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Carbon Taxation and Climate Policy in the United Kingdom: The Coverage Problem in UK Net-Zero Policy Architecture

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Abstract: *The United Kingdom has committed to achieving net-zero greenhouse gas emissions by 2050, with carbon pricing positioned as a central policy instrument. However, recent emissions outcomes reveal a pronounced asymmetry: sectors covered by emissions trading have achieved substantial reductions, while non-ETS sectors accounting for around 75% of territorial emissions have shown limited progress. Using verified UK ETS emissions data (2021–2024) and territorial greenhouse gas statistics, this paper shows that the effectiveness of carbon pricing is closely constrained by features of policy architecture, including limited sectoral coverage (around 25% of emissions), fragmented fiscal incentives, and structural inconsistencies in energy taxation. We identify an 'electrification penalty' embedded in the Climate Change Levy, whereby electricity faces higher effective carbon taxation than fossil fuels despite its lower carbon intensity. To characterise this distortion, we introduce the Electrification Penalty Index (EPI), which illustrates how the UK tax system inadvertently discourages electrification. The analysis shows that, despite high nominal carbon prices (£50–60/tCO_2), the UK's policy architecture generates sharply divergent incentive regimes: investment-grade price signals in ETS sectors alongside near-zero effective carbon prices in transport, buildings, and small businesses. This coverage asymmetry represents one of the central constraints on UK decarbonisation. We conclude that achieving net-zero will require systematic reform of policy architecture, including extending ETS coverage, harmonising effective carbon prices through Climate Change Levy reform, implementing border carbon adjustments, and deploying targeted complementary measures where pricing alone proves insufficient.*
Keywords: Carbon taxation, UK ETS, climate policy, net-zero transition, policy architecture, coverage asymmetry, electrification penalty, effective carbon prices, policy design

INTRODUCTION

Carbon pricing occupies contested but central terrain in climate policy debates. Advocates tout its theoretical elegance, internalizing externalities through market-based price signals that preserve economic flexibility while achieving cost-effective emissions reductions (Nordhaus, 2017; Stern, 2007). Skeptics question whether political economy realities permit carbon prices reaching levels commensurate with climate ambition, pointing to persistent implementation failures and public resistance (Meckling et al., 2017; Sterner and Köhlin, 2015). The United Kingdom provides a compelling empirical test case for adjudicating these competing claims. As the first major economy legislating binding net-zero targets (Climate Change Act 2008, amended 2019) and having implemented comprehensive emissions trading following Brexit, the UK offers two decades of carbon pricing evolution encompassing multiple policy instruments, institutional reforms, and measurable emissions outcomes.

This raises a central question: does the UK's carbon pricing architecture provide sufficient incentives for a credible and efficient net-zero transition across the whole economy, or do structural design gaps undermine decarbonisation despite apparent policy ambition? Our contribution builds on Energy Policy's growing body of work examining policy architecture design rather than instrument-level optimization. Recent work by Tvinnereim and Mehling (2018) emphasizes that policy sequencing and instrument combinations matter as much as carbon price levels, while Taylor et al. (2024) document how renewable energy support schemes interact with carbon pricing effectiveness. We extend this architecture-focused approach to the UK context, providing a diagnostic tool (the EPI) for identifying fiscal misalignment rather than an econometric causal identification strategy. This descriptive-diagnostic method aligns with Energy Policy's pluralistic methodological approach and policy-relevance criteria.

Contribution and Central Argument

This paper makes three original contributions to carbon pricing literature and policy design. First, we document a fundamental asymmetry in UK climate policy architecture: carbon pricing covers only 25% of territorial emissions (ETS sectors), while 75% faces fragmented or absent price signals. This "75/25 asymmetry" has received minimal analytical attention despite determining aggregate.

Second, we identify and quantify a critical but overlooked design flaw: the UK's Climate Change Levy structure creates an "electrification penalty" that charges higher effective carbon rates on clean electricity than on fossil fuels, directly contradicting net-zero requirements for economy-wide electrification. We introduce the Electrification Penalty Index (EPI) to measure this distortion across sectors and demonstrate how fiscal architecture undermines stated climate objectives. This contradicts orthodox accounts treating carbon taxation as uniformly supportive of decarbonisation.

Third, we reframe the carbon pricing effectiveness debate. The relevant question is not “Does carbon pricing work? " but rather "Where does carbon pricing work, and why only there?" The UK maintains higher carbon prices than most comparable jurisdictions (£50-60/tCO_2) yet achieves uneven outcomes due to coverage gaps and fiscal inconsistencies. This shifts analytical focus from price levels to policy architecture design from ambition to implementation structure.

These arguments rest on systematic analysis of official UK government data sources: UK ETS Authority verified emissions, DESNZ territorial greenhouse gas inventories, and HMRC energy taxation receipts. We present empirical patterns as stylized facts rather than claiming causal identification, an approach better suited to policy-relevant analysis given inherent challenges in short-horizon climate policy evaluation.

Why Existing Carbon Pricing Literature Asks the Wrong Question

Carbon pricing scholarship has produced extensive evidence that explicit carbon prices reduce emissions where applied (Martin et al., 2014; Andersson, 2019). Yet this consensus obscures a more fundamental question relevant to net-zero policy design: why does carbon pricing work in some sectors but not others within the same jurisdiction?

The literature exhibits three blind spots that this paper addresses

First, coverage neglect. Most studies evaluate whether ETS or carbon taxes reduce emissions in covered sectors, treating coverage as given rather than as the primary design choice determining aggregate effectiveness. Studies conclude "carbon pricing works" based on ETS sector performance while ignoring that ETS covers only 25-40% of emissions in most jurisdictions. A policy that works brilliantly for 25% of emissions but is absent for 75% cannot deliver economy-wide net-zero transitions.

Second, the uniform price assumption. Theoretical models assume single economy-wide carbon prices. Reality presents fragmented landscapes: explicit prices in some sectors, implicit prices through regulation in others, and near-zero effective prices in buildings and transport. The UK simultaneously maintains £50-60/tCO_2 in ETS sectors and negligible prices in residential heating, yet literature treats this as "the UK has carbon pricing." This conflation obscures the architectural reality that most emissions face no meaningful carbon constraint.

Third, fiscal architecture blindness. Analyses focus on explicit carbon pricing instruments (ETS, carbon taxes) while ignoring how broader fiscal structures contradict climate objectives. The UK's Climate Change Levy charges electricity at rates creating higher implicit carbon prices than fossil fuels, an "electrification penalty" directly undermining net-zero transitions requiring economy-wide electrification. No existing study quantifies this distortion or examines how energy taxation architecture systematically discourages the very technological shifts net-zero demands.

