Title: A Bottom-up Design of Market-Based Policy Interventions to Improve the Economic Viability of Industrial Decarbonization Solutions

Background

Industrial decarbonization remains economically challenging due to the high cost of low-carbon technologies across multiple sectors. Industrial decarbonisation solutions like Sustainable aviation fuels (SAF) cost two to five times more than conventional jet fuel, while e-methanol and e-ammonia for shipping are five to seven times more expensive than heavy fuel oil. Green hydrogen production requires a 78% cost reduction to compete with natural gas, while transitioning to clean ethylene via methanol synthesis (MS) and methanol-to-olefins (MTO) necessitates a carbon price increase of 750% to 2096% over current levels in the European Economic Area. Direct air capture (DAC) for carbon dioxide removal costs between $250 and $750 per tonne CO_2, and its deployment remains far below what is required to meet net-zero targets. Addressing these cost gaps necessitates market-based policy interventions designed from the bottom up, ensuring alignment with sector-specific demand constraints, firm/plant size, technology cost curves, and regional regulatory conditions.

Methodology

A multi-market penetration optimization model is developed and applied to assess market-based interventions in five industrial decarbonization solutions: sustainable aviation fuels, e-methanol and e-ammonia for shipping, MS+MTO for clean ethylene production, direct air capture across the US, EU, and UK, and green hydrogen production. The model integrates learning curves, demand projections, cost trajectories, and policy cost-effectiveness metrics to determine the optimal combination of Contracts-for-Difference (CfD), Carbon Contracts-for-Difference (CCfD), Emissions Trading Schemes (ETS), carbon taxes, and subsidies in bridging cost gaps and trigger economic tipping points This approach allows for a bottom-up assessment of policy measures tailored to different real-world market environments and demand data. Ultimately, the model provides insight into the policy combinations necessary to accelerate adoption in different market environments.

Case Study Applications and Key Findings

Sustainable Aviation Fuels (SAF)

The aviation sector, which accounts for approximately 3% of global greenhouse gas emissions, requires an urgent transition to sustainable fuels. However, SAF remains uncompetitive with conventional kerosene without policy intervention. This study demonstrates that a CfD mechanism for SAF could reduce government support costs by 30%, while Carbon Contracts-for-Difference (CCfDs) linked to emissions reductions could enable cost parity by 2040 under a carbon price of $150 per tonne CO_2. Additionally, implementing a kerosene tax alongside CfDs and direct production subsidies would create sufficient demand-pull to encourage investment in SAF infrastructure. Without these policy interventions, large-scale SAF adoption would remain economically unfeasible.

E-Methanol and E-Ammonia for Shipping Decarbonisation

The maritime industry faces significant barriers in transitioning to zero-carbon fuels such as e-methanol and e-ammonia. By 2050, demand for e-ammonia is projected to reach 3.5 EJ, while e-methanol will require 0.85 EJ to align with global shipping decarbonization targets. Without intervention, these fuels will remain substantially more expensive than fossil-based heavy fuel oil. This study finds that a carbon tax of $33.6 to $162.8 per tonne CO_2, combined with subsidies ranging from $32.3 to $79.15 per MWh, could reduce e-ammonia costs by 24% and e-methanol costs by 29%. A policy approach integrating

ETS credits, carbon pricing, and production subsidies is required to drive long-term cost reductions and encourage large-scale adoption.

MS+MTO for Clean Ethylene Production

The petrochemical industry must transition to cleaner processes to reduce its significant emissions, but the current cost structure of MS+MTO makes widespread adoption impractical. Achieving cost parity with conventional ethylene production requires an estimated carbon price of €1,350 per tonne CO_2, which is far beyond the current EU ETS price. This study reveals that targeted subsidies, coupled with moderate increases in ETS carbon pricing and reductions in feedstock costs, could enable the economic viability of MS+MTO within the next two decades. Policy frameworks must distribute the financial burden between industry and government to avoid excessive reliance on carbon pricing while ensuring that clean ethylene production remains a viable alternative.

Direct Air Capture (DAC)

