Market Mechanisms for Financing Industrial Decarbonisation: Steel Case Study

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Abstract

This study investigates the potential of market-based mechanisms to enhance the financial viability of industrial decarbonisation, using the UK steel sector as a case study. The research evaluates how the implementation of an Emissions Trading Scheme (ETS) revenue recycling model and Carbon Contracts for Difference (CCfDs) can improve the net present value (NPV) of a steel plant integrating carbon capture, utilisation and storage (CCUS) technologies.

A techno-economic model was developed to simulate the plant's performance under different policy scenarios, comparing baseline operations with and without the application of market mechanisms. Results show that both ETS recycling and CCfDs substantially increase project NPV, indicating that well-designed market instruments can reduce the investment risk and cost barriers associated with industrial decarbonisation. The findings suggest that aligning carbon pricing revenues with sectoral reinvestment and providing long-term revenue certainty through CCfDs could accelerate low-carbon technology deployment in heavy industry.

Overall, the study highlights the critical role of targeted market mechanisms in enabling an economically feasible transition toward net-zero steel production in the United Kingdom.

Contents

1. Introduction

1.1 Background – Climate Change and Industrial Emissions

Climate change poses one of the most significant global issues of the 21^{st} century: global warming. Evidence for the warming of the planet can be seen in Figure 1[1] – with global mean annual temperatures rising by over +1.5 degrees Celsius from pre-industrial levels.

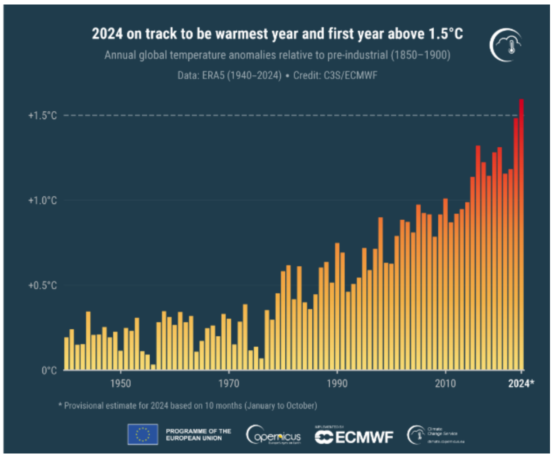

Figure 1: A graph to show global annual temperature increase, relative to pre-industrial temperatures

Global warming is driven largely by the rise in concentrations of greenhouse gases (GHG) in the atmosphere, such as carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), fluorinated gases and water vapour (H2O). These absorb solar radiation and radiate it back towards the Earth, creating a warming effect which is known as the 'Greenhouse Effect'.

[1] The year 2024 set to end up as the warmest on record | Copernicus

The increase in atmospheric GHG, as evidenced in Figure 2[2], can be attributed to anthropogenic causes – such as the increase in the release of industrial emissions since the Industrial Revolution in the 18th century. The burning of fossil fuels such as coal and oil releases the carbon built up and stored over millions of years in just a few hundred years. Based on the annual analysis from the National Oceanic and Atmospheric Administration's (NOAA) Global Monitoring Lab, the average global atmospheric carbon dioxide was 422.8 parts per million (ppm) in 2024 – a new record high. This is also the largest annual increase on record, jumping 3.75ppm from 2023.[3]

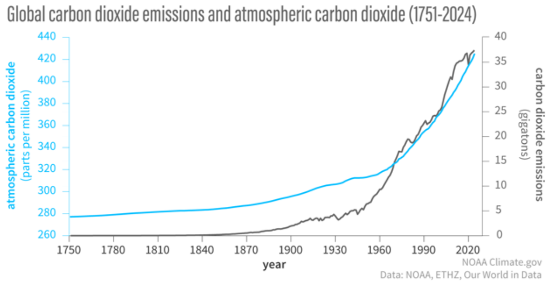

Figure 2: A graph to show global CO2 increase since the Industrial Revolution

1.2 The role of the steel sector in UK emissions

The steel sector is a significant contributor to the UK's GHG emissions – responsible for 14.2% of industrial emissions and 2.4% of the UK's total GHG emissions.[4] The UK has committed to achieving net zero GHG emissions by 2050, with an interim target of reducing industrial emissions by two-thirds by 2035. Decarbonisation of the steelmaking industry is therefore imperative for the overall decarbonisation of the UK industry.[5]

In 2024, the UK experienced a 9% decline in industrial emissions, primarily driven by the recent decline in coal use nationwide, which led to the closure of blast furnaces in the iron and steel-making industry. Notably, Britain's largest steelworks in Port Talbot, Wales, halted production in September 2024, after more than 100 years of operation.[6] Tata Steel is replacing the furnace with a greener electric arc furnace, which will use UK-sourced scrap steel and will not rely on coal. However, this will not be operational until 2028.[7]

This is just one example of the future of steel production in the UK. Many plants are being forced to close rather than switching to low-carbon technologies or attempting to decarbonise and reduce their emissions. This is due to the lack of affordability that comes with decarbonising the steel sector.

In the past, under the EU ETS, it was more affordable for UK companies to pay the fine administered under the carbon tax than to invest in switching to low-carbon technologies to avoid the tax. However, in recent years, following the UK's departure from the EU and the introduction of its own ETS, the carbon tax has increased significantly. Whilst the carbon tax has increased, the cost of low carbon technologies has not decreased proportionately – essentially removing the 'cheaper' option. This has led to the closure of many companies that cannot afford to pay the carbon tax or switch to green technologies.