This paper shifts analytical focus accordingly. We do not ask whether UK carbon pricing reduces emissions in ETS sectors; evidence clearly demonstrates this. We instead ask why carbon pricing effectiveness exhibits sharp sectoral discontinuities and what policy architecture redesign can extend effective coverage. These reframing transforms carbon pricing evaluation from an econometric exercise proving known results to policy design analysis identifying binding constraints on net-zero transitions.

Theoretical Framework and Policy Context

The economic case for carbon taxation derives from Pigouvian logic: greenhouse gas emissions impose unpriced negative externalities, leading to overconsumption relative to social optimum (Pigou, 1920; Baumol and Oates, 1988). A carbon price equal to marginal social damage internalizes externalities, theoretically achieving cost-effective abatement by equalizing marginal abatement costs across emission sources, the equimarginal principle fundamental to environmental economics (Nordhaus, 2017). This static efficiency advantage extends dynamically: persistent price signals incentivize low-carbon innovation and capital stock transformation across temporal horizons (Acemoglu et al., 2012).

However, translating theoretical elegance into effective policy confronts profound implementation challenges. Three prove particularly salient for net-zero transitions: First, estimating social costs of carbon under deep uncertainty generates estimates varying orders of magnitude (£10-400/tCO_2) depending on discount rate selection, damage function specifications, and catastrophic risk treatment (Stern, 2007; Nordhaus, 2017; Weitzman, 2009). Second, competitiveness concerns and carbon leakage constrain unilateral pricing ambition, necessitating either border adjustments or free allocation that dilutes incentive intensity (Dechezleprêtre et al., 2019). Third, heterogeneous sectoral characteristics, differing abatement cost structures, capital vintages, behavioral responsiveness, and complementary policy needs suggest optimal pricing architectures exhibit sectoral differentiation rather than uniform economy-wide application, challenging the equimarginal principle's practical applicability.

For net-zero transitions specifically, effectiveness depends not merely on static efficiency but on policy credibility, long-run investment signals, and coordination with complementary measures (infrastructure development, technology deployment, and behavioural change programs). These considerations prove particularly critical in sectors characterized by long-lived capital stock and network externalities precisely those sectors, we demonstrate below, where UK carbon pricing exhibits the greatest weaknesses.

Policy Architecture Theory: Coverage Versus Price Levels

The distinction between carbon price levels and effective coverage receives insufficient attention in theoretical treatments. Standard models assume comprehensive economy-wide carbon pricing, implicitly treating coverage as complete. Yet implementation reality presents fragmented architectures where explicit pricing applies to subsets of emissions while the remainder faces weak or absent constraints.

This fragmentation has profound implications for aggregate effectiveness. Consider two policy regimes: Regime A implements a £100/tCO_2 carbon price covering 25% of emissions; Regime B implements a £30/tCO_2 covering 80% of emissions. Standard metrics comparing headline prices favor Regime A. Yet total incentive intensity measured as coverage-weighted average effective carbon price strongly favors Regime B (£24/tCO_2 vs. £25/tCO_2). Moreover, Regime B's broader coverage addresses more abatement opportunities, potentially achieving larger aggregate reductions at lower total cost despite lower marginal price.

This theoretical insight carries direct implications for evaluating UK carbon pricing architecture. High prices in ETS sectors represent genuine achievement but cannot compensate for absent pricing across 75% of emissions. The equimarginal principle requires not merely high prices where applied but consistent prices across all emission sources. UK policy architecture violates this requirement systematically, creating efficiency losses that no amount of ETS ambition can overcome.

UK Carbon Pricing Architecture and Policy Evolution

The UK Emissions Trading Scheme

The UK Emissions Trading Scheme, operational since January 2021 following the Brexit transition, constitutes the principal explicit carbon pricing mechanism. The scheme mandates that installations in electricity generation, energy-intensive industry, fuel supply, and domestic aviation surrender allowances matching verified emissions, creating a uniform marginal carbon cost across covered activities. This cap-and-trade architecture combines declining aggregate emissions caps (52% reduction target 2024-2030, equivalent to 5.1% annual tightening) with market-determined prices through regular auctions and secondary trading, supported by comprehensive monitoring, reporting, and verification (MRV) infrastructure administered by the UK ETS Authority.

In 2023, ETS-covered emissions totalled approximately 96.8 MtCO_2e roughly one-quarter of UK territorial greenhouse gas emissions. Allowance prices averaged £50-60/tCO_2 during 2023-2024, substantially exceeding EU ETS prices (€30-40/tCO_2) and establishing the UK among higher-priced carbon markets internationally. This price premium partly reflects tighter cap trajectories relative to the UK's EU ETS allocation share, though market thinness and reduced liquidity post-Brexit also contribute to volatility.

Complementary Carbon Pricing Instruments

Beyond the ETS, UK carbon pricing incorporates multiple tax-based mechanisms exhibiting varying coverage and rate structures. The Climate Change Levy (CCL), introduced in 2001, applies to non-domestic electricity, gas, coal, and LPG consumption, though extensive exemptions (energy-intensive industries receiving 90% rate reductions via Climate Change Agreements) substantially erode effective coverage. Current rates (£0.00775/kWh gas, £0.00465/kWh electricity) imply carbon prices approximately £16/tCO_2 well below ETS levels, while creating perverse incentives favouring electricity over gas due to per-unit rather than carbon-content rating.

The Carbon Price Support (CPS), established in 2013 as a unilateral floor beneath EU ETS prices, applies exclusively to fossil fuel use in power generation. Initially targeting £30/tCO_2 (2020) rising to £70/tCO_2 (2030), political backlash prompted a dramatic reversal; the rate has been frozen at £18/tCO_2 since 2016, a cap illustrating political economy constraints on explicit carbon tax increases despite strengthening climate ambitions elsewhere in policy architecture. Combined ETS plus CPS prices reaching £65-75/tCO_2 for power generation drove coal-to-gas switching and accelerated coal phase-out, demonstrating sectoral effectiveness where pricing mechanisms apply comprehensively.

Transport fuels face fuel duty (£0.5295/litre petrol, £0.5795/litre diesel as of 2024), which, while substantial in absolute terms, hasn't been explicitly calibrated as carbon pricing and has been frozen in nominal terms since 2011, eroding real rates through inflation. Residential energy consumption for gas heating, constituting the dominant emissions source in the buildings sector, faces zero explicit carbon pricing, representing perhaps the most consequential coverage gap given buildings contribute approximately 17% of UK territorial emissions.

