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Carbon leakage in emissions trading systems: a systematic review and meta-analysis of ex-ante and ex-post evidence

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ABSTRACT

Emissions Trading Systems (ETSs) are a widely adopted policy tool for reducing greenhouse gas emissions. However, emission reductions achieved within ETSs can be partially offset by increases in emissions elsewhere , a phenomenon known as carbon leakage. This paper systematically reviews the global literature on carbon leakage associated with ETSs through a combined quantitative meta-analysis and qualitative synthesis. Findings show that ex-ante modelling studies generally report positive carbon leakage rates, with estimates varying widely across schemes. Leakage rates are typically lower when more of the global emissions are covered, anti-leakage measures are included, and when using a computable general equilibrium (CGE) model. Ex-post studies find leakage through channels such as interstate electricity trade in the U.S. and investment relocation in the EU ETS and China pilot ETSs. Findings on goods trade and carbon transfer within firms are mixed. These findings highlight the differences in results between ex-ante and ex-post studies, the heterogeneity of leakage outcomes across schemes, and the critical role of country-specific context in designing ETSs and associated anti-leakage measures.

Key policy insights

- The systematic review finds that ex-ante studies estimate a lower leakage rate when emissions coverage is broader, anti-leakage measures are included, and computable general equilibrium models are used.
- Ex-post studies evidence leakage through specific channels including investment leakage in the EU ETS and Chinese pilot ETSs, and coal-to-gas substitution in the U.S. regional ETSs.
- Jurisdictions designing a mitigation policy should account for context-specific leakage risks when evaluating alternative policy instruments. Further ex-ante evidence on leakage is needed for emerging ETSs beyond the major schemes.
- To comprehensively address carbon leakage, a broader, integrated policy mix incorporating both demand- and supply- side anti-leakage measures, enhanced international cooperation, and sector-specific supports is recommended.

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Emissions trading system; cap and trade; carbon leakage; carbon pricing; systematic review

1. Introduction

Under the Paris Agreement, countries define their own climate targets through Nationally Determined Contributions, resulting in varying levels of ambition and policy stringency. This asymmetry creates differences in carbon cost burdens faced by firms in different countries, raising the risk of carbon leakage – where emissions

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are shifted rather than reduced globally. Carbon pricing is a key policy instrument to internalizing the external costs of greenhouse gas (GHG) emissions. Among the various instruments, Emissions Trading Systems (ETSs) have emerged as the most widely implemented and institutionally complex form of carbon pricing. As of 2025, 38 ETSs are in operation worldwide, covering approximately 23% of global GHG emissions (ICAP, 2025). ETSs use a cap-and-trade mechanism to create a market for emissions permits (Hahn & Hester, 1989), allowing for dynamic price formation, trading flexibility, and varied allocation rules. These features distinguish ETSs from other carbon pricing instruments such as carbon taxes and may create distinctive firm-level and sectoral responses. In particular, the behavioural responses of regulated firms – shaped by uneven carbon cost burden across jurisdictions – can lead to carbon leakage instead of genuine decarbonization, potentially undermining their effectiveness. Given the growing global reliance on ETSs, understanding their specific leakage risks is essential for designing more robust climate policies.

Carbon leakage can be defined as a carbon mitigation policy-induced change in emissions outside a country or region (IPCC, 2007). It can be positive or negative, may occur across or within regulated areas, and can unfold over the short or long term (Baylis et al., 2014; Habermacher, 2011; Perino et al., 2019). Carbon leakage can occur through multiple channels (Branger & Quirion, 2014a; Cameron & Baudry, 2023), but leakage mechanisms of carbon pricing schemes have not been satisfactorily defined in the literature and terminology varies. The carbon price raises production costs of regulated carbon-intensive products, affecting firms' competitiveness and leading them to relocate or lose market share to firms without carbon constraints. These effects change imports, exports, investment flows and affect income. Carbon pricing also creates incentives for low-carbon technological innovation and diffusion, leading to negative leakage – a spillover of emissions reductions into unregulated regions – as firms adopt cleaner technologies or as global supply chains become less carbon-intensive. Carbon pricing also reduces the demand for carbon-intensive energy, lowering global energy prices, which can increase carbon-intensive energy use elsewhere. The responses of exporters to falling prices may further shape carbon leakage over time. Carbon leakage can also result from policy design when only a subset of firms within a sector is covered or when free allocation is poorly implemented (Venmans et al., 2020).

