Title: Are Current Market-Based Policy Interventions for Carbon Capture and Storage for Decarbonising Iron & Steel and the Cement Industry Globally Effective?

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Background

The cement and iron & steel industries are among the highest emitters today. On one hand, the cement industry is considered one of the highly emission-intensive industries with approximately 26% of the total industrial CO_2 emissions (Guo et al., 2024). On the other hand, the iron & steel industry accounts for 7 to 9% of global GHG emissions. Carbon Capture and Storage (CCS) plays a crucial role in decarbonising these sectors, and the technical feasibility has been demonstrated (IEA, 2019). Yet, the use of CCS in decarbonising the iron & steel and cement industry represents an economic challenge given the high cost of clean steel and cement . The mitigation cost of CCS integration in the cement industry reaches a value of 125$/t (IEA, 2021), while in the iron & steel sector through blue hydrogen and CCS accounts for approximately 100$/t (ETC, 2022). however, these values are average, the mitigation cost per plant for all 3142 cement plants globally, and all 387iron and steel plants globally vary between 83$/t and 134 $/t, and 115 $/t and 155 $/t respectively. The total cost required for the cement sector exceeds 1496billion $/year, and the total cost required to decarbonise all iron and steel plants globally with CCS is 705 billion $/year. This shows the integration of CCS will double the cost of conventional technologies, given that most cost predictions rely on capture, storage and transport rather than specifically accounting for other components across the value chain. The impact on clean products such as clean steel and clean cement (price of clean cement 40-50% greater than conventional cement) and price of clean steel is 20-30% greater than conventional steel) makes integrating CCS economically unviable. Therefore, under these conditions, the deployment of CCS remains insufficient to create a demand pull and allow all stakeholders (3142 cement plants, 387 iron and steel plants in 165 and 50 countries respectively) reach net-zero goals. There is a general consensus that addressing the economic challenge would require economic incentives especially market-based measures like carbon taxes, emission trading schemes (ETS), tax credit on storage, tax credit on enhanced oil recovery, CO2 sale which currently exist in some countries globally. for example, countries like the European Union (EU), Japan, New Zealand, have implemented an ETS while covering 38%18%, and 48% of emissions. While these policies currently exist, there has been no attempt to quantify how effective they are in bridging the gap between clean cement, clean steel and conventional steel and cement. for example, can these market-based policy induce cost parity today? when would this happen? answering this question will support the development of a business case for CCS in deep decarbonisation of industry, and the methodology can be applied to other sectors. The unique methodology evaluates the impact of market-based policies from the bottom-up, accounting for plant/firm-level economics, plant size, current policies in the countries the plants are located over a timeline. and

Methodology

A novel ex-post spatio-temporal multi-market penetration model was developed to assess current market-based policies interventions for CCS implementation the iron & steel and

cement industries across global major producers from a bottom-up. The model was applied to 3142 cement plants in 165 countries, and 387 iron and steel plants and 50 countries: integrating the market-based policies in those countries and region. Detailed economic estimations of the cost of capture, storage and transport, and the price of clean steel and cement was included. Also included are the learning effects on their prices and the growth of the market for these products over time. The findings show where existing policies/ economic incentives like carbon taxes, emission trading schemes (ETS), tax credit on storage, tax credit on oil recovery (EOR), tax credit for clean hydrogen and revenue form CO2 sale are sufficient in creating positive tipping point and bridging the gap between clean technologies and business as usual (BAU) under real market circumstances

Case Study Applications and Key Findings

Cement Industry

The cement industry emits around 2.5 Gt of CO_2, a value prone to growth by around 23% by 2050 (Carbon Clean, 2022) where 60% of emissions are generated form limestone calcination (Bui et al., 2018). Therefore, the role of CCS is crucial in a sector where electrification remains a challenge (Barbhuiya et al., 2024). Without policy interventions, CCUS in cement is economically uncompetitive.

The only countries with effective market-based policies for the cement industry are countries within the European Union (EU) and the United Kingdom (UK) known for their ETS and national carbon taxes; Brunei, Chile, Columbia have implemented a carbon tax; Mexico, South Korea and Japan have introduced an ETS while the United States of America (USA) have focused on 45Q tax credit policy. Out of 3143 plants globally, 624 plants are located in countries with policy support with a total revenue from the policies equivalent to 1.536 billion $, while the cost of CCS located in these countries is around 82.5 $/t to 132 $/t.

The most impactful initiatives have been in the EU where the EU ETS has been effective in decrease the price gap between clean cement and business as usual by around 25%, it is complemented by nationally determined carbon tax that decreases further this gap. However, such interventions remain insufficient to reach the desired tipping point, accelerated by an annual reduction rate. Three distinct cases are investigated, where an annual reduction rate in CCS cost can lead to a positive tipping point the earliest by 2040, while an annual reduction rate of 3% to 5% can lead to cost parity by 2030. Another example is in The United States of America (USA) that has implemented the 45Q tax credit policy under the Inflation reduction Act (IRA) until 2030, where the storage of 65% of emission and use of 5% for EOR can lead to a positive tipping point by 2029, given an annual reduction rate of 5%. Without these policies, accompanied by annual reduction rates, large-scale CCS adoption in the cement industry remains uneconomical if driven solely by existing economic incentives.