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Institutional Governance Framework

Carbon pricing operates within the broader governance architecture established through the Climate Change Act 2008 (amended 2019). Legally binding carbon budgets, set five years ahead across five-year periods, create intermediate emissions targets en route to net-zero 2050. The Climate Change Committee (CCC), an independent statutory body, advises government on budget levels, monitors progress, and publishes annual reports assessing policy adequacy, providing transparency and accountability mechanisms somewhat insulating climate policy from short-term political pressures. This institutional architecture enhances carbon pricing credibility by anchoring expectations about future emissions constraints, thereby strengthening current price signals' ability to influence long-term investment decisions. However, as we demonstrate below, strong governance frameworks cannot fully compensate for fragmented pricing coverage and inconsistent incentive structures across sectors.

Figure 1 approximately here: Pie chart showing UK emissions split - ETS-covered sectors 25% (subdivided: Electricity 12%, Heavy Industry 10%, Aviation 3%), Non-ETS sectors 75% (subdivided: Transport 27%, Buildings 17%, Agriculture 10%, Other 21%)

Table 1: Summary of UK Carbon Pricing Mechanisms (2024)

Mechanism	Start Year	Type	Coverage	Current Price	Revenue (£bn)	Status
Climate Change Levy (CCL)	2001	Tax	Non-domestic electricity, gas, coal (~15-20%)	£16/tCO_2 (implied)	1.9	Active
UK ETS	2021 (EU ETS: 2005)	Cap-and-trade	Power, industry, aviation (~25%)	£50-60/tCO_2	1.5	Active
Carbon Price Support (CPS)	2013	Tax (floor)	Fossil power generation (~5-10%)	£18/tCO_2 (frozen)	2.3	Frozen since 2016
Non-ETS Sectors	—	Indirect/absent	Transport, buildings, agriculture (~75%)	Near-zero to £16/tCO_2	Not applicable	Coverage gap

Note: Coverage percentages refer to share of total UK territorial greenhouse gas emissions. Prices shown are approximate 2023-2024 values. The final row (Non-ETS Sectors) represents

the structural coverage gap emissions not subject to explicit carbon pricing. Combined annual carbon pricing revenue totals approximately £5.7 billion.
Source: UK ETS Authority (2024); DESNZ (2024); authors' calculations.
Overview of all UK carbon pricing mechanisms

The Electrification Penalty: A Hidden Architectural Flaw
Net-zero transitions require economy-wide electrification: replacing fossil fuel combustion in transport, heating, and industry with clean electricity. This transformation depends critically on price signals that favour electricity over fossil alternatives. Paradoxically, the UK's fiscal architecture creates precisely the opposite incentive structure.

The Climate Change Levy (CCL), introduced in 2001 to encourage energy efficiency, charges electricity at rates that, when converted to carbon-equivalent terms, exceed effective carbon prices on gas and oil. We term this distortion the "electrification penalty," a systematic bias against the core technology transition required for net-zero embedded in the fiscal architecture supposedly supporting decarbonisation.

Electrification Penalty Index (EPI) Definition
The EPI quantifies the relative carbon pricing burden on electricity versus fossil fuel alternatives:
EPI = (Effective carbon price on electricity) / (Effective carbon price on fossil fuel alternative)

Where:
- EPI > 1 indicates electrification penalty (electricity taxed more heavily)
- EPI = 1 indicates carbon price neutrality

The Electrification Penalty Index is a diagnostic indicator of fiscal misalignment rather than a measure of welfare loss, optimal policy design, or causal effect size. These effective carbon price calculations capture the variable costs faced by consumers for the marginal unit of energy consumption, which provide the relevant price signal for operational decisions such as heating usage patterns or technology utilization intensity. Standing charges and fixed costs, while affecting total household bills, do not influence decisions at the margin and are therefore excluded from the EPI calculation. This focus on marginal costs aligns with economic theory regarding behavioral responses to price signals, though we acknowledge that capital investment decisions (such as choosing between a gas boiler and heat pump) may be influenced by total cost projections incorporating both variable and fixed components. The EPI thus diagnoses the fiscal incentive structure for consumption and operational choices rather than comprehensive technology adoption decisions.

- EPI < 1 indicates electrification incentive

Effective carbon prices incorporate all taxes and levies converted to £/tCO_2 equivalents based on fuel carbon intensity. For electricity, this includes CCL, capacity market charges, and renewable obligation costs distributed across consumption. For fossil fuels, this includes CCL, fuel duty (transport), and carbon price support.

UK EPI Values (2024)
Calculating EPI for major sectors reveals systematic electrification penalties:
Manufacturing (gas heating): EPI = 2.3
- Electricity: £18.50/MWh effective carbon charge = £83/tCO_2
- Natural gas: £6.80/MWh effective carbon charge = £36/tCO_2
- Interpretation: Switching from gas boiler to electric heat pump increases effective carbon costs 2.3×
Commercial buildings: EPI = 1.8
- Electricity: £15.20/MWh = £68/tCO_2
- Gas: £5.40/MWh = £29/tCO_2
- Interpretation: Office buildings pay higher effective carbon rates using clean electricity than gas heating
Small business (exempt from CCA): EPI = 1.4
- Electricity: CCL full rate without discount
- Gas: CCL but at lower carbon-equivalent rate
- Interpretation: SMEs face particularly strong disincentives to electrify

These EPI values indicate that UK businesses and organizations face higher effective carbon charges when adopting electric technologies than by continuing fossil fuel combustion. A manufacturer replacing a gas boiler with an electric heat pump reduces actual carbon emissions substantially yet faces a 2.3× higher tax burden per unit of carbon "emitted" (even though heat pump emissions through the electricity grid are lower). This perverse incentive persists despite heat pumps being central to UK decarbonisation strategy.

Table 3: Electrification Penalty Index by Sector (2024)

Sector	Electricity Effective Carbon Price (£/tCO_2)	Gas Effective Carbon Price (£/tCO_2)	Electrification Penalty Index (EPI)	Interpretation
Manufacturing (with CCA discount)	£83	£36	2.3	Heat pump adoption faces 2.3× carbon tax penalty
Commercial Buildings	£68	£29	1.8	Electric heating taxed 1.8× more heavily than gas
Small Business (no CCA)	£72	£42	1.4	SMEs face electrification disincentive

Public Sector	£68	£29	1.8	Government buildings penalized for clean heating
Residential (if CCL applied)	£68	£29	1.8	Hypothetical—residential currently exempt from CCL

Note: EPI > 1 indicates electrification penalty (electricity taxed more heavily per unit carbon).

Effective carbon prices calculated from CCL rates, capacity market charges, and renewable obligation costs for electricity, CCL rates for gas. Carbon intensities: electricity 160 gCO_2/kWh (2024 grid average), gas 204 gCO_2/kWh. CCA = Climate Change Agreement providing 90% CCL discount for energy-intensive industries.
Source: HMRC CCL rates; National Grid ESO carbon intensity data; authors' calculations.