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[2] Images and Media: dashboard-carbon-dioxide-emissions-vs-atmospheric-concentration-1751-2024.png | NOAA Climate.gov
[3] Climate change: atmospheric carbon dioxide | NOAA Climate.gov
[4] CDP-2023-0016.pdf
[5] Green steel
[6] Britain's greenhouse gas emissions fell 4% in 2024, government data shows | Reuters
[7] Tata Steel: UK's biggest steelworks shuts down final furnace after more than 100 years | UK News | Sky News

2. Market Mechanisms for Decarbonisation

2.1 Overview of Market-based Policy Tools

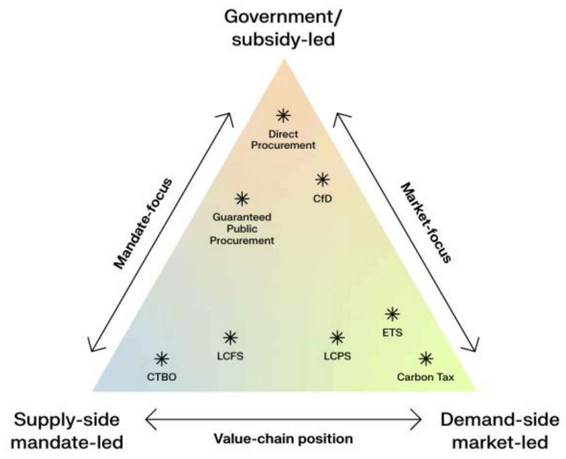

Figure 3: Schematic visualising CCS policy space

Market mechanisms (or interventions) are a range of actions taken by governments or regulatory bodies to influence or alter the functioning of a market. They are typically aimed at either correcting a market failure or achieving specific economic outcomes. Market mechanisms differ from mandates in the sense that, instead of simply enforcing a rule for a desired result, they use price signals and financial incentives/disincentives to manipulate the market towards the desired outcome - in a way that encourages innovation and cost-effectiveness.

The dangers of relying on mandates alone to enforce an outcome can be seen in the decline of the UK's steel sector, with the UK's ban on coal for power causing the closure of the plants, as covered in section 1.2. Without the use of government subsidies to cover Tata's switch to an electric arc furnace, the company would likely be unable to switch to this low-carbon technology, resulting in its closure.

Figure 3 shows a schematic visualising policy space specific to carbon capture and storage (CCUS), taken from the 2025 Markets and Mandates paper. Corners represent policy categorisations: Government (subsidy-led) policy in orange, Demand-side (market-led) policy in green, and Supply-side (mandate-led) policy in blue. Examples of individual policies are represented by stars.[8]

2.2 Carbon Pricing Approaches

Carbon pricing is an example of a market-based policy tool where a monetary value is assigned to GHG emissions, aiming to reduce emissions and help mitigate climate change. By putting a set price on emissions, carbon pricing aims to disincentivise producers against emitting – instead pushing them towards innovation and investing in cleaner technologies to avoid paying the price.

There are many ways to incorporate carbon pricing into market mechanisms, but the two primary mechanisms are as described below:

2.2.1 Carbon Taxes

Carbon taxing is a simple mechanism which comprises simply charging a fixed price for every tonne of CO2 emitted. The price is set by the government, and the emitters simply decide whether to pay the fine or to decarbonise to comply with regulations and avoid the cost.

[8] Markets-Mandates-2025.pdf

2.2.2 *Emissions Trading Schemes (ETS)*

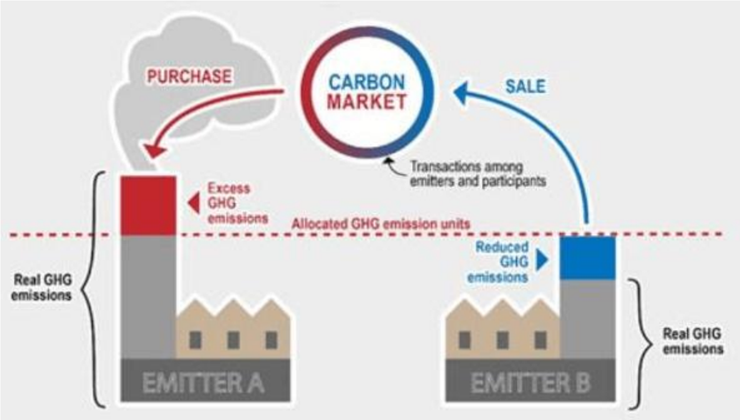

Figure 4: Diagram explaining the concept of allowances

Emissions trading schemes (ETS) (or 'cap and trade' systems) work differently from carbon taxes by creating the opportunity for businesses to profit from the system – incentivising decarbonisation and investment in low-carbon technologies.

The government sets a cap on total emissions and issues tradable allowances equal to the cap set (where each allowance permits 1 tonne/CO2 to be emitted). Allowances can either be auctioned (companies buy them) or given for free (which prevents competitiveness or "carbon leakage"). At the end of each year, companies must surrender their allowances equal to their emissions for that year – if they emit more than their allowances can cover, they must either pay a fine or buy extra permits. This is demonstrated in Figure 4.[9]

Companies are able to profit from an ETS system if they emit less than they are per mitted to by their allowances – this enables them to sell their remaining allowances to other companies that are emitting more than they are permitted to. The allowances can be bought and sold in an open market, where the price is determined by the supply versus demand for the permits. Governments can introduce a price floor/ceiling to reduce the volatility of prices and provide stability – for example, in 2017, a price ceiling was added to California's Cap-and-Trade system.

ETS are considered to be market-based policies as companies have the flexibility to decide how they comply, with price signals driving investment and behaviour rather than prescriptive rules/mandates.

2.3 Revenue Recycling and Incentives

Revenue recycling refers to how the funds collected by the government from carbon pricing are used – whether they are used elsewhere in the economy or recycled back into funding to support decarbonisation. Sources of government revenues include the auctioning of allowances in an ETS and carbon tax payments from the emitting companies.

Revenue recycling is important as it addresses cost concerns, where heavy industries, such as the steel sector, can face higher operating costs (OPEX) due to carbon pricing from the government. By recycling the revenues generated from the carbon tax, the government can offset the costs and make industries more competitive. Revenue recycling also promotes investment in low-carbon technologies – funds generated can be directed towards the adoption/switch over to green, cleaner technologies, such as CCUS, electric arc furnaces or energy efficiency upgrades in the steel sector. By

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[9] UK's ETS Will Demonstrate Its Ability to Impact Emissions if Appropriate Future Market Policies are Put in Place - Climate Scorecard

linking funding directly to low-carbon investments, revenue recycling increases incentives to reduce emissions.

Incentives enabled by revenue recycling:

Incentive	What it does
Direct investment support	Grants/subsidies for low carbon tech (eg, CCUS at steel plants).
(Carbon) Contracts for difference (CCfD)	Fixed carbon abatement revenue to reduce investment risk (e.g., ETS revenue fund CCfD for CCUS deployment in the steel sector).
Tax reductions/rebates	Reducing corporate taxes for companies investing in decarbonisation.
Innovation funding	Research and development for new technologies.
Consumer /household support	Compensating for higher energy costs from carbon pricing.

