it, thereby enabling flexible operation of the plant. The operational expenditure was estimated to lie in the range of 361–640 €/t steel,

[6] While there are a few H-DR projects that have received investment support approved, the full investment costs are typically not disclosed. Since there are still no full-scale H-DR plants in operation there is no information about actual realized investment costs.

Table 1
General assumptions for each roadmap. The column labelled 'EU production in Year (2050)' presents the levels of both primary and secondary steel for the steel industry, as well as the levels for cement.

Roadmap/References[a]	Goal in Year (2050	Region	Options included	EU production in Year (2050
Cement				
CASS1 (CEMBUREAU, 2020)	Climate neutrality along the cement and concrete value chain by Year (2050).	EU	Fuel switching, energy efficiency measures, electrification, CCS, decarbonated raw materials, carbonation.	176 Mt cement (Year, 2022)
CPRIV1 CPRIV2 (Material Economics, 2019)	Net-zero industrial CO_2 emissions in Year (2050). CPRIV 1 focuses on new processes, while CPRIV2 has a CCS focus.	EU	Energy efficiency measures, fuel switching, electrification, CCS.	140 Mt cement 165 Mt cement
CACA1 CACA2 CACA3 (Favier et al., 2018)	65% CO_2 savings in Year (2050) compared to Year 1990. 75% CO_2 savings in Year (2050) compared to Year 1990. 95% CO_2 savings in Year (2050) compared to Year 1990.	EU + UK	Efficiency of clinker production, alternative fuels, clinker substitution, CCS, alternative binders.	157 Mt cement
Steel				
SPRIV1 SPRIV2 (Material Economics, 2019)	Net-zero industrial CO_2 emissions in Year (2050). SPRIV 1 focuses on new processes, while SPRIV2 has a CCS focus.	EU + UK	Energy efficiency measures, fuel switching, natural gas-based direct reduction (as a transition step), H-DR, electrification, CCS.	193 Mt primary steel
SEC1 SEC2 (European Commission, 2023d)	Net-zero CO_2 emissions in Year (2050). SEC1 focuses on the competition between electrification and hydrogen production, and SEC2 assumes that commodities such as iron sponge are imported from outside of Europe.	EU + UK	Increased use of EAF steel, H-DR, CCS.	151 Mt primary steel
SASS1 (EUROFER, 2019)	Reduction of direct and indirect CO_2 emissions up to 80% compared to the Year 1990 levels.	EU + UK	Energy efficiency measures, H-DR, CCS.	200 Mt primary steel
SPRIV3	Reduction of Scope 1 emissions by 90% in Year (2050), as compared to the levels in Year (2020).	EU + UK	Demand reduction, increased scrap recycling, material efficiency, fuel switching, H-DR, CCS.	213 Mt primary steel
SPRIV4 SPRIV5 (Mission Possible Partnership, 2022)	Near-zero Scope 1 emissions in Year (2050). Net-zero Scope 1 emissions in Year (2050).			
SPPP1 (GreenSteel for Europe, 2021a)	Reduction of the iron and steel industry's CO_2 footprint by 80%–95%, compared to Year 1990 levels, by Year (2050).	EU	Efficiency measures, reduction agent switch, electrification, H-DR, CCS.	155 Mt primary steel

[a] XACA, Academia; XASS, industry association; XEC, European Commission; XPRIV, private sector; XPPP, public-private partnership. The first letter X indicates whether it is cement, C, or steel, S.

Table 2
Technology cost data assumed in this work.

Technology	Overnight investment cost	OPEX[a]	Reference
Retrofitted post-combustion CCS			
Cement	120–420 €/t cement capacity	20–32 €/t cement capacity	(Anantharaman et al., 2016; Gerbelová et al., 2017; IEAGHG, 2013a; Liang and Li, 2012)
Steel	100–325 €/t steel capacity	35–90 €/t steel capacity	(Ho et al., 2013; IEAGHG, 2013a; 2018; Tsupari et al., 2013)
Newly built H-DR			
Steel	450–905 €/t steel capacity	361–640 €/t steel capacity	(Fischedick et al., 2014; Mission Possible Partnership, 2022; Vogl et al., 2018; Wörtler et al., 2013)

[a] The costs for transportation and storage of CO_2 are also added to the OPEX for CCS.

depending on the technology set-up and electricity price profile, and whether or not the plant is operated flexibly (Vogl et al., 2018; Wörtler et al., 2013).