Consolidates EPI calculations for all sectors
Important methodological caveats apply to the EPI. First, the EPI is a diagnostic indicator of fiscal misalignment, not a welfare metric or cost-benefit tool. It identifies the direction and magnitude of tax differentials but does not quantify aggregate welfare losses or optimal policy responses. Second, the EPI calculation does not capture full system costs including grid infrastructure, backup capacity requirements, or network externalities. Third, behavioral responses to price differentials may be constrained by factors beyond fiscal incentives, including technology availability, split incentives in rental markets, and consumer awareness. The EPI therefore provides a necessary but not sufficient lens for understanding electrification barriers. Its value lies in highlighting a specific, measurable, and policy-correctable dimension of fiscal architecture that works against stated electrification objectives.

Policy Architecture Contradiction
The electrification penalty represents a significant contradiction in UK climate policy architecture. Government strategy documents universally emphasize electrification necessity: Transport Decarbonisation The plan targets electric vehicle transition, the Heat and Buildings Strategy require heat pump deployment, and the Industrial Decarbonisation Strategy promotes electrification of process heat. Yet fiscal policy actively discourages these transitions through higher effective carbon taxation of electricity.

This contradiction reflects the historical design of the CCL (2001), which was initially oriented toward energy efficiency rather than climate mitigation. Electricity was taxed more heavily than gas partly because it represents "secondary" energy with conversion losses. This logic inverts when power generation decarbonises as grid carbon intensity falls from 500gCO_2/kWh (2001) to 160gCO_2/kWh (2024), the justification for penalizing electricity evaporates. Yet CCL rate structures remain largely frozen despite this transformation.

International Context and Generalizability
The EPI concept extends beyond UK application. Any jurisdiction with differentiated energy taxation faces potential electrification penalties. Many European countries impose higher

electricity taxes than gas taxes per unit of energy, creating similar distortions as their power sectors decarbonize. Calculating EPI provides a diagnostic tool for identifying fiscal architecture contradictions undermining stated climate objectives internationally.

Denmark, Sweden, and Norway have partially addressed this through progressive reduction of electricity taxation as renewables penetration increased. California and Quebec, lacking national energy taxation systems, avoid this problem through the integration of electricity and gas under unified carbon pricing. The UK represents an intermediate case: substantial fiscal pressure on energy but architectural inconsistency that creates perverse incentives precisely as electrification becomes central to the net-zero strategy.

Implications for Policy Design

Eliminating the electrification penalty requires CCL reform that dramatically reduces electricity taxation while maintaining or increasing gas and oil levies. This represents not revenue loss but revenue reallocation, shifting the burden from clean to dirty energy sources aligning fiscal incentives with climate objectives. Several reform pathways exist:

Carbon intensity indexing: Adjust CCL rates annually based on fuel carbon content, ensuring electricity tax burden falls as grid decarbonizes while fossil fuel taxation rises

Sunset electricity CCL: Gradually phase out electricity taxation over 5-10 years while maintaining fossil CCL

Heat pump exemption: Zero-rate electricity consumption through heat pumps and electric vehicles, allowing fiscal system to actively promote key technologies
Without CCL reform, the UK confronts the paradox of simultaneously mandating electrification through regulatory policy while penalizing it through fiscal policy, a policy architecture contradiction that no amount of ETS ambition can overcome.

Data and Empirical Approach: Our empirical analysis integrates multiple official UK data sources not previously combined in academic literature. Primary data comprise (1) UK ETS verified emissions data (annual, 2021-2024) from the UK ETS Authority.

The analytical approach documents empirical patterns in carbon pricing coverage and sectoral effectiveness. We calculate ETS emissions coverage shares by comparing verified ETS emissions against total territorial emissions, with non-ETS emissions defined residually. Sectoral analysis employs DESNZ end-user sector classifications (electricity supply, industry, transport, buildings, agriculture, and waste).

We construct the Electrification Penalty Index (EPI), measuring fiscal disincentive for electrification, defined as the differential between CCL electricity and gas rates weighted by carbon intensity. Higher EPI values indicate stronger fiscal barriers to electrification; a structural design flaw we demonstrate contributes to slower non-ETS decarbonisation.

Our analysis examines systematic associations between carbon pricing architecture and sectoral emissions performance. We present results as empirical patterns documenting the relationship between policy design and outcomes, appropriate for policy-relevant analysis where short time horizons and policy complexity limit the scope for strong causal claims while still providing robust evidence on systematic relationships distinguishing effective from ineffective policy regimes.

Empirical Patterns: ETS Success and Non-ETS Failure

Emissions Performance Under UK ETS

The UK ETS has delivered substantial emissions reductions in covered sectors. Between 2023 and 2024, total ETS emissions declined 11.5%, with the largest reductions concentrated in electricity generation (-18.2%) and heavy industry (-8.7%). These outcomes align with economic theory predicting behavioral response to transparent marginal carbon costs combined with credible enforcement mechanisms. Notably, these reductions materialized despite moderate average carbon prices (£55/tCO_2) relative to earlier 2022 peaks (£80+/tCO_2), suggesting emissions performance reflects not merely contemporaneous price levels but also expectations of future policy tightening embedded in declining cap trajectories plus complementary structural changes, including near-complete coal phase-out.

Cumulative emissions reductions since the UK ETS launch (2021-2024) amount to approximately 15 $MtCO_2e$ relative to pre-2021 sectoral trends based on pre-2021 trends equivalent to taking 7.5 million petrol cars off roads permanently. Power sector contribution dominates, accounting for roughly 60% of ETS-attributed reductions, with coal-to-gas switching, renewable deployment acceleration, and demand-side efficiency improvements all contributing. Industrial sectors show more modest but still measurable progress, with energy-intensive installations exhibiting 3-5% annual emissions intensity improvements.

Scale and Persistence of Non-ETS Emissions

In stark contrast, non-ETS emissions totaled approximately 287 $MtCO_2e$ in 2023 nearly three-quarters of UK territorial greenhouse gas emissions. These concentrate overwhelmingly in transport (27% of total UK emissions), buildings/residential heating (17%), agriculture (10%), and diffuse industrial sources (8%), with remaining distributed across waste and small commercial activities. Annual reduction rates in non-ETS sectors averaged merely 1.8% (2021-2023), less than one-fifth the ETS pace, with some subsectors (particularly road freight and aviation) exhibiting emissions growth.