The reallocation of emissions from regulated entities to underregulated or unregulated ones is a growing challenge. Designing an effective ETS and addressing carbon leakage requires a comprehensive understanding of its magnitude and mechanisms. Modelling and econometric methodologies have both been employed to examine carbon leakage from ETSs. Previous reviews have focused primarily on either ex-ante studies using specific methods such as computable general equilibrium (CGE) models (Carbone & Rivers, 2017; Pan et al., 2020; Xie & Rousseau, 2024) or ex-post studies of the European Union ETS (Joltreau & Sommerfeld, 2019; Verde, 2020). Recent studies have expanded the scope of these analyses. The review by Cameron and Baudry (2023) explores carbon leakage channels and discusses the effectiveness of EU carbon border adjustments policy. Grubb et al. (2022) examine leakage and anti-leakage measures from a consumption-based perspective, focusing on embedded emissions in traded goods. Caron (2022), the most similar in scope to this study, integrates ex-ante and ex-post evidence. It focuses on trade-related leakage and takes a technical approach, including trade elasticities data and energy price differentials, to explain limited leakage in CGE and empirical studies. In contrast, this review follows a systematic approach, includes evidence from ETSs worldwide, and conducts a quantitative meta-analysis and qualitative synthesis of carbon leakage. Although the reviewed studies concentrate on a small number of major ETSs and provide only sparse evidence for other schemes, the available literature still highlights diverse leakage mechanisms and substantial country-level heterogeneity.

Based on the included studies and the focus of this analysis, five carbon leakage channels[1] are examined in this review: (1) the competitiveness channel: emission changes in international trade induced by higher production costs due to ETS regulation. In the long run, investment leakage may occur as firms shift investments to maintain competitiveness; (2) the energy channel: emission changes due to decreased high-carbon energy demand under ETSs, which can lower international energy prices and increase energy consumption elsewhere; (3) the technology channel: emission changes resulting from the spillover effects of low-carbon technologies, where innovations in regulated areas influence emissions in unregulated areas; and (4) the income or demand channel: emission changes in unregulated areas driven by real income effects, which arise indirectly from the first three channels. Some studies identify further forms of leakage, such as within-sector leakage resulting from incomplete policy design, which are classified as (5) internal leakage following Perino et al. (2019). These forms of leakage are further examined in the analysis section below. Leakage channels are illustrated in Figure A1.

Building on prior work, this review provides a comprehensive synthesis of research across diverse methodologies and policy contexts. To the best of our knowledge, no comprehensive systematic review on carbon leakage in ETSs exists.[2] This review has three main objectives: (1) to systematically examine existing ex-ante and ex-post studies, with a focus on their findings on the extent of carbon leakage caused by ETSs; (2) to explore the channels through which carbon leakage occurs, and (3) to discuss the policy implications of unilateral carbon pricing, with particular attention to mitigating leakage through diverse channels.

Next, section 2 explains our systematic review methodology. Section 3 reports the quantitative and qualitative synthesis of evidence from ex-ante and ex-post studies. Section 4 discusses the key insights from the review, and section 5 concludes by offering directions for future research.

2. Methods

The review followed the Collaboration for Environmental Evidence (CEE) guidelines, and a review protocol was published on the Open Science Framework (OSF).[3] A keyword-based search was used for literature retrieval, and the scoping review was reported using the ROSES Flow Diagram of CEE guidelines (Figure A2) (Haddaway N et al., 2017). The search string included ETS and its variants AND carbon leakage and its variants in the title, abstract or keywords. The search was conducted in Scopus and Web of Science, without restrictions on publication year (Table A1). The document type was limited to 'article', and the language to 'English'. The search was conducted on 27 May 2024.

