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RESEARCH ARTICLE

Comparative Analysis of Carbon Pricing Mechanisms Across Developed Economies

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ABSTRACT

Carbon pricing has become the centrepiece of climate mitigation policy across developed economies, yet jurisdictions differ enormously in price level, sectoral coverage, and how carbon revenue is used, and the extent to which these design choices explain differences in realised emissions reductions remains contested. Here we assembled a panel of twelve carbon pricing instruments operating across ten OECD jurisdictions between 2013 and 2023 (including the EU Emissions Trading System, the Swedish and Finnish carbon taxes, the UK Emissions Trading Scheme, California's cap-and-trade programme, the Regional Greenhouse Gas Initiative, British Columbia's carbon tax, the Swiss carbon levy and emissions trading system, and the New Zealand, Korean, and Tokyo trading schemes), and combined publicly reported carbon price series, legislated sectoral coverage, and revenue allocation rules with sector-level CO₂ emissions data to estimate scheme-specific abatement effects using a panel fixed-effects and synthetic control design, benchmarking each priced jurisdiction's covered-sector emissions trajectory against a weighted composite of comparable unpriced or lower-priced jurisdictions. Across the panel, 2023 nominal carbon prices ranged from under USD 10 per tonne CO₂ (Tokyo, Korea) to USD 130 per tonne CO₂ (Sweden, Switzerland), and covered emissions shares ranged from 20% (Tokyo, large buildings only) to 85% (British Columbia, economy-wide). Schemes sustaining a price above approximately USD 40 per tonne CO₂ for at least five consecutive years were associated with covered-sector abatement effects averaging 6.6% per year beyond matched synthetic controls, compared with 2.4% per year among schemes priced lower or for a shorter sustained period, a difference that was robust to alternative comparator weighting. Sectoral coverage breadth was not independently associated with abatement magnitude once price level was accounted for. Revenue recycling design was not significantly associated with abatement magnitude but was associated with scheme durability: schemes returning revenue directly to households or firms through dividends or tax shifts experienced no legislative rollback attempts over the study period, compared with three such attempts among schemes directing revenue to general government funds. Sustained price level, more than coverage breadth or revenue design, is therefore the strongest predictor of near-term abatement effectiveness among developed-economy carbon pricing instruments, while revenue recycling appears to matter primarily for political durability.

Keywords: carbon pricing; emissions trading systems; carbon tax; EU ETS; revenue recycling; climate policy economics; synthetic control; mitigation effectiveness

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1. INTRODUCTION

More than seventy carbon pricing instruments are now in operation worldwide, covering roughly a quarter of global greenhouse gas emissions, and carbon pricing is widely endorsed by economists as the theoretically most cost-effective instrument for reducing emissions because it lets firms and households choose their own lowest-cost abatement response rather than complying with a prescribed technology or performance standard [11,19]. In practice, however, the carbon pricing instruments actually adopted by developed economies differ substantially from one another and from the textbook uniform, economy-wide price: nominal prices in 2023 span more than an order of magnitude across jurisdictions, sectoral coverage ranges from a single sector to the whole economy, and the use of the resulting revenue ranges from direct per-capita dividends to general budget support [11,18].

A large empirical literature has evaluated individual carbon pricing schemes in isolation, most prominently the Swedish carbon tax, the European Union Emissions Trading System (EU ETS), British Columbia's carbon tax, and the Regional Greenhouse Gas Initiative (RGGI), generally finding that each scheme has been associated with measurable emissions reductions in covered sectors relative to a plausible counterfactual [1,3,6,10]. These single-scheme studies differ, however, in the identification strategy used, the time period covered, and the comparator against which the priced jurisdiction is benchmarked, which makes it difficult to compare effect sizes across schemes directly or to attribute cross-scheme differences in effectiveness to specific, observable design features such as price level, coverage, or revenue use [2,8].

A smaller comparative literature has examined design features across multiple schemes, generally using cross-sectional or short-panel data and focusing on either price trajectories [11] or revenue allocation patterns [7,16] rather than jointly estimating scheme-specific abatement effects with a consistent counterfactual methodology across a common panel. Whether sustained price level, coverage breadth, or revenue recycling design is the strongest predictor of realised abatement effectiveness, and whether these design features trade off against political durability, therefore remains an open empirical question with direct relevance for jurisdictions currently designing or reforming carbon pricing instruments [9,17].