It is important to note that the costs for CCS, if considering post-combustion technology, represent the costs for retro-fitting, while the costs for the H-DR technology represent greenfield costs. Thus, when comparing H-DR and CCS implementation in the steel industry, the cost for H-DR might seem much more expensive. However, eventually blast furnaces will reach their end-of-life and will have to be replaced (implying that retro-fitting with CCS is no longer an option), bringing the investment cost of H-DR closer to that of CCS when comparing greenfield investment costs [assuming that the H-DR technology becomes a successful option, with the technology having a Technology Readiness Level (TRL) of 6–7 in the 2020's (GreenSteel for Europe, 2021b)]. H-DR also provides additional benefits compared to post-combustion CCS, such as the discontinued use of fossil fuels. Moreover, it should be noted that the investment decisions of individual firms are based on a range of factors and not just the monetary ones.

It is important to note that many high-cost investments, such as H-DR and CCS, turn out to be more expensive than first projected when one includes site-specific costs and alternative costs (Flyvbjerg, 2014; Roshan Kumar et al., n.d.).

3.2. The value chain transition fund – the application

The time-frame in which the VCTF could be used to finance overnight investments in transformative technologies in the EU steel and cement industries was quantified based on the roadmaps shown in Table 1. A certain amount of the cement demand projected in year 2050 by the roadmaps (Table 1) must be produced using CCS, with the average being 91 Mtonnes of cement (ranging from 40 to 165 Mtonnes). This means that approximately 75 cement plants, each with a production capacity of 1.2 Mtonnes of cement per year, would need to implement CCS, out of around 200 plants currently in operation. Similarly, we assume a primary steel demand of 43 Mtonnes produced with CCS and a demand for 48 Mtonnes of H-DR steel, which would correspond to 7 and 8 transformed steel plants, respectively, each with a capacity of 6 Mtonnes, out of the 20 primary steel plants in the EU-27 today. To showcase how the VCTF premium would affect end-use consumers, a product value chain analysis was used to illustrate the cost increase for end-products when applying the VCTF premium. The steel industry is exemplified by a passenger electric vehicle (EV) as the end-product and the cement industry is illustrated by a high-speed railway. For further details on the end-products, see Appendix A and (Hörbe Emanuelsson and Johnsson, 2023) for the passenger EV and railway, respectively. This has been shown by assuming that the VCTF premium is 100% of the difference in production cost between a carbon-intensive material and a low-carbon material, where it is assumed that the carbon-intensive material does not include any internalised carbon costs from policy measures. As previously mentioned, the premium level should be set by the supply-chain actor formation, but it is in this work arbitrarily chosen to the difference in cost between carbon-intensive and low-carbon materials to illustrate the application of the VCTF. The carbon-intensive materials were assumed to have a production cost of 52 €/t cement (Hörbe Emanuelsson and Johnsson, 2023) and 371 €/t steel (Toktarova et al., 2020). The production cost, C_s^m, of the low-carbon materials, m, for each sector, s, is calculated according to Eq. (1):

$$C_s^m = CAPEX_s + OPEX_s^{var} + OPEX_s^{fix} \tag{1}$$

where $CAPEX_s$ is the annualised investment cost, assuming a discount rate of 8% and economic life-time of 25 years, $OPEX_s^{var}$ is the variable operational expenditures, and $OPEX_s^{fix}$ is the fixed operational expenditures. The investment cost and operational expenditures were assumed to lie in the ranges listed in Table 2. For the quantification of the VCTF we in this work assume the premium level to be calculated according to Eq. (2):

$$Premium = C_s^{m,low\ emission} - C_s^{m,carbon\ intensive} \tag{2}$$

where $C_s^{m,low\ emission}$ is the production cost of the low-emission technology and $C_s^{m,carbon\ intensive}$ is the production cost of the carbon-intensive technology option. Thus, the premium level of the premium and annual premium income will in this work vary. This results in a VCTF premium of 55–105 €/t cement and 65–190 €/t steel depending on the technology and the range of the cost data in the literature. It was further assumed that plants that apply transformative technologies in their production facilities according to the roadmaps also apply the VCTF premium during the consumption stage of their materials. The premium revenues are amassed in the VCTF. Thereafter, the fund is used to make investments in the transformative technologies described in Table 2 (i.e., CCS and H-DR). The number of years needed to recoup all the overnight investments is calculated by dividing the total overnight investment need by the yearly premium revenue, as in Eq. (3):

$$Years = \frac{\text{Total overnight investment cost} + \text{Additional OPEX}}{\text{Yearly VCTF premium revenue}} \tag{3}$$

Two different set-ups of the VCTF were explored, in which: 1) the overnight investment is covered by the VCTF; and 2) both the overnight investment and additional operational expenditures for the first 5 years of operation are covered. The first set-up obviously only addresses the issue of acquiring funding while the second set-up addresses all the issues intended with the VCTF (i.e. raising capital, market barriers and risk sharing). The second set-up is similar to that of the EU Innovation Fund, where a share of the investment cost is covered together with 10 years of operational expenditures. However, we investigated the case of 5 years rather than 10 years because it was desirable that the projects become self-sufficient as soon as possible.