Examples of revenue recycling: UK Industrial Decarbonisation Fund + EU ETS.

Revenue recycling strengthens the effectiveness of market mechanisms by making high-cost abatement financially feasible, reducing the risk of investing encouraging the adoption of new, green technologies which would otherwise be unaffordable for a company being taxed under a carbon price alone.

2.4 Contracts for Difference (CfDs and CCfDs)

Contracts for difference (CfDs) are an example of a market-based intervention set by the government, in which the government will guarantee a fixed ‘strike’ price for a product (normally electricity). If the market price is lower than the strike price, the government will pay the producer the difference. However, if the market price is higher, the producer will pay the difference back. This guaranteed price provides financial stability to companies by helping to protect them from price fluctuations and market volatility.

Carbon contracts for difference (CCfDs) are an adaptation of the CfD model for carbon abatement, rather than electricity. The strike price is set on the cost of CO2 abated – if the market price (ETS) is below the strike, the government will pay the difference, and if the ETS price rises above the strike, the company will pay the difference. The benefits of CCfDs are the same as CfDs, for industrial decarbonisation – they provide revenue certainty for investors by de-risking investments in expensive low-carbon technologies (for example, CCUS).

2.5 Free Allowance Allocation and Leakage Prevention

Carbon leakage refers to the process of shifting production abroad to regions with weaker or no carbon pricing, when policies raise the costs too high for domestic producers. Under an ETS, companies must purchase allowances to cover their emissions – but a certain portion of these are allocated to producers for free. Free allowances help to protect companies against sudden cost changes and shocks, and to prevent carbon leakage by incentivising production to remain domestic.

Free allowances are normally allocated based on benchmarks of emissions efficiency – a plant will only receive enough free allowances to cover what an efficient plant would need. If they require more (ie, emit more), they will not have enough permits to cover their emissions and will either need to reduce them or purchase more permits. This way, the most efficient producers benefit, whilst inefficient plants face more cost pressure – an incentive to decarbonise.

Using free allowances has many benefits, including protection of companies from competitiveness (from both domestic and international producers), preventing carbon leakage and supporting a gradual transition towards investment in low-carbon technologies. However, when the percentage of free allowances allocated is too high, some negative repercussions include; weakening of the carbon price signal (if emissions are covered by the permits, there is less of an incentive to reduce emissions); inequity between certain industrial sectors; a temporary fix (not sustainable in the long run as it doesn't push for low-carbon adoption).

Free allocation of allowances softens the impact of the UK ETS on steel NPVs – without them, costs would be much higher and the NPV more negative. However, free allowances delay investment in low-carbon technologies by lowering the carbon price signal, which is counterproductive in the long run, being unsustainable for both the company and the planet. By reducing the number of free allowances and recycling ETS revenues into supporting CCfDs, decarbonisation is directly supported and de-risked – by both disincentivising emissions and lessening the financial burden of low carbon technologies.

2.6 International Examples of Market Mechanisms in Industry

As covered in section 2.1, market-based mechanisms can take the form of both incentives for decarbonisation and disincentives against releasing emissions. Some examples of both can be found in the table below:

Incentives	Disincentives
Subsidies and grants = reduce upfront cost and financial risks of adopting low-carbon tech. e.g. EU Innovation Funds (60% project costs); US CCS Grants.	Fossil fuel subsidy removal = phasing out public subsidies for fossil fuels to level the playing field for clean alternatives. E.g., Indonesia's fossil fuel subsidy reforms.
Contracts for Difference (CfDs) = pays the difference between market and fixed 'strike' price for low-carbon output (ie, Guaranteed price). E.g., UK CfD for offshore wind, low-carbon hydrogen.	Regulatory penalties = fines or legal consequences for exceeding emissions limits or violating environmental rules. E.g., US Clean Air Act.
Feed-in-Tariffs (FiTs) = guaranteed above-market price for energy from clean sources over a fixed term (~10-20yrs). E.g., UK FiTs – historically for renewable energy.	Carbon Border Adjustment Mechanisms (CBAM) = applying a carbon price on imported goods based on their embedded emissions. E.g., EU CBAM (phased 2023-2026).

Examples in detail:

1. Subsidies and grants:

- The EU Innovation Fund takes recycled EU ETS revenues to cover the cost of innovative projects in energy-intensive industries, renewables and carbon capture to accelerate decarbonisation. The fund covers up to 60% of the project cost and is disbursed flexibly based on the project's financing needs, taking into consideration the milestones achieved in the project's lifetime.[10]
- The US CCS Grants are federally funded programmes, providing cost-shared support for innovation and deployment of carbon capture and storage technologies to reduce industrial and power sector emissions. They are financed by the US federal government budgets, not by carbon pricing revenue.[11]

2. Contracts for difference:
    - In the UK, CfDs have been implemented for offshore wind farms - making the electricity produced here competitive and de-risking renewable electricity.[12] A similar CfD has been introduced for Low Carbon Hydrogen – called the Low Carbon Hydrogen Agreement (LCHA)[13]
3. Feed-in Tariffs (FiTs):
    - Between 2010-2019, the UK operated a feed-in tariff scheme to promote the uptake of renewable and low-carbon electricity generation. It was replaced by the Smart Export Guarantee (SEG) in 2020.[14]
4. Fossil fuel subsidy removal:
    - Indonesia's government has a long history of fossil fuel subsidies, making energy and electricity cheap for consumers. However, over time, they have been reforming the subsidies, notably with two acts in 2005 and 2014. The reforms include: (i) reducing the number of subsidised fuel products from seven to three; (ii) implementing a conversion program to encourage the use of LPG instead of kerosene; and (iii) introducing a semi-automatic fuel pricing mechanism with fixed per-litre subsidies.[15]
5. Regulatory penalties:
    - The US Clean Air Act acts as a regulatory penalty mechanism by setting legally enforceable air quality and emissions standards, imposing fines or enforcement actions on facilities that fail to comply. Non-compliance can lead to monetary penalties, injunctions, or even criminal charges, creating a financial and legal deterrent against excessive pollution.
6. Carbon Border Adjustment Mechanisms (CBAM):
    - The EU's CBAM is due to come into effect in 2026 (with a phase-in period from 2023-2026). The mechanism is the EU's tool to put a fair price on carbon emitted during the production of carbon-intensive goods that are entering the EU, and to encourage cleaner industrial production in non-EU countries.[16]