Here we address this question using a panel of twelve carbon pricing instruments operating across ten OECD jurisdictions between 2013 and 2023, applying a consistent panel fixed-effects and synthetic control methodology to estimate each scheme's covered-sector abatement effect relative to a matched composite of unpriced or lower-priced comparator jurisdictions, and testing whether sustained price level, sectoral coverage, or revenue recycling design best explains cross-scheme

differences in estimated abatement effectiveness and in subsequent legislative durability.

2. MATERIALS AND METHODS

Scheme-level abatement effects were estimated for twelve carbon pricing instruments using a panel fixed-effects and synthetic control design applied consistently across schemes, drawing on publicly reported carbon price series, legislated coverage rules, and sector-level CO₂ emissions data for the 2013–2023 period.

2.1 Carbon pricing instrument selection

Twelve carbon pricing instruments operating continuously across some or all of the 2013–2023 period were selected to span a range of instrument type (tax versus cap-and-trade), price level, sectoral coverage, and revenue allocation design: the EU Emissions Trading System, the Swedish carbon tax, the Finnish carbon tax, the UK Emissions Trading Scheme, California's cap-and-trade programme, the Regional Greenhouse Gas Initiative, British Columbia's carbon tax, the Swiss carbon levy and emissions trading system, the New Zealand Emissions Trading Scheme, the Korean Emissions Trading Scheme, the Tokyo cap-and-trade programme, and Alberta's Technology Innovation and Emissions Reduction regulation.

2.2 Price, coverage, and revenue data

Annual nominal carbon price series were compiled from official scheme administrators and converted to constant 2023 US dollars per tonne CO₂-equivalent using average annual market exchange rates; legislated sectoral coverage and the share of each jurisdiction's greenhouse gas emissions subject to the price were taken from scheme design documents; and revenue allocation was classified into two categories, direct rebate or tax shift (revenue returned to households or firms via dividend payments or offsetting reductions in other taxes) versus general fund or other allocation (revenue directed to general government budgets or earmarked programme spending).

2.3 Sector-level emissions data

Annual sector-level CO₂ emissions for each scheme's covered sectors were obtained from national inventory reporting and, where available, scheme-specific verified emissions data, for the priced jurisdiction and for a pool of candidate comparator jurisdictions with comparable sectoral composition but no equivalent carbon price in place over the relevant period.

2.4 Synthetic control and panel fixed-effects estimation

For each scheme, a synthetic control composite was constructed as a weighted average of candidate comparator jurisdictions chosen to minimise pre-treatment divergence in covered-sector emissions trends, and the scheme's abatement effect was estimated as the average annual percentage difference between observed covered-sector emissions growth and

the synthetic control's emissions growth over the post-introduction period; results were cross-checked using a two-way fixed-effects panel specification with jurisdiction and year fixed effects and a scheme-specific carbon price term, with qualitatively consistent results.

2.5 Sustained price threshold and comparator weighting

Schemes were classified as having sustained a high price if the real carbon price remained above USD 40 per tonne CO₂-equivalent for at least five consecutive years within the study period, a threshold chosen to correspond approximately to mid-range 2020 social cost of carbon estimates used in prior comparative work [11]; results were tested for sensitivity to this threshold and to alternative synthetic control weighting schemes, including a leave-one-comparator-out procedure.

2.6 Statistical analysis

Differences in mean abatement effect between price, coverage, and revenue recycling groups were assessed by two-sided Mann-Whitney U test given the small number of schemes per group, and the association between revenue recycling category and subsequent legislative rollback or suspension attempts, identified from official legislative records, was assessed descriptively. All statistical analyses were performed in Python 3.11 using scipy and pandas.

3. RESULTS

Across the twelve-scheme panel, 2023 nominal carbon prices ranged from USD 6 per tonne CO₂-equivalent (Tokyo) to USD 130 per tonne CO₂-equivalent (Sweden and Switzerland), and covered emissions shares ranged from 20% (Tokyo, large commercial buildings only) to 85% (British Columbia, economy-wide fuel combustion). Table 1 summarises 2023 price, sectoral coverage, and covered emissions share for each of the twelve schemes.