4. Results

4.1. *Overnight investment needs and operational expenditures for carbon mitigation*

Fig. 3 shows the estimated magnitude of the overnight investment needs (Fig. 3a) and operational expenditures (Fig. 3b) for the first 5 years of operations for retro-fitted post-combustion CCS and newly built H-DR for the cement and steel industries. Fig. 3 reflects the range of cost estimations given in the literature and the assumptions made regarding the diffusion of CCS and H-DR until Year 2050, according to the roadmaps in Table 1. The cement industry is estimated to have an overnight investment need for CCS of 5–53 billion €, and the operational expenditures for the first 5 years of operation of CCS in the cement industry are 8–53 billion € (see Fig. 3a and b, respectively). Fig. 3 also reflects the emission reduction ambition level for each roadmap, with the roadmaps representing the lowest overnight investment need and operational expenditures (e.g. CACA1) also representing the least ambitious CO_2 reduction target (65% emission reductions compared to Year, 1990). Similarly, the roadmaps with more ambitious emission reduction targets of net- or near-zero emissions in the cement sector in Year (2050) (e.g. CPRIV1 and CACA3) also have much higher overnight investment needs. Thus, these results do not imply that certain roadmaps can achieve a less costly implementation of transformative technologies, rather than that they simply have lower ambitions. The wide range within each roadmap reflects the range of implementation costs reported in the literature, see Table 2. As the actual costs become clearer through the implementation of the technology, the estimated cost range within each roadmap is likely to narrow, resulting in more precise projections.

The steel industry in the EU has an overnight investment need of 1–23 billion € for CCS, and the operational expenditures for 5 years of operation are in the range of 1–58 billion € (see Fig. 4a and b). The minimum values represent the lower range of the investment costs from Table 2, together with the roadmaps that assume a low level of implementation of CCS in Table 1. In three of the roadmaps, CCS is either not included as a decarbonisation option or is out-competed by other options. Thus, these roadmaps do not have any overnight investment costs or operational expenditures for CCS. Furthermore, the overnight investment need for H-DR is 11–64 billion € by Year (2050) and the operational expenditures are far more expensive than the investment costs in the technology, being in the range of 45–230 billion €. This may imply that the second set-up of the VCTF, whereby both the investment costs and operational costs are covered, will be even more crucial for the

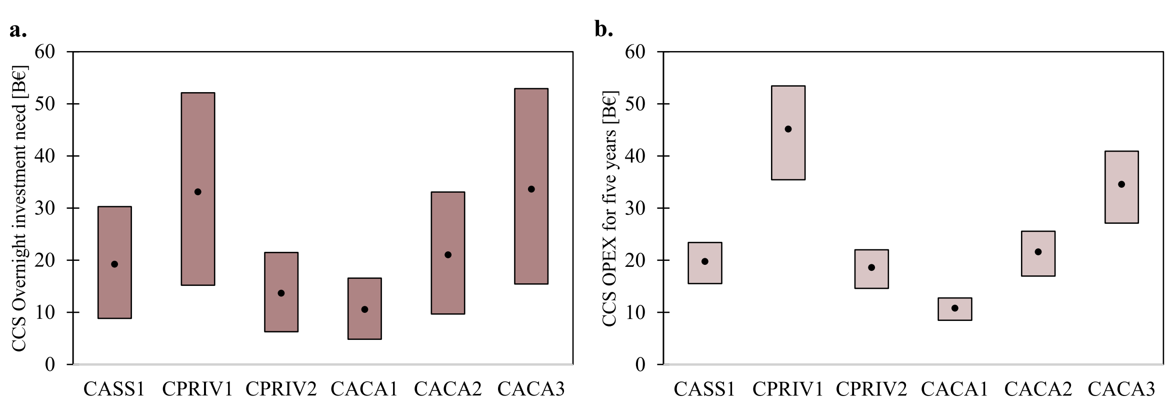

Fig. 3. Estimated overnight investment needs (a) and OPEX (b) over the first 5 years of operation for CCS in the EU cement industry (dots represent mean values). The *x*-axis lists the roadmaps explored in this work as described in Table 1.