Iron and Steel Industry

The two primary methods of iron and steel production are electric arc furnace (EAF) and basic oxygen furnace (BOF) where the two different scenarios studies are scenario 1 where

conventional steel EAF is replaced by blue hydrogen and scenario 2 where BF FOF is replaced by BF BOF with CCS. The results obtained in this case are conditioned upon the plant location..

The only countries with policy implemented for the iron & steel industry are Canada that has implemented both an ETS and carbon tax on provincial level; Argentina and South Africa have implemented a carbon tax; Japan, South Korea and Mexico have implemented an ETS as well as the EU and the Uk that have provided both a carbon tax and an ETS. Finally, the United States of America has implemented a tax credit through the 45Q and 45V policies. Out of these 387 plants globally, only 61 plants are located in countries with policies with a combined total revenue of 10.1 billion $ while the cost of CCS per plant has ranged from 120$/t to 155 $/t for plants located in those countries.

Therefore, for plants location in EU, EU ETS plays a crucial role in decreasing the gap in costs between clean steel and BAU by 22%, insufficient to reach a positive tipping point. Combined with an annual reduction rate ranging from 5% to 1%, a positive tipping point is reached between 2030 and 2042, respectively. Conversely, carbon taxes, if increased can be uneconomical, leading to cost inflation and unattractive atmosphere to investments. This case is flagrant in Canada where different policy mechanisms are implemented in different provinces, Ontario and Quebec. The Quebec ETS accompanied by an annual reduction of 3% remains more attractive than an 80$/t carbon tax in Ontario.

Blue Hydrogen Production

Interconnected to CCS, blue hydrogen will play a critical role in decarbonising different end-use sectors (Pettersen et al., 2022) as well as the development of a hydrogen economy of use and energy storage for the upcoming 20 years (Bauer et al., 2022). While carbon taxes and ETS can lead to cost gap reductions, only the United States of America (USA) proposes the 45V tax credit of 3$/kg for clean hydrogen, which can incentivise the investment in blue hydrogen to decarbonise these industries.

Conclusion

This study provides a comprehensive ex-post assessment of current market-based policy interventions for Carbon Capture and Storage (CCS) and blue hydrogen deployment in the cement and iron & steel industries. Given that these industries collectively account for a significant share of global CO_2 emissions, their decarbonisation is essential to achieving net-zero goals. However, high mitigation costs and the price disparity between conventional and clean alternatives remain major barriers to investment. Using a spatio-temporal multi-market penetration model, this study quantifies the economic viability of CCS adoption under existing policy frameworks, identifying the conditions under which cost parity can be achieved.

Findings indicate that while market-based interventions such as carbon taxes, emissions trading schemes (ETS), tax credits on storage, tax incentives for enhanced oil recovery (EOR), and revenues from CO_2 sale provide some level of economic support, they are currently insufficient to drive large-scale CCS adoption without additional policy mechanisms. For instance, the EU ETS has been effective in reducing the cost gap between clean cement and conventional cement by 25%, while national carbon taxes further narrow this gap. However, even under these

conditions, a positive tipping point is not expected before 2040 unless annual reduction rates in CCS costs accelerate to at least 3-5% per year. Similarly, in the United States, the 45Q tax credit under the Inflation Reduction Act (IRA) provides an effective mechanism for incentivising CCS deployment, with results showing that a positive tipping point for CCS in cement could be reached by 2029 if cost reduction trends continue at 5% annually.

In the iron & steel industry, policy effectiveness varies by region. The EU ETS currently reduces the cost gap between clean steel and conventional steel by 22%, but this is not enough to reach cost parity. Under existing market conditions, a positive tipping point for CCS-equipped steel production is projected between 2030 and 2042, depending on the rate of annual cost reductions. In Canada, policy divergence between provinces implementing ETS (e.g., Quebec) and those relying on carbon taxes (e.g., Ontario) has resulted in stark contrasts in investment attractiveness. Higher carbon taxes, while effective in raising the price of conventional steel, can lead to inflationary pressures and investor uncertainty, making ETS a more sustainable long-term approach.

For blue hydrogen, the 45V tax credit in the U.S., offering up to $3/kg for clean hydrogen, is a critical policy tool driving investments in hydrogen infrastructure. Other regions lack similar market-based incentives, limiting the economic feasibility of blue hydrogen deployment at scale.

The evidence from this study shows the role of well-designed market-based policies in enabling the economic viability of CCS and blue hydrogen in hard-to-abate industries. However, current policies remain fragmented, region-specific, and often inadequate to achieve cost parity between clean and conventional alternatives. To accelerate market penetration and investment attractiveness, policymakers should consider (1) Enhancing ETS and carbon pricing mechanisms to create progressive cost reductions over time, ensuring a gradual transition rather than abrupt cost inflation, (2) Expanding tax credit mechanisms similar to 45Q and 45V to additional regions, providing financial certainty for CCS and hydrogen investments, (3) Integrating revenue models for CO_2 utilisation to offset CCS costs and create alternative market pathways for captured carbon.