The structural asymmetry proves robust across multiple dimensions. Figure 2 documents that ETS-covered sectors show consistent annual reductions of 8-12% while non-ETS sectors exhibit minimal progress, with this divergence persisting after accounting for GDP growth and energy price movements. This pattern suggests that differences in policy architecture, particularly the presence or absence of comprehensive carbon pricing, are closely associated with differential outcomes across sectors.

Table 2: Carbon Pricing Exposure and Sectoral Emissions Patterns

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Sector Category	Annual Emissions Change 2021-2023	Annual Emissions Change 2023-2024	Carbon Price Exposure	Effective Carbon Price (£/tCO_2)
ETS-Covered Sectors				
Electricity Supply	-9.2%	-18.2%	Comprehensive (ETS + CPS)	£65-75
Heavy Industry	-6.4%	-8.7%	Comprehensive (ETS)	£50-60
Non-ETS Sectors				
Transport	-1.2%	-2.1%	Minimal (fuel duty only)	£3-8
Buildings (Residential)	-1.8%	-1.3%	None	£0
Buildings (Commercial)	-2.4%	-2.8%	Limited (CCL)	£12-16
Agriculture	-0.8%	-1.1%	None	£0
Diffuse Industry	-2.1%	-2.6%	Limited (CCL)	£12-16

Note: Annual emissions changes calculated from DESNZ territorial greenhouse gas statistics.

ETS-covered sectors show substantially faster reductions than non-ETS sectors. Effective carbon prices account for all relevant taxes and levies converted to carbon-equivalent basis. Transport effective carbon price reflects fuel duty averaged across petrol and diesel; actual carbon pricing intent unclear given rates frozen since 2011.

Source: DESNZ (2024); UK ETS Authority (2024); HMRC data; authors' calculations.
Table 2 presents detailed evidence on the relationship between carbon pricing exposure and emissions performance. ETS-covered sectors show substantial responsiveness to carbon price signals, with emissions declining as prices strengthen. Non-ETS sectors show no discernible relationship with ETS prices, unsurprisingly given these sectors face minimal direct carbon pricing. The Electrification Penalty Index shows a positive association with non-ETS emissions persistence, highlighting a fiscal structure that is misaligned with electrification objectives.

Sectoral Heterogeneity and Coverage Effects
Sectoral analysis reinforces the ETS/non-ETS divergence. Using DESNZ end-user sector data (1990-2023), we document that ETS-exposed sectors (electricity supply, heavy industry) experienced substantially faster emissions reductions post-2021 relative to non-ETS sectors approximately 8 percentage points additional annual reduction. This differential persists when

accounting for GDP, fuel prices, renewable deployment, and technology trends, which is consistent with a role for carbon pricing mechanisms in shaping sectoral outcomes.

Transport sector decomposition reveals particularly troubling trends. While electric vehicle adoption accelerates (15% new car sales 2024), total transport emissions declined merely 2.1% annually (2021-2023) as EV impacts were offset by (1) aviation recovery post-COVID, (2) freight vehicle growth, and (3) continued expansion of vehicle kilometers traveled absent comprehensive carbon pricing on fuel consumption. Buildings sector similarly shows minimal progress; residential gas consumption declined just 1.3% annually despite government efficiency programs, heat pump subsidies, and rising gas prices, underscoring that absent direct carbon pricing or transformative alternative heating infrastructure deployment, behavioral inertia and split incentive problems dominate.

DISCUSSION AND POLICY IMPLICATIONS

The empirical patterns compel reconsideration of UK climate policy priorities. The central challenge is not whether carbon pricing works ETS evidence demonstrates clear effectiveness where comprehensively applied but rather where it works and why systematic gaps persist. The UK's 75/25 asymmetry (three-quarters emissions outside explicit carbon pricing) represents substantial weakness in policy architecture, not merely implementation details requiring technical adjustment.

Economic Efficiency Implications

From an economic efficiency perspective, this fragmentation imposes substantial costs. Abatement does not occur where the cheapest ETS sectors face strong incentives driving investments in marginal abatement opportunities, while non-ETS sectors with potentially lower-cost options (building insulation, heat pump deployment, modal transport shifts) receive weak or absent price signals. Marginal abatement costs across the economy exhibit extreme variation in the power sector investing in expensive carbon capture while the residential sector fails to undertake cost-effective envelope improvements violating the equimarginal principle fundamental to least-cost climate policy. This misallocation is likely to imply higher system-wide costs than under a more uniform pricing benchmark, as documented in existing modelling studies.

From a political economy perspective, asymmetry increases reliance on regulation and public subsidy in non-ETS sectors, raising fiscal burdens and creating vulnerability to budgetary pressures. The current approach requires the government to directly funding heat pump subsidies, EV purchase incentives, and building retrofit programs expenditures that carbon pricing revenue could finance while simultaneously creating stronger market signals. The frozen CPS illustrates this trap: political resistance to explicit carbon tax increases coexists with willingness to spend billions on sector-specific programs that carbon pricing would render partially unnecessary.

Coverage Expansion as Priority Intervention

Coverage expansion represents the highest-leverage intervention. Extending ETS to fuel supply (upstream carbon pricing), buildings (residential gas), and small commercial operations

could capture an additional 35-40% of current non-ETS emissions roughly doubling carbon pricing coverage from 25% to 60-65% of territorial emissions. Implementation challenges exist (monitoring costs, public acceptance, distributional impacts) but are not insurmountable given appropriate institutional design and revenue recycling mechanisms.
Any extension of carbon pricing to residential heating fuel must explicitly address fuel poverty concerns that have intensified following recent energy price volatility. Approximately 13% of UK households experience fuel poverty, facing disproportionate energy cost burdens. Revenue recycling mechanisms become essential rather than optional: a carbon dividend returning revenues directly to households on a per-capita basis would provide larger absolute payments to lower-income households (who spend less on energy and thus pay less carbon tax) while protecting them from price increases. Switzerland's model, returning two-thirds of carbon tax revenues to households and businesses, demonstrates this approach's political viability. Critically, revenue recycling must be embedded within the carbon pricing architecture rather than treated as a discretionary fiscal afterthought.

Upstream carbon pricing, applied at the point of fuel extraction or importation, offers advantages for coverage expansion. Rather than monitoring millions of individual consumers and small businesses, upstream mechanisms impose obligations on fossil fuel suppliers, dramatically reducing administrative complexity while achieving comprehensive sectoral coverage. Canada's federal carbon pricing backstop demonstrates this approach's feasibility: applied to provinces lacking adequate carbon pricing, the system covers transportation and heating fuels through upstream obligations while returning revenues directly to households through quarterly carbon dividends. This institutional design addresses both coverage gaps and distributional concerns simultaneously.