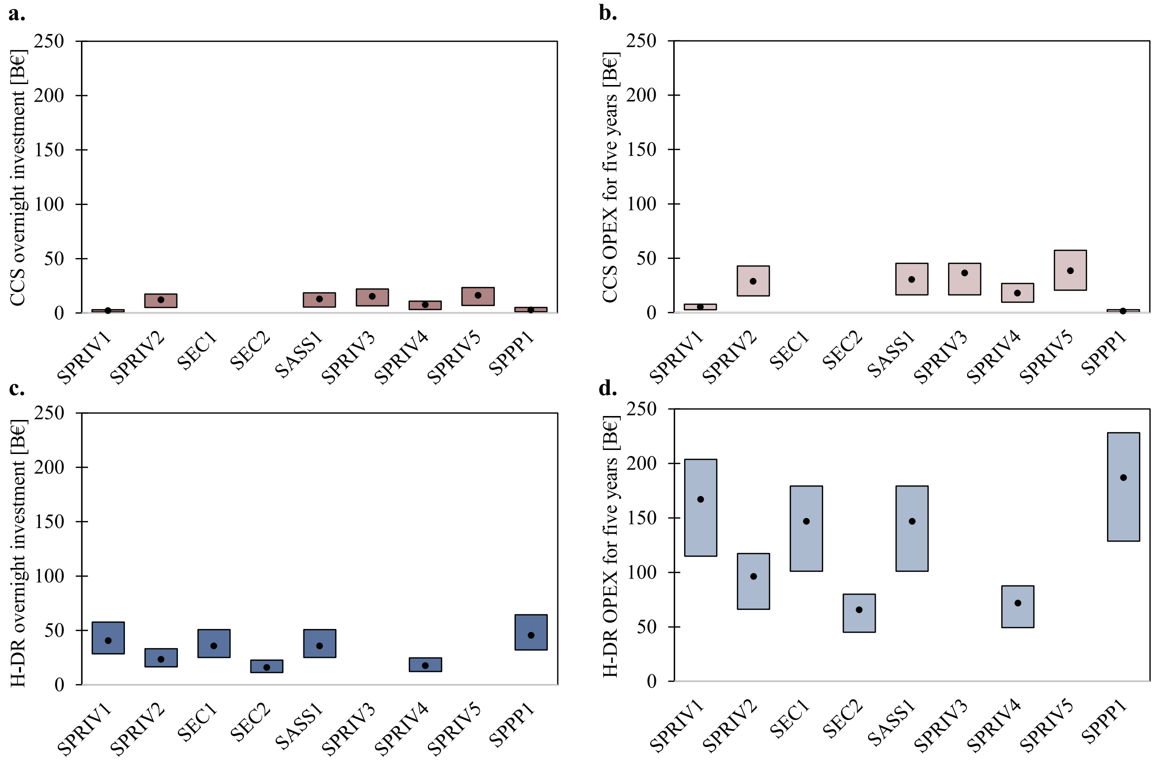

Fig. 4. Estimated overnight investment needs for (a) CCS and (c) H-DR. Also shown are the OPEX values for (b) CCS and (d) H-DR over the first 5 years of operation of the transformative technology options in the EU steel industry (dots represent mean values). The *x*-axis lists the roadmaps explored in this work (see Table 1).

steel industry.

The above estimates of the overnight investment needs for the EU cement and steel industries can be compared to the approximate 65 billion € that are distributed through the EU innovation Fund, EU Just Transition Fund, the programme for Environment and Climate Action (LIFE), and the additional 12 billion € of national governmental funding for RD&D projects aimed at industry. However, it is important to note that those initiatives are mostly aimed at demonstration and First-of-a-kind projects and will be distributed across many sectors. As those funds are intended for multiple industries (i.e., energy-intensive industries, renewable energy production, energy storage technologies, CCS, and net-zero mobility and buildings), they will not be sufficient for the transition. Instead, the funds will – as is their intention – support first-of-a-kind and flagship projects to demonstrate and gain initial experiences with new technologies.