The search yielded 1170 hits from Scopus and 597 from Web of Science. After deduplication and a two-stage screening process (title and abstract, then full text), 79 studies were included; full search and screening details are reported in the Appendix B1 and Figure A2. The retained studies were split into subsamples of 38 ex-post and 41 ex-ante studies for data extraction. For the ex-post studies, information on carbon leakage effect size was recorded, including the estimated effect size, the standard error and the significance level. Additional details on study design were also captured, such as the treatment policy, study period, policy coverage, methodology, key independent and dependent variables, and key outcomes. For the ex-ante studies, the methods, industry coverage, policy scenario, key assumptions and limitations were documented (see the supplemental material).

The methodological quality and risk of bias in ex-post studies were assessed using criteria adapted from the ROBINS-I tool from Cochrane.[4] Studies with medium or high risk of bias – due to biases such as poor control group selection, confounding factors, or unclear reporting – were excluded, resulting in a final sample of 64 studies. Figure 1 illustrates the distribution of included studies by publication year and country context. Key characteristics of the included studies are provided in the Appendix B2. To improve transparency without

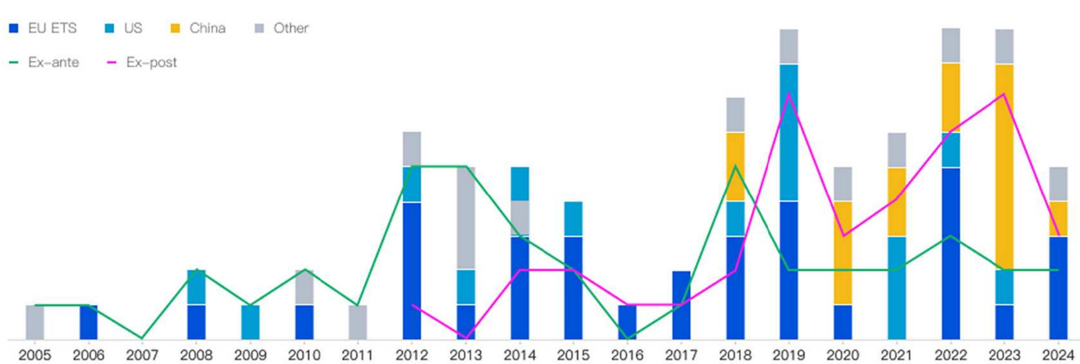

Figure 1. Research publication year and country context distribution.

Note: For statistical convenience, the graph represents the main country contexts of the included studies rather than a strict geographical distribution of policies. California's CaT and RGGI are grouped as 'U.S.', while the Chinese ETS Pilots and National ETS are categorized under 'China'. The 'Other' category includes the UK ETS, multi-country policies, Canada's ETS, Quebec's CaT, South Korea's ETS, Tokyo CaT, and Saitama ETS.

overloading the main text, detailed descriptions of data processing steps, analytical techniques, and methodological considerations are provided in Appendix B3.

This systematic review has limitations. First, the keyword-based search strategy may have excluded relevant studies that used different terminology and were therefore not captured. Second, due to the lack of a standardized critical appraisal tool for modelling studies, critical appraisals were only conducted on empirical studies, which may introduce bias. Third, the relatively small sample sizes in the quantitative synthesis may limit the explanatory power of the findings, warranting cautious interpretation. In particular, studies that had limited data on key variables influencing leakage rates and used different measures for independent variables could not be included. Fourth, as Figure 1 indicates, the majority of included studies focus on a small number of major ETSs, which limits the generalizability of our findings to other schemes. Finally, potential omissions of relevant studies – due to language barriers, publication location, or subjective assessments of study quality – may introduce further limitations.

3. Results

3.1. Ex-ante evidence of carbon leakage

A non-parametric method was used to summarize the distribution of carbon leakage estimates in ex-ante studies, given the heterogeneity in their scope and methodology. Leakage rates across 25 studies ranged from −8.25% to 90%, with a mean of 27.27%[5], highlighting notable variation across countries and sectors (see Appendix B4 for details).