[10] What is the European Union Innovation Fund? - European Union Innovation Fund
[11] Billions in Federal Funding Earmarked for Power Plant CCS Projects: Here's a Snapshot
[12] UK's Seventh CfD Allocation Round Launched | Offshore Wind
[13] Hydrogen production business model - GOV.UK
[14] Feed-in Tariffs (FIT) | Ofgem
[15] https://documents1.worldbank.org/curated/en/099748505212431959/pdf/IDU1e31e5e531f16114baa1b62c1b3201c9c2e68.pdf
[16] https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_enhttps://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en

3. UK Policy Context

3.1 UK Net Zero Targets and Industrial Strategies

The UK Net Zero target is a legal commitment to reduce all greenhouse gas emissions to net zero by the year 2050. The UK was the first major economy to pass laws requiring the end of its contribution to global warming in 2019.

In 2019, the UK became the first major economy to pass laws requiring a 100% reduction of GHG emissions (with the expectation of reaching net zero emissions by 2050). They did so by setting interim carbon budgets, which are legally binding caps on the maximum level of emissions ('the net UK carbon account') for a period of five years.[17] The budgets increase over time, so emission caps also increase. So far 6 carbon budgets have been set, with the 7th due to be set by June 2026, covering emissions from 2037 to 2042.

As well as its own Clean Air Acts and carbon budgets, the UK has also pledged to reduce emissions by 81% from 1990 levels by 2035 through its 'nationally determined contribution' to the international Paris Agreement.

The industrial strategies in place to achieve the goal of net zero carbon in time for the 2050 target include:

1. Ten Point Plan (2020) – a government strategy to accelerate the transition to a net-zero economy by investing in green technologies and infrastructure. The plan aims to create 250,000 green jobs and attract significant private investment to build a leading global green economy. The ten points of the plan are demonstrated in Figure 5.[18]

	Sector	Ten Point Plan Implications
	Offshore Wind	40GW of offshore wind by 2030
H_2	Hydrogen	5GW of low carbon hydrogen production to be developed by 2030
	Nuclear	£170m invested in advanced modular reactors and £215m in small modular reactors
	Jet Zero & Maritime	£20m to the Clean Maritime Demonstration Programme and £15m to FlyZero for technology development
	Electric Vehicles	Ban on sales of new petrol and diesel cars in 2030 and £1.3bn to increase charging infrastructure
	Public Transport	£120m invested in 4000 new zero emissions buses in the next year and £5bn towards cycling, walking and bus infrastructure
	Homes & Buildings	£1bn next year for funds to insulate homes and public buildings and provide a further £5.8 bn to support heat pumps installation
	Nature	£40m for round two of the Green recovery Challenge Fund
CO_2	Carbon Capture	£1bn to create 4 industrial clusters to remove 10MTCO_2 by 2030
	Innovation & Finance	£1bn to the Net Zero Innovation Portfolio

Figure 5: A table to show the UK's Ten Point Plan and it's implication on each sector

[17] https://commonslibrary.parliament.uk/what-are-carbon-budgets/
[18] THE TEN POINT PLAN FOR A GREEN INDUSTRIAL REVOLUTION

2 Net Zero Strategy (2021) – a comprehensive plan to achieve net-zero emissions by 2050, encompassing various sectors and utilising a range of policy and investment tools.

3 Powering up Britain (2023) – the UK government's combined energy security and net zero growth plan. Key elements include:

- Expanding renewables, nuclear, and CCUS clusters.
- Supporting low-carbon hydrogen production.
- Driving investment into EVs, heat pumps, and efficiency upgrades.
- Mobilising private capital through a "Green Prosperity Plan" and incentives.
- Positioning the UK as a global leader in clean technology industries.

To achieve the goals they have set, the government has set out these industrial strategies alongside sector-specific initiatives such as the Industrial Decarbonisation Strategy. These combine market mechanisms (CCfDs, UK ETS) with targeted support for hydrogen, CCUS, and industrial clusters, aiming both to cut emissions and position UK industry competitively in the global low-carbon economy.

3.2 The UK ETS: Structure, Scope and Price History

The UK ETS was launched on January 1st 2021, following the UK's exit from the European Union (EU) in 2020. It covers 25% of UK terrestrial emissions, including the UK's power sector, energy-intensive industry, and emissions from domestic flights, flights from the UK to the European Economic Area (EEA), flights from GB to Switzerland, and flights between the UK and Gibraltar.[19] The government plans to include Maritime emissions under the scope of the ETS by 2026, and waste incineration by the end of the decade.

The UK ETS follows a cap-and-trade structure, with a declining annual cap - the cap trajectories are set aligned to the carbon budgets (covered in section 3.1). Reducing the cap each year sets a tighter limit on the emissions permitted, and incentivises companies to decarbonise and adopt greener, low-carbon technologies to comply with regulations and avoid paying the tax. Companies receive free allowances and, should they require extra permits, are able to purchase more via auction or secondary market trade from other consumers. At the end of the year, companies surrender the number of permits required to cover their annual emissions and can either purchase more from the government (or from other companies) or sell their remaining permits for a profit.