4.2. VCTF for a passenger electric vehicle and high-speed railway

Figs. 5 and 6 show the number of years for which the VCTF needs to recoup all the overnight investment needs for CCS in the EU steel and

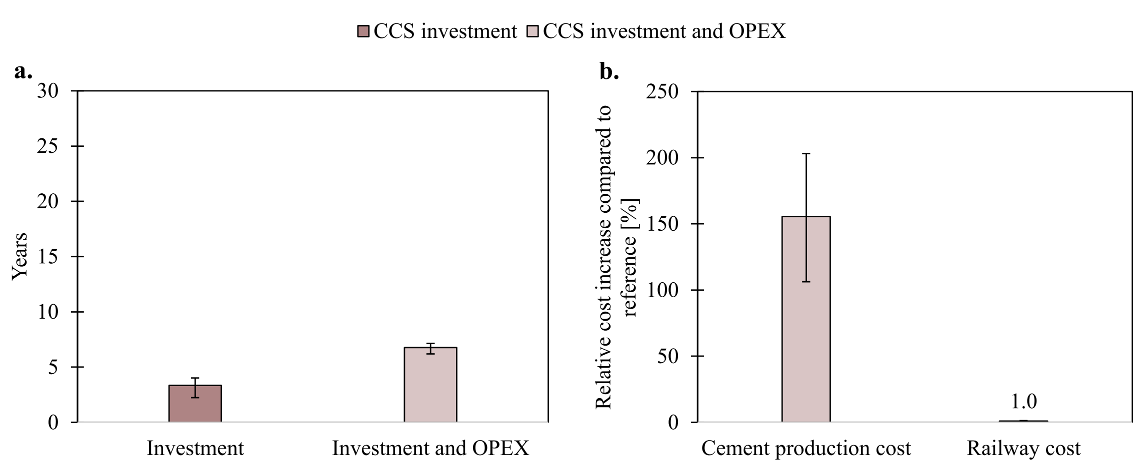

Fig. 5. a) The number of years needed to finance the overnight investment needs and operational expenditures of CCS in the European cement industries, based on the previous assessment of the roadmaps. b) The relative production cost increase on cement when implementing CCS and the impact on end-product the end-product – a high-speed railway – of applying a VCTF premium, defined as 100% of the difference in production cost (including both the capital and operational expenditures) between conventionally produced materials and low-carbon materials. The bars represent the mean values of the overnight investment needs and operational expenditures, as shown in Fig. 4, and the error bars show the maximum and minimum values.

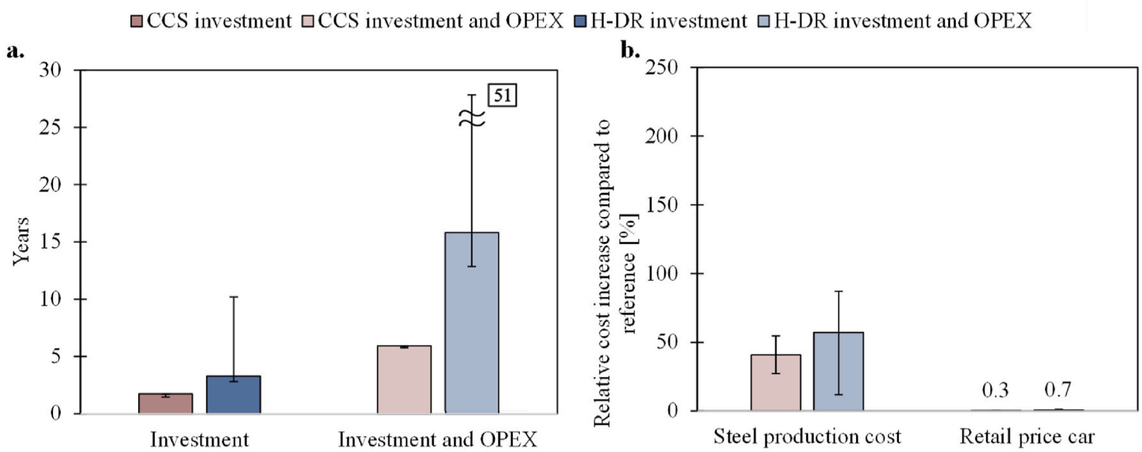

Fig. 6. a) The number of years needed to finance the overnight investment needs and operational expenditures of CCS and H-DR in the European cement industries, based on the previous assessment of the roadmaps. b) The relative production cost increase on cement when implementing CCS and the impact on end-product the end-product – a passenger electric vehicle – of applying a VCTF premium, defined as 100% of the difference in production cost (including both the capital and operational expenditures) between conventionally produced materials and low-carbon materials. The bars represent the mean values of the overnight investment needs and operational expenditures, as shown in Fig. 4, and the error bars show the maximum and minimum values.

cement sector (Figs. 5a and 6a) and the relative production cost increases for steel and cement when applying CCS and H-DRI, and the costs and price impacts on end-products – a high-speed railway and passenger EV, respectively – when applying a VCTF (Fig. 5b and 6b). The average yearly premium revenue for the cement industry is 7.3 billion € at an assumed premium level of 80 € per tonne of cement and an average cement demand of 91 Mtonne. In the steel industry, the average yearly premium revenue is €5.5 billion for CCS-produced steel and €10.2 billion for H-DR steel, based on premium levels of €127 and €212 per tonne, respectively, with demands of 43 million tonnes and 48 million tonnes. The bars in Fig. 5 correspond to the mean values of the estimated overnight investment needs and operational expenditures, as presented in Fig. 4, and the error bars show the maximum and minimum values.