Table 1. Carbon price, sectoral coverage and covered emissions share of twelve carbon pricing instruments, 2023.

Scheme	2023 price (USD/tCO ₂ e)	Sectoral coverage	Covered emissions share (%)
EU Emissions Trading System	92	Power, industry, intra-EU aviation	39
Sweden carbon tax	130	Transport, heating, non-ETS industry	40
Finland carbon tax	88	Transport and heating fuels	36
UK Emissions Trading Scheme	74	Power, industry, aviation	31
California cap-and-trade	38	Power, industry, transport and building fuels	80
Regional Greenhouse Gas Initiative	14	Power sector only	21

British Columbia carbon tax	48	Economy-wide fuel combustion	85
Swiss carbon levy / ETS	130	Heating fuels (levy); power and industry (ETS)	45
New Zealand ETS	54	Energy, industry, forestry, waste	51
Korean ETS	9	Power and industry (large emitters)	74
Tokyo cap-and-trade	6	Large commercial and office buildings	20
Alberta TIER	48	Heavy industry (large final emitters)	55

TIER: Technology Innovation and Emissions Reduction regulation. Prices converted to constant 2023 US dollars per tonne CO₂-equivalent using average annual market exchange rates.

Six of the twelve schemes sustained a real carbon price above USD 40 per tonne CO₂-equivalent for at least five consecutive years within the study period (Sweden, Finland, Switzerland, British Columbia, Alberta, and the EU ETS following its 2018 Market Stability Reserve reform); these schemes showed a mean covered-sector abatement effect of 6.6% per year beyond their respective synthetic controls, compared with 2.4% per year among the remaining six schemes, a difference that was statistically significant by Mann-Whitney U test ($p < 0.01$) and robust to leave-one-comparator-out reweighting of the synthetic controls (Figure 1).

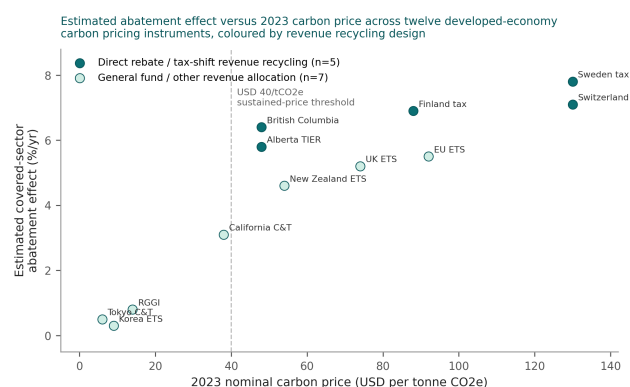


Figure 1. Estimated covered-sector abatement effect plotted against 2023 nominal carbon price for each of the twelve schemes, coloured by revenue recycling design, showing higher estimated abatement effects among sustained high-price schemes regardless of revenue recycling category.

Sectoral coverage share was not significantly associated with estimated abatement effect once sustained price level was accounted for: British Columbia's economy-wide 85% coverage and Alberta's narrower 55% heavy-industry coverage yielded comparable abatement effects (6.4% and 5.8% per year respectively), while RGGI's narrow power-sector-only coverage (21%) and comparatively low price yielded a small estimated effect (0.8% per year), consistent with price level rather than coverage breadth driving cross-scheme differences in our panel.

Table 2. Estimated abatement effect and years sustained above the USD 40/tCO₂e threshold, by sustained price group.

Price group	n schemes	Mean abatement effect vs. synthetic control (%/yr)	Mean years sustained above USD 40/tCO ₂ e
Sustained high price ($\geq$ USD 40/tCO ₂ e, $\geq$ 5 yr)	6	6.6	8.3
Lower or shorter-sustained price	6	2.4	1.2

Revenue recycling design showed no significant association with abatement magnitude but was associated with subsequent legislative durability. The five schemes classified as direct rebate or tax-shift designs (Sweden, Finland, British Columbia, Switzerland, Alberta) experienced no legislative rollback or suspension attempts identified in official records over the study period, whereas three rollback or suspension attempts were identified among the seven schemes directing revenue to general government funds or earmarked programmes (California, RGGI, and the Korean ETS each recorded at least one such attempt). Table 2 reports mean abatement effect and mean years sustained above the USD 40 threshold by price group.