As part of the Summit on Future Partnership in May 2025, the UK Government and the EU have agreed to work towards linking the UK ETS and the EU ETS. This agreement follows the promise made in 2021 during the UK-EU Trade and Cooperation Agreement to collaborate on carbon pricing. The summit this May "set out parameters for a potential linking agreement" between the UK and EU.[20]

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[19] https://www.gov.uk/government/consultations/uk-ets-scope-expansion-maritime-sector/uk-emissions-trading-scheme-scope-expansion-maritime-analytical-annex-html#section-1-uk-ets-overview

[20] https://www.gov.uk/government/publications/uk-emissions-trading-scheme-uk-ets-policy-overview/uk-emissions-trading-scheme-uk-ets-a-policy-overview

3.3 Current Free Allowance Rules for Steel

As of 2025, the UK Emissions Trading Scheme (UK ETS) provides free allocation of allowances to the steel sector to mitigate the risk of carbon leakage - the potential relocation of production to countries with less stringent climate policies. This allocation is determined based on benchmarks reflecting the best-performing technologies in the sector, aiming to incentivise emission reductions.[21]

The free allocation methodology is set to be reviewed and updated ahead of the next allocation period, which will begin in 2027. This review aims to focus support on sectors most at risk of carbon leakage and to align with the introduction of the UK's Carbon Border Adjustment Mechanism (CBAM), which will cover the steel sector. The outcome of this review, including any changes to the free allocation rules, is expected to be published by the end of 2025.[22]

3.4 Carbon Price Support and Other UK Carbon Taxes

The UK's carbon price support mechanism (CPS) was introduced in 2013 and is a tax on fossil fuel electricity generation that supplements the EU/UK Emissions Trading Scheme (ETS) price, ensuring a minimum carbon cost and encouraging low-carbon power. As of 2024/25, the CPS rate is maintained at an equivalent of £18 per tonne of CO2. This rate is set to continue through March 2027.[23]

In addition to the CPS, the UK employs the Climate Change Levy (CCL), a tax on business energy use, with reduced rates for renewable energy and energy-intensive industries under Climate Change Agreements . The government also utilises fuel duties and vehicle taxes to incentivise transport decarbonisation and electric vehicle adoption.

Together, these measures complement the UK's ETS, creating a comprehensive carbon pricing framework that encourages emissions reductions across electricity, industry, and transport sectors.

3.5 UK CCUS Strategy and Funding Mechanisms

The UK government has committed to achieving net zero greenhouse gas emissions by 2050, with Carbon Capture, Usage, and Storage (CCUS) playing a pivotal role in decarbonising hard-to-abate sectors such as heavy industry and power generation. To support this transition, the government has outlined a comprehensive strategy and established various funding mechanisms.

CCUS Strategy - The UK's CCUS strategy focuses on developing industrial clusters equipped with shared infrastructure for CO2 transport and storage. Key initiatives include:

- Track 1 and Track 2 CCUS Clusters: These clusters aim to capture and store significant volumes of CO2 annually, facilitating economies of scale and reducing costs for individual emitters.
- HyNet and East Coast Clusters: These are among the leading projects, with ongoing development funding to support their progress.

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[21] UK ETS Allocation Table for operators of installations - GOV.UK
[22] UK Emissions Trading Scheme: free allocation review - GOV.UK
[23] https://2ea.co.uk/ccl-cps-rates-briefing-27th-november-2024/

- Acorn Project: Located in Scotland, this project will receive £200 million in development funding, with discussions ongoing regarding further support to integrate it into the national strategy.

Funding Mechanisms- The UK government has allocated substantial financial resources to support CCUS development:

- £21.7 billion over 25 years: Announced in November 2024, this funding will be invested across two clusters, covering both capital and operational costs.
- £1 billion Net Zero Innovation Portfolio: This initiative, announced in the Ten Point Plan is a £1 billion fund to "accelerate the commercialisation of low-carbon technologies, systems and business models in power, buildings, and industry"[24]. This will decrease the costs of decarbonisation.
- £170 million Industrial Decarbonisation Challenge: Matched by £261 million from industry, this funding supports low-carbon technology development in UK industrial clusters.

Challenges and Considerations- While the strategy is ambitious, several challenges remain:

- Financial uncertainty: The exact allocation and timing of funds for future projects, including those in Track 2 clusters, are yet to be fully determined.
- Public perception: There is ongoing debate about the role of CCUS in the broader energy transition, with some stakeholders questioning its effectiveness compared to renewable energy solutions.
- Regional disparities: Some regions, particularly Scotland, have expressed concerns about being underrepresented in the CCUS strategy, despite having significant potential for CO_2 storage.

In summary, the UK's CCUS strategy is a critical part of its decarbonisation efforts and is supported by substantial government funding. However, addressing the remaining challenges and ensuring fair development across all regions will be essential for the successful implementation of this strategy

4. Case Study: UK Steel Plant

4.1 Overview of Plant Characteristics and Operations

The data used in this project were compiled by a fellow researcher at the Grantham Institute within Imperial College. His source is stated as: 2013-04 Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill).pdf.

The Excel spreadsheets containing the model used have been provided to me by my supervisor, Gbemi Oluleye, to use market interventions to manipulate the NPV of the Steel plant to a positive or zero value.

[24] Net Zero Innovation Portfolio - GOV.UK

4.2 Functioning of the Plant Before Government Intervention

In sections 4.3 - 4.6, the following variables shall remain unchanged:

Inputs	
Steel plant	**Value**
Capacity (tons)	4,000,000.0
OPEX ($ / yr)	1,781,800,000
OPEX Capture CCUS ($/yr)	184,430,000
Total OPEX CCUS ($/yr)	283,738,462
Total OPEX ($/yr)	2,065,538,462
Selling price - Year 1 ($/ton of steel)	650.000
CAPEX ($)	4,124,000,000
CAPEX Capture CCUS ($)	914,000,000
Total CAPEX CCUS ($)	1,406,153,846
Total CAPEX ($)	5,530,153,846
Cost of capture (%)	65%
Steel Produced (tons)	4,000,000
Emissions before CCUS (tons/yr)	8,376,554
Capture rate (%)	50%
Emissions after CCUS (tons/yr)	4,179,900
Decarbonisation (ton/yr)	4,196,654
CO2 price ($/t)	60
CO2 sold (%)	5%

Additional data	Value
Inflation	1%
Discount rate (nominal, pre-tax)	10.0%
Free allowances	77%
Decrease of allowances	8%
ETS price ($)	70
ETS increase	10.0%

4.3 Baseline Economics (no policies, no CCUS) Profile

When looking at the steel plant with no policies and no CCUS – ie. Business as usual (BAU) before the implementation of carbon taxes and regulations, the NPV came out as a positive number - **US$ 2,445,535,896.**

A positive NPV of this value indicates that the business is profitable and the operations of the plant are economically viable.