Fig. 5a and 6a, show that the VCTF can be used to recoup all overnight investment needs for CCS in the European cement sector within 2–4 years. When also including pay-outs for operational expenditures, this time-frame is extended to 6–7 years. The funds estimated to be needed for CCS in the steel industries can be recouped over a time-frame of less than 2 years (excluding the roadmaps that have excluded CCS as a decarbonisation option or where the technology is non-competitive). This period is extended to 5–6 years when operational expenditures are included. Similarly, around 3 years (with a range of 2–10 years) is needed for the overnight investments that have been estimated for H-DR, while this is extended to 16 years when including the operational expenditures. However, the number of years required to recoup the costs in the H-DR case ranges from 12 to 51, with the maximum value being an extreme value that occurs at the minimum total overnight investment cost and the minimum premium level. In this work, we have assumed that the premium level corresponds to the difference in production costs between carbon-intensive and low-emission production. As a result, the annual premium income is reduced in this scenario, leading to a longer time required to recoup the costs. In this case, the premium would realistically have to be raised to shorten the period required to recoup the costs. The maximum end of the range represents the minimum VCTF premium and the minimum overnight investment needed. A lower VCTF premium results in a lower yearly premium revenue stream, which would extend the time needed to collect the needed funds, even when combined with the lower range of overnight investment cost. The opposite situation occurs for the minimum end of the range presented in Fig. 5a and 6a.

From the materials production cost calculations [Eq. (1)] and the related value chain analysis assuming full cost pass-through, it is found that the steel production cost increases 15%–50% and 12%–90%, while the retail price of the EV only increases by 0.2%–0.4% and 0.2%–1.1% (Fig. 6b) for CCS and H-DR, respectively. The cement production cost increases by 100%–200%, while the construction cost of the railway increases by 0.3%–0.6% (Fig. 5b). The cost-increase results are similar to those reported in previous studies by the authors ((Hörbe Emanuelsson and Johnsson, 2023; Rootzén and Johnsson, 2016a, 2016c; Subraveti et al., 2023).

In summary, the results suggest that applying a VCTF based on the assumed premium all investments needed for transformative technologies for deep-emission cuts in the cement and steel industries can be recouped within a time-frame of 6 years, which is extended to under 8 years for CCS in the cement and steel industries and 16 years for H-DR in the steel industry, while entailing a cost increase for end-consumers of only 0.2%–1.1%.

5. Discussion

Based on the plans of action that have been presented for the cement and steel industries within the EU, it is clear that, in spite of the proposed revisions of the EU ETS, announcements of expanded public support, and the introduction of new policy instruments (e.g. Carbon Contracts for Difference (CCfDs) and green labelling of products) there are currently insufficient incentives for most producers of basic materials across the EU to invest in low-emissions technologies. This is the situation despite these investments being essential for complying with the Paris Agreement, bearing in mind also the long lead times in the basic materials industry and associated value chains. The available EU climate funding mechanisms are mainly available for pilot-scale, demonstration, First-of-a-kind, and single flagship projects, and there are additional difficulties with acquiring funding from private investors due to the high market and technological risks associated with such investments. The primary purpose of the VCTF is the full-scale implementation and roll-out of technologies and measures that have reached a high TRL level (i.e., TRL 8–9). This is because there already exist financial instruments for public co-financing for research and demonstration projects on low-carbon technologies, such as those from the EU Innovation Fund (European Commission, 2023c).

The results presented in this work demonstrate how a VCTF can be used to share the financial risk of the high up-front investments and increased operational costs along the value chain to enable investments required to transform key CO_2-intensive production processes in industry. While we use investments in industrial production processes (such as CCS and H-DR) as examples in this work, the VCTF could also be suitable for financing common supporting infrastructure necessary for the transition. In addition, the VCTF is designed to: create a bottom-up system where basic material producers can be frontrunners in the transition without necessary governmental involvement; internalise the value of low-carbon processes in the end-product; and create funding for projects that are associated with high technological and market risks. Yet, it is important that the increased costs related to investments in transformative technologies can be transferred to the end-consumer in a transparent way, with the VCTF being one potential mechanism for doing so, so that a limited effect on the price of the final product can be demonstrated and communicated to the end-consumer in a credible way. Thus, communication with consumers must be transparent and engage the public in a way that creates markets for low-carbon products. Furthermore, it is of importance that emissions reductions are verified by third-party actors, to assure consumers of full credibility and transparency.