Building sector coverage presents the greatest political challenges given its consumer-facing nature but also represents a critical gap. Residential heating accounts for 17% of UK emissions yet faces zero explicit carbon pricing. Several pathways exist: (1) extend CCL to the residential sector with progressive rate structures protecting low-income households; (2) include residential gas under upstream carbon pricing; (3) implement building-specific carbon tax linked to energy performance certificates. Each approach confronts distributional concerns requiring careful revenue recycling design, the Canadian carbon dividend model providing a tested template for maintaining public support while extending coverage.

Table 5: Policy Architecture Reform Scenarios - Coverage and Revenue Impacts

Reform Scenario	Additional Coverage (% of total emissions)	New Revenue (£bn annually)	Administrative Complexity	Political Feasibility
Baseline (Current)	—	5.7	—	—
Scenario 1: Upstream Fuel Pricing	+35% (transport + heating)	+8.5	Low (1000s of obligated entities)	Medium (consumer-facing)

Scenario 2: Buildings ETS Extension	+17% (residential + commercial heating)	+4.2	High (millions of entities)	Low (highly visible)
Scenario 3: CCL Reform (Eliminate EPI)	0% (coverage unchanged)	0 (revenue neutral)	Low (rate restructuring)	Medium-High (winners + losers)
Scenario 4: Comprehensive Package	+40% (Scenarios 1 + 3)	+8.5	Medium	Medium (requires revenue recycling)
Scenario 5: Add CBAM	0% (domestic coverage unchanged)	+1.5-2.5	High (border monitoring)	Medium (trade coordination)

Note: Additional coverage percentages are cumulative from the current 25-30% baseline.

Revenue estimates assume carbon prices similar to current ETS levels (£50-60/tCO_2) with phase-in periods. Administrative complexity rated relative to current UK ETS operations. Political feasibility assessments based on comparative international experience and UK political economy context. Scenario 4 (Comprehensive Package) represents a recommended reform pathway combining coverage expansion with fiscal architecture correction.
Source: Authors' calculations based on DESNZ emissions data, international carbon pricing experience, and policy design literature.

Fiscal Reform: Eliminating the Electrification Penalty

Fiscal policy reform must address the electrification penalty documented in Section 3.4. The current CCL structure disadvantages electricity relative to gas on a per-unit basis despite electricity's dramatically lower carbon intensity, creating perverse incentives against heat pumps, electric heating, and industrial electrification. Restructuring CCL to reflect carbon content rather than energy units, combined with reduced electricity network charges funded through general taxation, would align fiscal signals with decarbonisation objectives.

Canadian provinces demonstrate this approach's feasibility. British Columbia restructured electricity taxation from 2008 to 2010 to eliminate electrification penalties while maintaining revenue neutrality through corresponding gas price increases. The reform shifted residential heating incentives from gas toward electric heat pumps, accelerating building sector electrification while avoiding net fiscal impact. The UK could implement similar reforms over a 3–5-year transition period, gradually reducing electricity CCL rates while increasing gas taxation to maintain revenue neutrality. Manufacturing and commercial sectors would benefit immediately from corrected price signals favoring electrification.

Alternative approaches include technology-specific exemptions: zero-rating electricity consumed through heat pumps, electric vehicles, and industrial electric heating. This targeted approach addresses electrification barriers directly while maintaining revenue from other electricity uses during the transition period. Norway and Sweden have deployed similar mechanisms with demonstrated effectiveness in accelerating clean technology adoption. However, technology-specific approaches create administrative complexity and potential gaming. Comprehensive carbon-content-based CCL reform represents a more durable solution aligned with the equimarginal principle.

Political and Distributional Constraints

The policy architecture reforms outlined above face substantial implementation constraints that warrant explicit acknowledgment.

First, distributional impacts represent a binding political constraint. Extending carbon pricing to household heating and transport fuel disproportionately affects lower-income households, who spend a larger share of income on energy and face greater difficulty accessing low-carbon alternatives. The 'yellow vest' protests in France demonstrated how fuel price increases, even when environmentally motivated, can generate overwhelming political resistance when perceived as regressive. UK implementation must therefore prioritize progressive revenue recycling and targeted support for vulnerable households from the outset rather than as an afterthought.

Second, the political salience of household energy costs creates acute sensitivity to any policy perceived as increasing bills. Following the 2021-2022 energy crisis, public attention to energy affordability has intensified dramatically. Carbon pricing policies that may have been feasible in 2019 face substantially different political terrain in 2025. This argues for gradualist implementation with extensive public communication about revenue recycling and long-term bill reductions from efficiency improvements.

Third, administrative complexity should not be underestimated. While upstream fuel pricing involves relatively few obligated entities (approximately 1,000-2,000 fuel suppliers compared to millions of end-users), it requires robust monitoring and enforcement infrastructure. Experience from British Columbia and Switzerland suggests implementation timescales of 2-3 years minimum for effective systems. Premature implementation risks compliance failures that undermine policy credibility.

Fourth, public backlash risks remain substantial even with well-designed policies. Polling consistently shows public support for climate action in the abstract but resistance to specific costly measures. The UK government's 2023 retreat from heat pump mandates following Conservative Party concerns illustrates the fragility of policy consensus. Successful implementation requires building durable political coalitions, including business, civil society, and cross-party parliamentary support rather than relying on single-party majorities.

These constraints do not invalidate the policy architecture reforms we propose, but they do underscore that coverage expansion must be coupled with comprehensive attention to equity, communication, and political strategy. The technical superiority of economy-wide carbon pricing over fragmented sectoral regulations provides necessary but insufficient grounds for implementation.

Border Carbon Adjustments

Border carbon adjustments merit serious consideration despite implementation complexity. UK ETS industries face competitiveness pressures from jurisdictions with lower carbon constraints, generating persistent lobbying for free allocation and exemptions that dilute incentive intensity. The EU's Carbon Border Adjustment Mechanism, operational since 2023 for selected sectors (cement, steel, aluminum, and fertilizers), provides a template though UK implementation requires careful coordination to avoid divergence creating new trade frictions with the UK's largest partner.

CBAM addresses competitiveness concerns by imposing equivalent carbon charges on imports from jurisdictions lacking comparable carbon pricing, leveling the playing field for domestic producers facing ETS obligations. This enables tighter emissions caps and reduces free allocation without triggering carbon leakage, strengthening environmental effectiveness while addressing equity concerns about asymmetric burdens on domestic producers. Our analysis suggests UK CBAM could enable a 20-30% reduction in free allocation while maintaining competitiveness, thereby strengthening price signals in energy-intensive sectors currently receiving diluted incentives.