4.4 Addition of an ETS to the BAU Model

The next situation to analyse is the implementation of the UK ETS to the previously mentioned BAU model. The UK ETS has a carbon price of 70 US$/t and gives an NPV of **US$ -6,877,500,057.**

As shown by the highly negative NPV, the addition of an ETS to the BAU model makes the steel plant not economically viable – the project will generate a lower return than the initial investment, which is bad for business and not cost-effective. This scenario will cause the closure of plants, as it is more cost-effective to simply halt production than it is to continue.

4.5 Addition of Carbon Capture, Utilisation and Storage (CCUS) to the BAU Model

The addition of a hypothetical CCUS scheme to the BAU model, without the addition of an ETS, puts the NPV value from US$ 2,445,535,896 (see section 4.3) down to **US$ -1,856,018,318.**

This demonstrates that, regardless of whether an ETS is in place or not, running a CCUS scheme without funding is not cost-effective for the plant. The NPV has been changed from a highly positive to a negative number, indicating that the return rate produced is lower than the initial investment.

When comparing the NPVs between sections 4.3 and 4.5, it is clear to see why little/no steel plants were investing in CCUS technologies before the addition of the UK ETS – despite being more sustainable for the environment, it makes their business unsustainable in the sense that earnings are slim, and money will eventually be lost

4.6 Addition of CCUS Technology to a Plant Under an ETS

The final base scenario, before implementation of market mechanisms, is the scenario where CCUS technology is added to the plant, which is under an emissions trading scheme (ETS). In this scenario, we see the NPV fall to **US$ -5,131,674,469.**

This is an increase of US$ +1,745,825,588 from the scenario of a plant under an ETS (with the same conditions) without CCUS (shown in section 4.4).

This increase in NPV shows that investing in CCUS whilst under an ETS will actually benefit the plant over time. Being low-carbon means they emit less (and are therefore taxed less), and also storing CO2 allows them to sell carbon at the market price – generating a profit. When a plant is under an ETS, it is more cost-effective to invest in CCUS technologies than it is to continue as usual.

However, despite the increase, the NPV here remains significantly negative. In most cases, plants will shut down, as they will lose money whether they invest in low-carbon technologies or not. This is where government intervention is needed to make the low-carbon tech more affordable, and to keep plants open.

5. Policy intervention scenarios

5.1 Changes Made to the Baseline Model

Along with the addition of policies, changes were made to the operations of the plant:

- The capture rate was increased from 50% to 77%.
- Carbon price was doubled from 60 US$/t to 120 US$/t.
- Free allowances decreased from 77% to 50%. Decreasing free allowances makes investing in CCUS technology a cheaper and more desirable option, increasing the capture rate.

These changes apply to the models from section 5.2 onwards.

Inputs

Wind	Value
Capacity (tons)	4,000,000.0
OPEX ($ / yr)	1,781,800,000
OPEX Capture CCUS ($/yr)	184,430,000
Total OPEX CCUS ($/yr)	283,738,462
Total OPEX ($/yr)	2,065,538,462
Selling price - Year 1 ($/ton of steel)	650.000
CAPEX ($)	4,124,000,000
CAPEX Capture CCUS ($)	914,000,000
Total CAPEX CCUS ($)	1,406,153,846
Total CAPEX ($)	5,530,153,846
Cost of capture (%)	65%
Steel Produced (tons)	4,000,000
Emissions before CCUS (tons/yr)	8,376,554
Capture rate (%)	77%
Emissions after CCUS (tons/yr)	1,926,607
Decarbonisation (ton/yr)	6,449,947
CO2 price ($/t)	120
CO2 sold (%)	5%

Additional data	Value
Inflation	1%
Discount rate (nominal, pre-tax)	10.0%
Free allowances	50%
Decrease of allowances	8%
ETS price ($)	70
ETS increase	10.0%

5.2 Addition of a Carbon Contract for Difference (CCfD) to the ETS + CCUS Model

A CCfD was applied to the model, with a strike price of 200 US$/tCO2. In my literature review, I found strike prices for CCfDs to range between US$ 270-100,[25] so the strike price of 200 was chosen for this model as a middle ground.

To look at the CCfD scheme alone, the revenue from selling carbon was made to equal zero.

Using this and the discounted amount of decarbonisation (in ton/yr), an annual top up payment was calculated and added to the yearly revenues for the plant.

Doing this increased the NPV from US$ -5,131,674,469 to **US$ -1,092,519,239.** This is proof that using a market mechanism can help shift companies to low-carbon technologies whilst also being the more affordable option.

Using Goal Seek, for the NPV to be zero, the strike price of the CCfD should be US$ 233. Since this strike price is higher than the average, I decided to explore alternative interventions alongside the CCfD, to keep the strike price lower.

5.3 Applying an ETS Revenue Recycling Scheme to the ETS + CCUS Model

Next, I looked at the option of using the recycling of revenues generated from the ETS to help fund CCUS, instead of a CCfD (section 5.2). The ETS price is US$ 70, so I looked at recycling half as an initiative (US$ 35). **-2,224,435,067**

This generates revenue for the government, which is then recycled into the plant's CCUS scheme and added to the yearly revenues for the plant. This increased the NPV from US$ -5,131,674,469 to **US$ -2,224,435,067.**

Using Goal Seek, for the NPV to be zero, US$ 102 needed to be recycled, which is not possible as it is higher than the ETS price.

When compared with section 5.2, we can see that despite this recycling scheme increasing the NPV, it wasn't as effective as doing so as adding a CCfD to the plant. And in both scenarios, whilst the NPV was improved, it wasn't raised to zero and therefore operations of the plant are still not considered financially viable.

The next step is to use these two mechanisms in conjunction with one another, to achieve an NPV of zero.