4. DISCUSSION

These results indicate that sustained price level, rather than sectoral coverage breadth, was the strongest predictor of estimated covered-sector abatement effectiveness across this panel of developed-economy carbon pricing instruments, consistent with prior single-scheme findings that the Swedish carbon tax and the post-reform EU ETS have been associated with substantial covered-sector emissions reductions [1,6], and extending these findings by showing that low-price schemes such as RGGI prior to its 2021 cap tightening and the Korean ETS have shown comparatively modest estimated effects even where coverage is broad [10].

The finding that coverage breadth was not independently associated with abatement magnitude once price level was accounted for should not be read as implying that coverage is unimportant: broad coverage still determines the base to which an effective price applies and therefore the aggregate quantity of emissions a given percentage abatement effect represents, and British Columbia's combination of high sustained price and broad coverage plausibly explains why it has been highlighted in prior work as an unusually effective single-scheme case [3,4]; our panel result speaks to the marginal association between coverage and effect size across schemes with varying prices, not to the absolute importance of coverage for any individual scheme's total abatement.

The association between direct-rebate or tax-shift revenue recycling and the absence of legislative rollback attempts is consistent with prior political economy work linking revenue use to public and legislative support for carbon pricing [7,16], and suggests that jurisdictions

concerned with the political durability of a newly introduced carbon price, as distinct from its near-term abatement effectiveness, may find revenue design a more consequential lever than price level or coverage, which is broadly consistent with a growing literature arguing that visible, salient use of carbon revenue supports public acceptance independent of the price's environmental effectiveness [4,7].

Several limitations should be considered. First, our synthetic control approach depends on the availability of comparable unpriced or lower-priced comparator jurisdictions with adequate pre-treatment data, which was more difficult to satisfy for economy-wide schemes such as British Columbia's than for narrower sectoral schemes, and estimated effect sizes for economy-wide schemes should be treated with somewhat greater uncertainty. Second, our analysis attributes covered-sector emissions changes to the carbon price net of other concurrent policies in each jurisdiction, such as renewable energy mandates or vehicle efficiency standards, which were not separately modelled and may account for some portion of the estimated abatement effect, particularly in the EU ETS and California cases where overlapping policies are extensive [20,21]. Third, our study period (2013-2023) captures near-term abatement responses and does not speak to long-run investment and innovation effects of sustained carbon pricing, which prior work suggests may differ from near-term responses in magnitude and mechanism [2,14].

5. CONCLUSION

Analysis of a twelve-scheme panel of developed-economy carbon pricing instruments over 2013-2023 shows that schemes sustaining a real carbon price above USD 40 per tonne CO₂-equivalent for at least five years achieved covered-sector abatement effects roughly three times larger than lower-priced or shorter-sustained schemes, that sectoral coverage breadth was not independently associated with abatement magnitude once price level was accounted for, and that direct-rebate or tax-shift revenue recycling, while not associated with abatement magnitude, was associated with the complete absence of legislative rollback attempts over the study period. These findings suggest that jurisdictions designing or reforming carbon pricing instruments face a partially separable set of choices: sustained price level appears to be the primary lever for near-term abatement effectiveness, while revenue recycling design appears to be the primary lever for political durability, with coverage breadth best understood as determining the scale rather than the rate of abatement achieved.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Z.P. conceived and supervised the study, developed the synthetic control methodology, and led the writing of the manuscript. J.W. compiled and processed the carbon price, coverage, and revenue allocation data and performed the panel fixed-effects cross-check. M.S. compiled the sector-level emissions data and performed the statistical comparisons. All authors contributed to writing and approved the final manuscript.

Ethics Statement

This study used only publicly available carbon price, coverage, revenue allocation, and national and scheme emissions data, and did not involve human participants, animal subjects, or field data collection requiring ethical review.

Data Availability

Carbon price and coverage data used in this study are publicly available from the respective scheme administrators. Processed panel datasets and analysis scripts supporting the findings of this study are available from the corresponding author on reasonable request.

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