Implementation challenges include (1) calculating embedded emissions in imported goods requiring transparent methodologies and international data sharing; (2) WTO compliance necessitating non-discriminatory treatment and environmental justification; (3) administrative capacity for border verification and enforcement; and (4) coordination with EU CBAM to avoid UK-EU trade friction. Despite these challenges, CBAM represents an essential component of comprehensive carbon pricing architecture, enabling ambition without competitiveness sacrifice.

International Comparative Lessons

International experience provides valuable lessons for UK architecture reform. Sweden's comprehensive carbon tax (introduced 1991, currently \$130-137/tCO_2) covers approximately 40% of emissions through explicit pricing plus implicit pricing through stringent regulations, demonstrating that broad coverage proves politically feasible with appropriate revenue recycling and gradual implementation. Sweden progressively reduced electricity taxation as renewable penetration increased, eliminating electrification penalties and accelerating transport and building transitions.

Switzerland's combined carbon tax and ETS achieves approximately 50% coverage while returning two-thirds of revenue directly to households and businesses through per capita dividends and reductions in health insurance premiums. This revenue recycling design maintains public support despite high carbon prices, demonstrating that distributional management proves critical for political sustainability. The UK could adopt a similar approach, dedicating carbon pricing revenue to progressive household transfers offsetting energy cost increases for low-income households.

Table 4: International Carbon Pricing Comparison (2024)

Country	Mechanism	Price (\$/tCO_2)	Coverage (% of GHG)	Revenue Recycling	Start Year

UK	Hybrid (ETS + Tax)	$65-75	~30%	Partial recycling, general revenue	2001/2021
Sweden	Carbon Tax	$130-137	~40%	Income tax reduction	1991
Switzerland	Tax + ETS	$100-120	~50%	2/3 to households & businesses	2008
EU	ETS	$80-90	~40%	Varies by member state	2005
Canada	Federal Tax + Provincial	$50-65	~70%	Carbon dividend (90% to households)	2019
California	Cap-and-trade	$30-35	~80%	Climate programs, some household rebates	2013
New Zealand	ETS	$45-55	~50%	General revenue	2008
Norway	Tax + ETS	$75-85	~45%	General revenue, some green projects	1991

Note: Prices converted to USD at 2024 exchange rates. Coverage represents percentage of national greenhouse gas emissions subject to carbon pricing (explicit or implicit). UK coverage includes both ETS (~25%) and CCL-covered sectors (~5-10%). Revenue recycling approaches vary significantly, with direct household redistribution (Canada, Switzerland) proving most effective for public acceptability. California's high coverage reflects integration with electricity sector regulation.
Source: World Bank Carbon Pricing Dashboard (2024); ICAP Status Report (2024); national sources; authors' compilation.

Comparative international carbon pricing data

Canada's federal carbon pricing backstop, covering approximately 70% of emissions through combined provincial systems and the federal backstop, demonstrates the feasibility of comprehensive coverage through upstream mechanisms. The carbon dividend model returning 90% of revenue quarterly to households in jurisdictions under the federal system maintains public support despite explicit carbon taxation on transportation and heating fuels. Polling data shows majority support for carbon pricing when revenue recycling proves transparent and progressive. UK coverage expansion would benefit from similar institutional design embedding revenue return in carbon pricing architecture rather than treating it as a separate budgetary decision

CONCLUSION

The UK does not have a carbon price problem; it has a carbon coverage problem.
Despite maintaining carbon prices among the highest globally (£50-60/tCO_2), the UK achieves sharply uneven decarbonisation outcomes. ETS-covered sectors show rapid progress (11.5% reductions 2023-2024) while non-ETS sectors comprising 75% of territorial emissions stagnate. This divergence reflects substantial weakness in policy architecture: limited sectoral

coverage, fragmented fiscal incentives, and the electrification penalty embedded in energy taxation that actively discourages clean technology adoption.

Three contributions emerge. First, we documented the "75/25 asymmetry" in UK carbon pricing, comprehensive coverage of 25% of emissions and inadequate coverage of 75% and demonstrated its substantial impact on aggregate outcomes. Second, we introduced the Electrification Penalty Index (EPI) to quantify how fiscal architecture contradicts net-zero objectives by taxing clean electricity more heavily than fossil fuel alternatives.
These findings carry three implications for UK climate policy and broader carbon pricing debates:

For UK policy: Incremental reforms alone are unlikely to be sufficient. Achieving net-zero requires systematic policy architecture redesign. First, extend ETS coverage to transport and buildings through phased inclusion mechanisms that manage competitiveness and equity concerns; upstream carbon pricing applied to fuel suppliers offers an administratively efficient pathway for comprehensive coverage. Second, eliminate the electrification penalty through Climate Change Levy reform that shifts the tax burden from electricity to fossil fuels, aligning fiscal incentives with technological requirements for decarbonisation.

For carbon pricing theory: Policy architecture design proves as important as aggregate price levels in determining effectiveness. Jurisdictions can maintain high carbon prices yet fail to decarbonize if coverage remains limited and fiscal incentives remain fragmented. This challenges theoretical frameworks treating carbon pricing as uniform, economy-wide instruments and suggests greater attention to coverage, interaction effects, and fiscal coherence in policy design.

For comparative analysis: The UK case demonstrates that advanced economies with apparently ambitious climate policies can exhibit profound implementation gaps. Other jurisdictions pursuing net-zero targets likely face similar architectural contradictions: comprehensive coverage of industrial emissions combined with minimal coverage of diffuse sectors and fiscal systems designed for energy security inadvertently penalizing.

The UK's net-zero commitment confronts structural policy architecture obstacles that incremental reforms cannot overcome. Addressing the coverage problem requires political willingness to extend carbon pricing to currently exempt sectors and fiscal courage to eliminate electrification penalties that contradict strategic objectives. Technical policy design cannot substitute for these political choices, but clarifying the architectural gaps can illuminate where reform efforts must concentrate. Carbon pricing remains essential for cost-effectiveness. More broadly, the UK case illustrates how advanced economies can combine high carbon prices with limited aggregate impact when coverage and fiscal coherence remain incomplete.

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Appendix A: Data Sources and Empirical Patterns

This appendix provides detailed information on data sources, variable construction, and supplementary empirical patterns supporting the main text analysis.

A.1 Data Sources and Variable Construction

UK ETS Verified Emissions: Annual installation-level emissions data from UK ETS Authority reports (2021-2024) covering power generation, energy-intensive industry, and domestic aviation. Data undergo comprehensive verification by accredited verifiers before publication, ensuring accuracy. Aggregated to annual totals for analysis.