Direct air capture (DAC) is a solution for large-scale carbon removal but remains economically unviable without stronger policy support. To meet net-zero goals, DAC deployment must significantly increase across key regions. In the United States, DAC must capture 850–2,250 $MtCO_2$ annually by 2050, requiring at least 7–9 $MtCO_2$ per year by 2030 to remain on track. In the European Union, DAC deployment targets range from 83 to 264 $MtCO_2$ per year by 2050, while in the United Kingdom, DAC must scale to 25 $MtCO_2$ per year by 2050, with an interim goal of 5 $MtCO_2$ by 2030 as part of its Sixth Carbon Budget. Despite these ambitious targets, the current economic framework is insufficient to support the necessary scale-up, as existing demand-pull policies fail to generate the financial incentives required for investment. In the United States, policy support for DAC primarily comes from the 45Q tax credit, which offers $180 per tonne CO_2 permanently stored and $130 per tonne for CO_2 utilized. Additionally, California's Low Carbon Fuel Standard (LCFS) allows DAC projects to generate credits that can be sold within the transportation sector. While these mechanisms provide some financial relief, they are not sufficient to drive large-scale deployment. The LCFS suffers from volatile credit prices, averaging $67 per tonne CO_2 in 2024, making revenue streams uncertain. This study finds that, under current policy conditions, DAC deployment in the U.S. is unlikely to meet net-zero targets unless credit values are at least doubled or tripled by 2030. An alternative approach, such as integrating DAC into a federal compliance carbon market or expanding Advance Market Commitments (AMCs), could offer a more stable demand-pull mechanism. AMCs, which guarantee future purchases of DAC credits at a fixed price, could help mitigate investment risks and provide a clearer path for scaling. In the European Union, DAC is expected to play a significant role in meeting the European Green Deal's climate neutrality target by 2050. However, DAC is not currently integrated into the EU Emissions Trading Scheme (EU ETS), meaning it does not generate compliance carbon credits. This limits its ability to attract investment, as DAC projects cannot sell allowances within the EU carbon market. The European Commission is set to review the inclusion of carbon removal projects in the EU ETS by 2026, but until then, DAC remains without a stable revenue stream. This study finds that integrating DAC into the EU ETS would significantly improve its financial viability by allowing DAC operators to monetize stored CO_2 at market-based carbon prices. Under existing ETS price forecasts, credits are expected to reach €80–€160 per tonne CO_2 by 2030, which, while an improvement, is still below the $250–750 per tonne CO_2 cost range for DAC. To close this gap, the EU would need to introduce supplementary subsidies or create a dedicated carbon removal crediting mechanism within the ETS. In the United Kingdom, DAC has been identified as a key technology for achieving net-zero emissions, with deployment targets of 5 $MtCO_2$ per year by 2030 and 25 $MtCO_2$ per year by 2050. The UK government has launched consultations on incorporating DAC into the UK Emissions Trading Scheme (UK ETS), but no

implementation date has been set. Without inclusion in the UK ETS, DAC remains reliant on limited government grants and private-sector purchase agreements through voluntary carbon markets. The uncertainty surrounding policy support has slowed investment, leaving DAC projects without the necessary financial backing for scale-up. This study finds that, to reach the UK's 2030 target, the government would need to introduce long-term revenue stabilization mechanisms, such as contracts-for-difference (CfDs) for carbon removals, or directly integrate DAC into the UK ETS with an enhanced carbon price floor. Without these measures, DAC is unlikely to progress beyond pilot-scale projects. Across all three regions, this study highlights that current policy mechanisms are insufficient to make DAC economically viable at the scale required for net-zero goals. The most effective interventions involve integrating DAC into compliance carbon markets, increasing credit values under ETS systems, and expanding AMCs to guarantee long-term purchase commitments. Without these market-based solutions, DAC risks falling into the "valley of death," where the high upfront costs prevent widespread adoption.

Green Hydrogen Production

Green hydrogen is expected to play a crucial role in industrial decarbonization, with UK hydrogen demand projected to increase from 0.68 TWh in 2025 to 73.27 TWh by 2050. However, existing policy measures are projected to achieve only a 39% cost reduction, leaving a significant gap in competitiveness. This study finds that integrating curtailed wind energy, waste heat utilization from electrolysis, and demand-side incentives through hydrogen purchase agreements could drive an additional 78% cost reduction. A combination of the UK Hydrogen Business Model, ETS revenues, and sustainability-linked bonds (SLBs) is identified as the most effective policy mix for enabling cost parity by the mid-2030s.

Conclusion

This study presents a bottom-up approach for designing market-based policy interventions for industrial decarbonization. Unlike macroeconomic models that simplify policy evaluations by omitting plant-specific cost structures to maintain model tractability, this approach provides granular insights into how interventions impact the economic viability of emerging technologies at the industrial level. This study bridges the gap between theoretical policy models and real-world deployment challenges, by incorporating plant-level details, offering a clearer pathway for aligning policy design with industry realities. Incorporating plant-level cost structures into policy design means governments and industry leaders can propose interventions that increase the diffusion of decarbonisation solutions to drive reductions in carbon emissions while maintaining economic stability. The findings indicate that standalone policies such as carbon taxes are insufficient to close the cost gap for industrial decarbonization technologies. Instead, a combination of incentives, carbon pricing, and revenue stabilization mechanisms is necessary to create an environment where decarbonisation solutions can scale effectively. The research also highlights the need for staged policy implementation, where early adoption is driven by government support through subsidies and CfDs, transitioning to market-based instruments such as ETS credits and tax incentives as technologies mature. the outcomes of these case studies inform macroeconomic models and policy decision-making processes. Industrial decarbonization requires policies that are both economically viable and scalable across different markets.