To investigate factors contributing to the variability in effect sizes, methodology, scope of regulation, carbon price level, border carbon adjustment (BCA) and output-based subsidies (OBS) were selected as meta-regression variables. Other potential covariates, such as Armington elasticity values, specific leakage channels, coverage sector and jurisdictional level, were considered. Descriptive statistics and variance inflation factors (VIFs) for these variables are provided in Table A3. The meta-regression model is specified as follows:

$$LR_{ij} = C + \beta_1\ CoaSize_{ij} + \beta_2 Anti_{ij} + \beta_3 GEM_{ij} + \beta_4 CP_{ij} + \mu_{ij} + \epsilon_{ij}$$

where LR_{ij} is the leakage ratio estimated in the jth study for the ith observation. GEM_{ij} and $Anti_{ij}$ are dummy variables, taking the value 1 if the study uses a general equilibrium model or includes a border tariff or output-based subsidy, and 0 otherwise. $CoaSize_{ij}$ captures the volume of emissions covered by ETSs as a percentage of global emissions based on World Bank data. CP_{ij} refers to carbon prices, adjusted to 2007 USD. μ_{ij} is the random effect associated with study j, capturing unobserved heterogeneity between studies. ϵ_{ij} is the residual error term.

The REML meta-regression results (see Table 1) indicate that 46.27% of the variability in effect sizes is due to between-study differences, highlighting the influence of study-specific factors. The findings should therefore be interpreted with caution, despite the meta-regression allowing for a comprehensive assessment of variability across studies.

The coefficient of coalition size is significant and negative – a 10% increase in global emissions coverage reduces the estimated leakage rate by 4.7%. This indicates the importance of collective action in addressing carbon leakage, as also highlighted in previous reviews (Branger et al., 2016; Xie & Rousseau, 2024). Paroussos et al. (2015) show that carbon leakage through the competitiveness channel would drop from 28% to just 3% if China joined the EU's mitigation efforts, due to China's market size and energy-intensive production. Boeters and Bollen (2012) emphasize that including fuel exporters in the coalition is crucial for reducing leakage, through the energy channel. The participation of carbon-intensive countries and dirty energy exporters is key to reducing carbon leakage and lowering associated risks.

The coefficient of carbon price is statistically significant and negative, but close to zero. To isolate contextual factors, a sensitivity analysis was conducted using a subsample focused solely on EU ETS (Table A4), but the results remain unchanged. This marginal negative effect is consistent with the finding of Pan et al. (2020). In the included studies, abatement targets serve as an alternative proxy for environmental policy stringency, and were therefore included as a complementary variable in the sensitivity analysis. The results indicate that

Table 1. Variables and results from REML mixed-effect meta-regression.

Variable		Description	(1)	(2)	(3)	(4)	(5)
$CoaSize_{ij}$		Coalition size in terms of percentage of worldwide emissions	−0.4772*** (0.1061)	−0.4797*** (0.07483)	−0.4688*** (0.0894)	−0.4698*** (0.1089)	−0.4571*** (0.0738)
CP_{ij}		Carbon price	−0.0021*** (0.0006)	−0.0023*** (0.0006)	−0.0017*** (0.0005)	−0.0021*** (0.0007)	−0.0021*** (0.0006)
$Anti_{ij}$		1 if anti leakage policy is applied, 0 otherwise	−0.0915*** (0.03009)	−0.0889*** (0.0312)	−0.0912*** (0.0257)	−0.0915*** (0.0301)	−0.0914*** (0.0302)
GEM_{ij}		1 if general equilibrium model, 0 otherwise	−0.1724** (0.0729)	−0.1879* (0.0748)	−0.2235*** (0.0615)	−0.1723*** (0.0743)	−0.1701** (0.0738)
Armington Value	Low	1 if using lower value Armington elasticity in the model, 2 if using higher value Armington elasticity in the model, 0 otherwise		0.0593 (0.0469)			
	High			0.0748 (0.0459)			
Leakage Channel	Mixed Channel	0 if the leakage effect size is only associated to competitiveness channel, 2 if associated to energy channel, 1 if associated to mixed channel.			−0.0423 (0.0453)		
	Energy Channel				−0.2896*** (0.0722)		
Jurisdictional level		1 if a regional carbon pricing is implemented, otherwise 0.				0.0343 (0.0912)	
Sector	Emission-intensive sectors	1 if the leakage effect is associated to emission intensive sectors, 2 if the effect is only associated to energy sector, otherwise 0.					0.0556 (0.0502)
	Energy sector						0.0252 (0.0523)
NO		Number of observations	217	209	207	217	217
NG		Number of groups	25	25	23	25	25
Var(_cons)		Between-group variability	0.1447	0.1476	0.1081	0.1484	0.151
Var (Residual)		Variability within groups	0.1680	0.1699	0.1440	0.1680	0.1673
I^2		Proportion of total variability in effect size that is due to between-study differences	46.27%	46.48%	42.88%	46.90%	46.12%
F test		Tests whether the model's predictors collectively explain significant variation	11.58	8.15	13.64	9.29	7.52