5.4 Using the ETS Recycled Revenues to Support the CCfD

In the baseline model, the top-up payments from the CCfD total to a sum of US$ 4,756,828,544 and the ETS revenues total to only US$ 1,955,616,095 – meaning that, in the best case, the ETS can only cover ~30% of the CCfD scheme. The most optional way to recycle the ETS revenues is into the CCfD top-up payments, as the government will need to find a way to pay this money. To do this, I redesigned the CCfD scheme so that the ETS recycling scheme can support the CCfD. I did this by using the function Goal Seek, and setting the goal to make the ETS revenues = Total top-up payments

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[25] Strike Price Adjustments - Low Carbon Contracts

by changing the strike price of the CCfD. The strike price drops to US$/tCO2 189. This makes the NPV negative with a value of **US$ -1,457,025,308.**

5.5 Using Both a CCfD and ETS Revenue Recycling Scheme Independently

Using the CCfD (with a strike price of US$ 200) and the ETS recycling scheme (set at US$ 35) together produced an NPV of **US$ +79,897,764.** While achieving a positive NPV is desirable, it only needs to reach zero to be a successful scheme. By reducing the policies, we can lessen the financial burden on the government and encourage investment elsewhere.

Since there are more than two variables present, instead of the Excel function 'Goal Seek', I used the function 'What's Best.' In this situation, the best value and constraint is that we want the NPV to be equal to zero, and the adjustables are the values of the ETS recycle rate and the strike price for the CCfD (ie, these are changed to make the NPV equal to zero).

The 'What's Best' function solved that, to achieve an NPV of zero, it was more cost effective to have a single CCfD scheme with a strike price of US$ 233, rather than combining the ETS revenue recycling with a lower strike price.

6. Economic Modelling and Results

6.1 Modelling Assumptions and Methodology

The main assumptions in the model were those of the operations of the plant, and the variables used remaining either constant or changing at the exact rates modelled. Changes to the variables or rates of change shown in sections 4.2 and 5.1 would alter the effectiveness of the market mechanisms explored in this research.

I began my research with a literature review and decided on the market mechanisms I thought would best fit the model and have the most positive impact on the NPV. After settling on the ETS revenue recycling scheme and CCfD, the next step was to apply them to the model, with variables such as strike price and recycle rate chosen through research conducted as part of my literature review.

Next was editing the model and variables to achieve a plausible and more positive NPV than the baseline model prior to government intervention and application of mechanisms.

6.2 Scenario Results – NPV Changes

The NPV changes experienced in the modelling were as expected – the use of market mechanisms caused an increase in the NPV from the scenarios without.

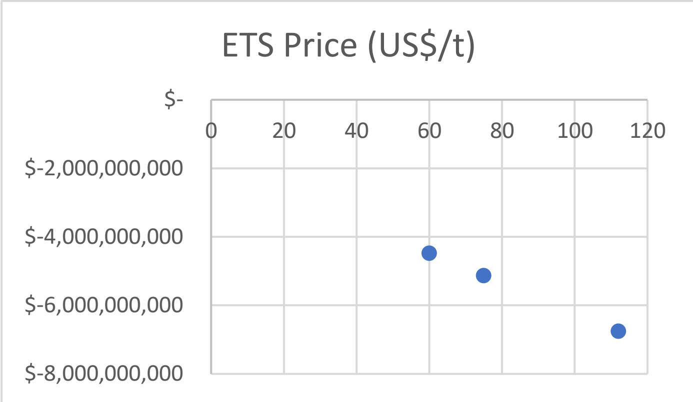
6.3 Sensitivity Analysis

Sensitivity performed on:

1. Carbon price (ETS price)

In the model, the carbon price is set at US$/t 75. Within the UK ETS, the carbon price has historically ranged between US$/t ~55-120, so the low case (-20%) will be set for US$/t 60 and the high case (+50%) will be set for US$/t 112.

Carbon prices are politically and market-driven, so this range captures plausible near-term volatility and regulatory uncertainty.

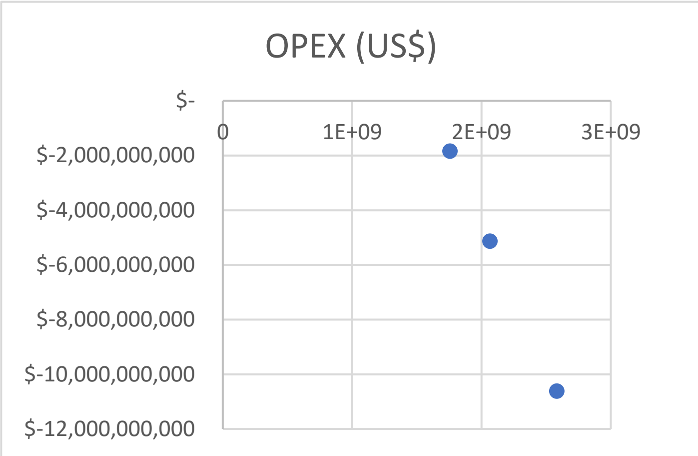


Range:

- Base case = US$/t 75
- Low case = US$/t 60 (-20%)
- High case = US$/t 112 (+50%)

2. Operating Expenditure (OPEX) of the plant

In the model, OPEX is set as US$ 2,065,538,462, but energy and hydrogen prices fluctuate with fuel markets and policy (e.g. electricity price support schemes). Operational efficiency or technology learning can reduce costs modestly.

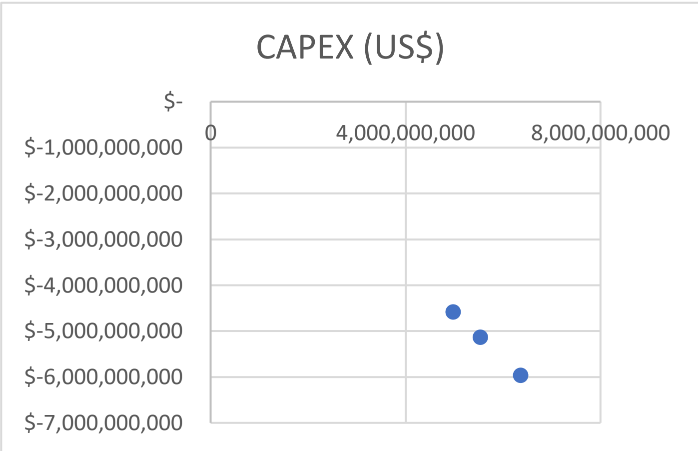


Range:

- Best case = US$ 2,065,538,462
- Low case = US$ 1,755,080,000 (-15%)
- High case = US$ 2,581,923,000 (+25%)

3. Capital Expenditure (CAPEX) of the plant

In the model, CAPEX is set to US$ 5,530,153,846. Despite steel plant construction and refurbishment costs being well-characterised, cost uncertainty is mostly from inflation, steel/energy prices, and project execution.