As indicated above, the largest investments that will be made to generate deep cuts in emissions along the supply chains to end-uses will be directed towards the cement- and steel-manufacturing industries. As this means that the VCTF funding is to be granted to a very limited number of firms in the supply chain, the process and investments need to be transparent, so as to create trust among the actors involved in building up the fund. Towards this goal, the government may support the establishment of a VCTF by means of state guarantees and co-operative arrangements with public involvement (Harring et al., 2021a). Depending on the type of basic materials industry, perhaps only a few stakeholders dominate the market. Entering the supply chain actor formation will create horizontal and vertical collaborations that have the potential to result in decreased competition (Harring et al., 2021a), which must be monitored. Thus, a sufficient number of actors must be involved to ensure fair competition on the market, which raises the question as to whether the VCTF should be a national initiative or based on some international platform with, for example, a Nordic or European scope. The solution to this issue may depend on the properties of the sector itself and the structure of the market in which it operates.

It is also likely that there will be a substantial willingness to pay for carbon-free materials, and that, for example, governmental procurement rules will require low-carbon materials once they are available on the market, even if they will be more-expensive (Åhman et al., 2023), and Ramboll, 2024 shows that nearly half of global companies are willing to pay a premium on low-carbon steel and concrete. This is an important argument for having transparent transfer of the mitigation cost to the end-consumer, as this will ensure, as shown in this work, that there will be only a marginal cost increase for the end-consumer. However, there is a risk for carbon leakage if lower-priced, but more-carbon-intensive materials can be purchased from outside the EU, which will be partly addressed through the implementation of CBAM (Magacho et al., 2023). It seems reasonable to assume that the provision of low-carbon materials will be a competitive advantage, assuming that the world is moving towards goals that are in line with the Paris Agreement. Thus, the point of departure must be that industry should comply with emissions cuts in line with what was agreed at the Paris meeting. This seems possible given that there is an emerging willingness in some sectors to compete by offering carbon-neutral products and services, and this willingness is likely to spread to other sectors. Awareness also seems to be increasing that governments have an important role to play in creating lead markets for green basic materials (e.g. through green procurement) (Otto and Oberthür, 2024). Some national, private-based initiatives, which use funds as a mechanism to accelerate a green transition process, have been initiated or proposed in recent years ((Hovi and Pinchasik, 2016);(Topham, 2018) Topham, 2018; (Ørsted, 2020)Ørsted, 2020). However, these initiatives do not cover the financing of lumpy technologies as the VCTF would, since they focus on granular technologies such as road transport and wind turbines. Another emerging trend is off-take agreements where basic materials producers secure an outlet for their fossil-free product by partnering with down-stream consumers, with agreements that cover several years ((Bataille, 2020); (Energy Transitions Commission, 2018); H2Green-Steel, 2024), but where the VCTF would provide broader risk sharing between actors in sectors which are largely fragmented such as the construction sector.(Ramboll, 2024)

Some elements of the VCTF have similarities with other non-governmental initiatives. For example, product labelling also intends to pass the cost increases along the value chain to the consumer in a transparent manner to showcase efforts made upstream the value chain (Taufique et al., 2022). As CCS and H-DR technologies become more well-established, it is plausible that the VCTF could gradually be replaced by labelling systems. Experiences of enforcing and working with an extended producer responsibility (EPR) for, for example, packaging or newspapers, can also provide valuable insights and analogies (OECD, 2016) to the VCTF. The VCTF proposed in the present work represents an inverted EPR. Along these lines, Wang et al., (2023) have proposed that the zero-draft of the Global Plastics Treaty should 'require polymer producers to address plastic pollution by paying a substantial fee pegged to the quantity of primary plastics produced', which would disincentivise the growth of fossil-based polymer production. A similar mixture of voluntary action by all stakeholders and a more-or-less explicit "threat" of government intervention (i.e., through a consumption charge as discussed above) could be an additional motivation for the VCTF. However, CCS and H-DR technologies are not yet well-established, and despite numerous proposals to accelerate their deployment, no commercial-scale plant is currently operational. These capital-intensive technologies face multiple barriers, including investment and market challenges, which must be addressed simultaneously. As Bataille et al. (2024) suggest, successful deployment will require iterative experimentation, acknowledging that many efforts may not succeed.