Note: Standard errors in parentheses. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

abatement targets do not significantly affect leakage size in our sample – a finding consistent with Branger and Quirion (2014b), but in contrast to the results of Xie and Rousseau (2024). This is an important observation. Among the included studies, 36% use non-general equilibrium models, where the carbon price is mainly treated as an exogenous variable. In contrast, 64% of the studies use CGE models, in which abatement targets are typically exogenous and carbon price is endogenously determined by market responses. In the CGE framework, both variables act as proxies for policy stringency but capture different dimensions of it: the abatement target reflects political ambition, whereas the carbon price reflects the economic cost of achieving that ambition. An abatement target implies an equilibrium carbon price that is sensitive to structural and policy factors such as coalition size, border carbon adjustments, and trade structure assumptions (Balistreri et al., 2018; Balistreri & Rutherford, 2012) – which raise concerns about endogeneity in estimating their effects on carbon leakage. Moreover, a high carbon price may lead to structural adjustments such as shifts toward cleaner production, potentially offsetting or reversing leakage over time (Holladay et al., 2018). These dynamics in models help explain why abatement targets may have no significant effect on leakage, and why the relationship between carbon price and leakage may be complex and non-monotonic. To further examine this, a subgroup analysis was conducted by restricting the sample to studies that use non-general equilibrium models. In this subset, the carbon price level is no longer statistically significant at the 5% level, although the coefficient remains negative (Table A4). Moreover, to test whether anti-leakage measures amplify the effect of carbon prices, an interaction term between carbon price and anti-leakage policy was added in the model (Table A4). However, the coefficient on the interaction term was small and statistically insignificant, suggesting that anti-leakage measures do not moderate the impact of carbon price levels. Döbbeling-Hildebrandt et al.

(2024) also highlight that carbon price levels cannot explain the size of the emissions reductions observed across ETSs. The empirical results in Section 4 reinforce the puzzling relationship between level of carbon price and carbon leakage.

The coefficient of anti-leakage policies shows that their introduction reduces carbon leakage by approximately 9%. In the sensitivity analysis, we included dummy variables for BCA and OBS. The estimated coefficient for BCA is −7.85% and statistically significant, while that for OBS is −6.54%, but is statistically insignificant. One explanation is the limited number of observations for OBS in the sample (mean = 0.1105, Std.Dev = 0.3143), which could lead to unstable coefficient estimates in the REML meta-regression. The result is consistent with Xie and Rousseau (2024) and Branger and Quirion (2014b). BCA and OBS are the most discussed anti-leakage measures in the literature which have their own limitations. BCA functions as a trade policy and raises concerns about possible impacts on free international trade, while OBS may distort domestic markets (Fowlie & Reguant, 2021). Nonetheless, the results indicate that such measures cannot fully eliminate carbon leakage. Previous reviews provide detailed explanations for this (Cameron & Baudry, 2023). Potential complementary measures to enhance leakage prevention are further discussed in Section 4.4.