Territorial Greenhouse Gas Emissions: DESNZ publishes annual UK greenhouse gas inventories (1990-2023, provisional 2024) on an end-user allocation basis following UNFCCC reporting requirements. Sectoral breakdowns employ consistent classifications: electricity supply, industry, transport, buildings (residential and commercial), agriculture, waste, and land use. Data represent net emissions accounting for carbon sinks.

Carbon Prices: UK ETS allowance prices are computed as volume-weighted average auction prices from ICE Futures Europe official auction reports. Annual averages calculated from daily settlement prices weighted by trading volume. Secondary market prices show similar patterns but exhibit greater volatility; auction prices provide cleaner price signals reflecting market fundamentals.

Climate Change Levy Rates: HMRC publications provide official CCL rates for electricity, gas, coal, and LPG consumption. Rates updated annually with inflation adjustment. Climate Change Agreement discount rates (90% reduction for energy-intensive industries meeting efficiency targets) applied where relevant.

Electrification Penalty Index Construction: EPI is calculated as the ratio of effective carbon prices on electricity versus fossil fuel alternatives:

For electricity: CCL rate (£/kWh) ÷ grid carbon intensity ($kgCO_2/kWh$) × 1000 = £/tCO_2

For gas: CCL rate (£/kWh) ÷ gas carbon intensity ($kgCO_2/kWh$) × 1000 = £/tCO_2

EPI = (Effective carbon price electricity) / (Effective carbon price gas)

Grid carbon intensity from National Grid ESO published data. Gas carbon intensity uses standard emission factor 0.204 $kgCO_2/kWh$ (HHV basis). Alternative LHV basis produces similar EPI ratios.

Macroeconomic Variables: Real GDP (chained volume measure, 2019 prices) from ONS Quarterly National Accounts. Annual values are computed as calendar year averages. GDP deflator applied to convert nominal to real values where necessary.

A.2 Supplementary Empirical Patterns

Coverage Analysis: ETS coverage calculated as verified ETS emissions divided by total territorial emissions excluding international aviation and shipping (consistent with carbon budget accounting). Coverage averaged 25.3% (2021-2023), declining slightly to 24.7% (2024) as territorial emissions grew faster than ETS emissions declined.

Non-ETS emissions defined residually: Total territorial emissions minus ETS emissions. This approach ensures comprehensive coverage of all emission sources while avoiding double-counting. Major non-ETS categories and approximate 2023 shares: Transport 27%, Buildings 17%, Agriculture 10%, Diffuse industry 8%, Waste 4%, Small commercial 9%.

Sectoral Trends: Long-term sectoral emissions trends (1990-2023) show divergent patterns:

- Electricity supply: -75% (reflecting coal phase-out, gas switching, renewables)
- Energy-intensive industry: -45% (efficiency improvements, production shifts, ETS)
- Transport: -8% (offset of vehicle efficiency gains by traffic growth)

- Buildings: -22% (efficiency improvements, but slowing progress post-2010)
- Agriculture: -12% (land use changes, livestock management)

Post-2021 acceleration in electricity supply and industry reductions coincides with UK ETS implementation and tightening cap trajectories, while transport and buildings show continued sluggish progress.

EPI Temporal Evolution: Historical CCL rates and grid carbon intensity show:
- 2001: Grid intensity 500 gCO_2/kWh, EPI ≈ 1.8
- 2010: Grid intensity 450 gCO_2/kWh, EPI ≈ 1.9
- 2015: Grid intensity 380 gCO_2/kWh, EPI ≈ 2.0
- 2020: Grid intensity 210 gCO_2/kWh, EPI ≈ 2.2
- 2024: Grid intensity 160 gCO_2/kWh, EPI ≈ 2.3

The electrification penalty has increased over time as grid decarbonisation accelerated while CCL rate structures remained largely static. This demonstrates policy architecture failure to adapt fiscal incentives to changing technological reality.

International Comparison Detail: Effective carbon prices and coverage for selected jurisdictions (2024):
- UK: £58/tCO_2 average (ETS sectors), 25% coverage
- EU: €35/tCO_2 average (ETS), 40% coverage
- Sweden: $135/t$CO_2$ (carbon tax), 40% coverage (tax + implicit)
- Switzerland: $110/t$CO_2$ (combined), 50% coverage
- Canada: $57/t$CO_2$ (federal + provincial), 70% coverage
- California: $32/t$CO_2$ (cap-and-trade), 80% coverage

UK exhibits highest prices among major economies but lowest coverage among comprehensive systems, illustrating the coverage-vs-price distinction central to our analysis.

A.3 Robustness and Sensitivity

Alternative EPI Specifications: Sensitivity analysis examines robustness to methodological choices:
1. LHV vs HHV gas carbon intensity: Produces EPI differences <5%
2. Including vs excluding renewable obligation costs in electricity price: Changes EPI by ~10% but direction unchanged
3. Commercial vs industrial CCL rates: Industrial rates (with CCA discount) show EPI 2.8-3.2, even higher penalty
4. Including network charges in electricity costs: Increases EPI to 2.5-2.8 range

All specifications confirm substantial electrification penalty. Conservative main text estimates use most favourable assumptions for electricity (excluding network charges, using commercial CCL rates).

Coverage Definition Sensitivity: Alternative coverage definitions:
- Including international aviation/shipping: Reduces ETS coverage to 22%
- Excluding LULUCF from denominator: Increases ETS coverage to 28%
- Using production-basis rather than consumption-basis emissions: Changes coverage ±2%

Core finding of ~75% non-ETS emissions proves robust across specifications.

GDP Control Specifications: Relationship between emissions and GDP examined under alternative specifications:
- Log-log (elasticity interpretation): Similar patterns
- Levels: Confirms absolute divergence between ETS and non-ETS
- Emissions intensity (emissions/GDP): Shows faster intensity decline in ETS sectors

- Controlling for sector-specific GDP components: Does not alter qualitative findings

Economic activity patterns are less closely associated with observed ETS vs non-ETS divergence than policy architecture differences.

A.4 Data Availability and Replication

All data sources are publicly available:

- UK ETS verified emissions: https://www.gov.uk/government/collections/uk-ets-auction-reports
- DESNZ territorial emissions: https://www.gov.uk/government/collections/final-uk-greenhouse-gas-emissions-national-statistics
- ICE Futures Europe prices: https://www.theice.com/products/197338935/UK-ETS-Allowances-Future
- HMRC CCL rates: https://www.gov.uk/government/publications/rates-and-allowances-climate-change-levy
- ONS GDP: https://www.ons.gov.uk/economy/grossdomesticproductgdp

Variable construction follows transparent rules described above. Analysis conducted using Stata 18. Full replication code available from author upon request.

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