Range:

- Best case = US$ 5,530,153,846
- Low case = US$ 4,977,138,000 (-10%)

- High case = US$ 6,359,677,000 (+15%)

The NPV fluctuations caused by these sensitivities would cause additional changes to be needed in the interventions and policies applied, to counteract the changes to the NPV.

6.4 Summary of Results

Overall, my results show that the use of market mechanisms can increase the NPV for a steel plant and help make CCUS operations economically viable.

The use of ETS recycling in conjunction with the CCfD scheme (explored in section 5.5) provided the best results with the highest NPV (US$ +79,897,764) and a CCfD scheme with a strike price set to US$ 233 provided an NPV of zero.

7 Discussion

7.1 Implications for UK Steel Decarbonisation

My results suggest that market mechanisms such as ETS revenue recycling and CCfD schemes can significantly improve the financial viability of decarbonised steel production in the UK. An increased NPV under ETS recycling and CCfD indicates that the current financial barriers to low-carbon steelmaking can be overcome with well-designed policy support. Because of the increase in NPV, private investment in CCUS-enabled steel plants could become more attractive, potentially accelerating deployment.

In proving, through support schemes, that CCUS technologies can become economically feasible, my findings can encourage continued innovation and cost reductions in capture, transport and storage systems.

This positions the UK as capable of developing a competitive, low-carbon steel industry – aligning with the government's Industrial Decarbonisation Strategy and net-zero targets. The results suggest that policy certainty and long-term schemes like CCfDs can mitigate investor risk and promote stable transitions. It also supports the case for linking the carbon market revenues to industrial decarbonisation (by recycling ETS revenues), rather than using general government budgets.

Overall, the findings imply that a well-integrated policy framework combining market mechanisms and technology-specific support could make deep decarbonisation of UK steel both technically and financially stable.

7.2 Risks and Uncertainties

The risks can be grouped into:

1. Economic and market risks

- The carbon price volatility under the UK ETS introduces uncertainty in projected revenues and investment returns.
- Future steel demand fluctuations could affect the project economics.
- Inflation or rising interest rates could raise the cost of capital, reducing NPV gains.

2. Policy and regulatory risks
    - Policy instability or changes in government priorities could undermine long-term confidence (eg. CCfD budget constraints, ETS rule changes).
    - Uncertainty around carbon leakage protection – if border carbon adjustments or free allocations are removed too quickly, domestic producers could face competitiveness pressures.
3. Technical risks
    - CCUS operational risks, including capture efficiency, transport reliability and storage integrity.
    - Potential for cost overruns or delays in CCUS infrastructure deployment.
4. Data and modelling uncertainties
    - Simplifying assumptions in the NPV model (discount rate, carbon price trajectory etc) introduces uncertainty into quantitative results.

While the modelling suggests strong potential for positive investment outcomes, these results are contingent on stable policy design, predictable carbon prices and successful technological deployment.

7.3 Policy Trade-offs and Competitiveness Concerns

The application of market mechanisms such as ETS revenue recycling and CCfDs introduces important policy trade-offs that must be carefully managed to ensure both effective decarbonisation and the continued competitiveness of the UK steel sector.

Recycling ETS revenues to support low-carbon investments directs funds toward accelerating the transition but simultaneously reduces government flexibility to allocate these revenues to other public priorities. Similarly, while CCfDs can de-risk capital-intensive technologies such as CCUS by providing predictable revenue streams, they may inadvertently create market distortions if support is uneven across technological pathways, potentially disadvantaging alternative routes such as hydrogen-based direct reduction.

Furthermore, the shift from free allowances toward full carbon pricing, although essential for driving emissions reduction, raises short-term production costs and may erode profit margins before efficiency gains and innovation offset these impacts. These pressures are particularly acute in a globally traded sector where UK producers compete against firms operating in regions with weaker or no carbon constraints.

Without adequate safeguards—such as transitional free allocation, border carbon adjustments, or demand-side measures like green public procurement—there is a heightened risk of carbon leakage and loss of industrial competitiveness. Coordinated policy design with trading partners, especially the EU ETS, is therefore critical to prevent market distortions and maintain a level playing field.

Overall, the findings highlight that while market-based instruments can make low-carbon steel production financially viable, their effectiveness ultimately depends on a balanced policy mix that aligns climate ambition with industrial resilience and global competitiveness. Balancing environmental ambition with industrial competitiveness will require careful sequencing of carbon pricing, support mechanisms and international coordination to ensure the UK stell sector remains viable throughout the decarbonisation transition.

8. *Conclusions and Recommendations*

My research explored three separate timelines:

1. Business prior to the addition of an ETS + CCUS technology – here the NPV is highly positive. The plant is releasing all of the emissions they produce and is making a high profit.
2. Business after the addition of an ETS + CCUS technology, but before the addition of market mechanisms – here the NPV was at its lowest; investment in CCUS technology and carbon tax on the plant drops the NPV to a highly negative number, and makes the plant's operations not financially viable. It is at this stage where most of the steel plants in the UK were forced to close.
3. Application of market mechanisms to the plant – here, we see the NPV increase. It was within my interest to observe which strategies caused the NPV to become:
    - More positive (but still negative).
    - Zero
    - Positive

The results of this study demonstrate that market mechanisms can play a decisive role in improving the financial feasibility of industrial decarbonisation within the UK steel sector. Both the ETS revenue recycling scheme and the Carbon Contract for Difference (CCfD) increased the plant's net present value, indicating that such instruments can effectively reduce investment risk and enhance project returns. The CCfD proved more effective than ETS recycling, primarily due to its ability to provide long-term price certainty and revenue stability. When applied together, the mechanisms produced a positive NPV, confirming their combined potential to make low-carbon steelmaking economically viable. However, the analysis found that the most efficient policy configuration was a single CCfD scheme with a higher strike price and no ETS revenue recycling, offering the strongest financial incentive for decarbonisation while maintaining policy simplicity.

These findings suggest that future UK industrial policy should prioritise stable, technology-specific support mechanisms such as CCfDs with appropriately high strike prices to accelerate investment in low-carbon steel production and achieve national net-zero targets.