In this work, we explore two different set-ups of the VCTF: one where only the capital expenditures are covered, and a second one which also covers the operational expenditures for the first five years of implementation. As previously discussed, the first set-up would only address one part of the gap the VCTF intends to fill, namely acquiring capital for the investment. Secondly, the VCTF aims to address market barriers when low-emission materials have to compete against cheap carbon-intensive materials, which the second set-up explored in this work addresses. However, operational expenditures would only be covered for five years which might be deemed too short for a market to be functioning properly for low-emission products (as compared to the EU Innovation Fund which covers operational of up to ten years although only part of the OPEX, and the CCfDs introduced in Germany which lasts for fifteen years). If the VCTF were to cover operational expenditures for the first ten years, the time required to recoup the costs would increase further. The time required for CCS in the steel industry extends to 10 years on average, and the time for H-DR extends to 28 years on average. While the time for H-DR becomes rather long, it should be remembered that the evaluated premium level only results in a cost increase on the passenger EV of 0.7%, and the premium level could be increased to shorten the time. However, an argument for shorter OPEX coverage is that the VCTF is designed as a transitional solution, with the expectation that policy instruments and market mechanisms will eventually be established, enabling green basic materials markets to sustain themselves independently.

It will be important to ensure that the VCTF is designed so that it will complement rather than undermine the efficiency of the EU ETS. Ideally, the funds generated in the value chain for the VCTF will be matched with funds from the above-mentioned EU Innovation Fund, when possible. Moreover, the VCTF is a way to hedge against political uncertainties regarding the climate agenda, as it will be a private, bottom-up initiative. However, it is also important to note that even though the European cement and steel sectors are used in this work as case studies, the importance of the VCTF for the transition may be even more-pronounced in other sectors and in regions with less-stringent climate policies than the EU. It is true to say that if the world moves towards emissions reductions in line with the Paris Agreement there will be very strong demand for CO_2-free products and services. In that scenario, companies that can offer CO_2-free materials will be winners.

6. Conclusion and policy implications

The successful and timely roll-out of alternative, low-CO_2 production processes up to Year 2050 requires immediate action towards the formulation of business cases and the establishment of appropriate funding mechanisms (in addition to the setting of a clear political direction). It is clear that there are currently insufficient policy incentives for most producers of basic materials across the EU to invest in low-emissions technologies. Therefore, we argue that it is important and logical that the actors along the supply chain for carbon-intensive materials, such as cement and steel, should become actively involved in incentivising and sharing the costs associated with implementing transformative technologies such as CCS and H-DR. The actors involved in cement and steel supply chains could play central roles in the transition process by sharing the risks associated with investing in high-cost abatement measures such as CCS and hydrogen-based steel through a VCTF of the type proposed in this paper. When combined with other policy measures, this would constitute a poly-centric approach to the collective problem posed by climate change mitigation. Applying a VCTF premium to end-products demonstrates that all the overnight investments needed for CCS in the European cement and steel industries can be recouped in under 3 and 2 years on average, respectively. This is extended to under 7 and 6 years, respectively, when also including operational expenditures. The overnight investments needed for hydrogen-based steel making in the European steel industry can be collected on average within 3 years, while this is extended to 16 years on average when including operational expenditures. If the VCTF were instead to cover operational expenditures for the first ten years, the time required to recoup the costs would increase on average to 10 years for CCS and to 28 years for H-DR in the steel industry. The VCTF premium results in an increase in consumer prices of 0.2%–1.1% in the case of a passenger EV (under the assumption of full cost pass-through and no additional margins), and an increase in production costs of 0.3%–0.6% in the case of a high-speed railway. There are, however, additional issues that need to be investigated before the conditions for and design of a VCTF can be established, including the possibility of using it to leverage other national and EU funding; decisions as to the level set for the VCTF premium; and the possible governance structure and the level of involvement of governmental support.

CRediT authorship contribution statement

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

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Declaration of competing interest

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Appendix A

The material requirements for the passenger electric vehicle (EV) have been assumed according to the Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model (GREET) (Wang et al., 2023). The composition of automotive steel regarding flat (primary steel) and long products (secondary steel) has been assumed to 21, 19, and 60% for hot rolled sheets, galvanised cold-rolled sheets and wire rod and beams respectively (Wang et al., 2023). The retail price for the passenger EV using carbon-intensive has been assumed to 32,000 € per car which is some average price for low to medium sized Battery Electric Vehicles sold on the European market (Cox et al., 2020). This represents a rather conservative price of passenger EVs since the average price of BEVs sold on the European market in Year (2022) was 61,300 € per car (Statista Market Forecast, 2023).

Data availability

Data will be made available on request.

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