The negative coefficient of GEM_{ij} indicates that studies using CGE models find 17% lower leakage rates than non-CGE models. This result is consistent with Karp (2012). In fact, the overall effect size in the sample is larger than estimates in reviews primarily focused on CGE models, such as Carbone and Rivers (2017). A closer look at studies using non-CGE models reveals that they often focus on energy sources (Bistline et al., 2020; Daubanes et al., 2021) or apply partial equilibrium models to specific carbon-intensive sectors (Ponssard & Walker, 2008), which may explain higher leakage rate estimates. Karp (2012) highlights that CGE models incorporate economy-wide interactions and adjustments, which can dampen carbon leakage effects compared to more narrowly scoped models. However, the result contrasts with previous reviews (Branger & Quirion, 2014b; Xie & Rousseau, 2024), which report higher leakage rates in CGE models. One possible explanation for this is that their non-CGE estimates are particularly low, representing one-fifth of the sample. Ex-ante studies using CGE models could be subject to upward and downward biases due to their standard settings and assumptions. Caron (2022) highlights that non-standard CGE models produce greater variability in leakage estimates, as discussed extensively in the literature (Paroussos et al., 2015).[6]

Jurisdictional level, leakage channels, and sectoral coverage could also influence leakage estimates. However, none of them have a statistically significant effect on leakage, except for the energy channel. This finding should be interpreted with caution. The meta-regression results do not mean that these variables are uncorrelated with leakage estimates. They just indicate that their statistical significance is limited within the sample, which has restricted explanatory power. For instance, while the Armington elasticity values have a positive relationship with leakage estimates in individual studies (Paroussos et al., 2015; Sue Wing & Kolodziej, 2008), they do not emerge as explanatory variables in the meta-regression. The summary statistics in Table A3 indicate that Armington elasticity values, the energy channel and jurisdictional level have a limited number of non-zero observations, which reduces their explanatory power. Only two studies in the sample decompose leakage effects into energy channels (Caron et al., 2015; Tan et al., 2018). Both studies find that leakage due to fossil fuel price changes is smaller than electricity trade channel (Caron et al., 2015) and goods trade channel (Tan et al., 2018). However, these studies estimate within-country leakage under a regional ETS and do not account for international energy market interactions. As a result, the statistically significant result for the energy channel cannot be generalized. A total of 42% of the modelling studies cover all sectors, 37% focus on the energy sector, and the rest examine only emission-intensive sectors. Sector coverage does not have statistically significant explanatory power for the variation in leakage estimates.

Qualitative synthesis of studies that do not report comparable leakage estimates provides valuable additional insights into underlying mechanisms and policy designs. A total of 16 studies were included in the qualitative review. The following analysis focuses on emerging research directions that have received limited attention in previous reviews. First, several studies raise concerns about the effectiveness of leakage risk metrics designed for anti-leakage measures, which has implications for ETS design and anti-leakage policy (Fournier Gabela & Freund, 2023; Fowlie & Reguant, 2021; Martin et al., 2014). These studies argue that current leakage risk metrics often fail to capture either sectoral and regional differences or factors that prevent or facilitate leakage, such as level of transport costs. Second, the income or demand channel has been largely overlooked in previous reviews (Cameron & Baudry, 2023; Carbone & Rivers, 2017), despite its strong link to the competitiveness channel. A loss of competitiveness due to carbon pricing directly affects real income, and carbon pricing also shifts consumer demand towards cleaner goods. These complex interactions make the income channel challenging to estimate. Karp (2013) and Holladay et al. (2018) argue that stricter environmental regulations may lead to negative emissions leakage through the income channel, while Tan et al. (2018) decompose carbon leakage and find that the income channel contributes to positive leakage. Third, several studies have examined internal carbon leakage within and across sectors. Kurz (2024) and Zhang et al. (2020a) show that ETS thresholds push resources toward unregulated, more polluting firms, causing within-sector leakage and distorting markets. Lanzi and Wing (2013) find negative leakage across sectors due to output declines, a pattern distinct from the abatement resource effect, where regulated sectors absorb clean resources from other sectors (Baylis et al., 2014). Winchester and Rausch (2013) argue that this effect depends on the elasticity of fossil fuel supply. Under RGGI, Sue Wing and Kolodziej (2008) find that rising power prices can induce firms and households to substitute away from electricity towards fossil fuels, thereby causing leakage in non-electric sectors. Analysis of internal carbon leakage focuses on the extent to which resources or production factors can be reallocated within and across sectors. These findings suggest that carbon pricing policies may distort domestic market competition and production patterns, potentially undermining their overall effectiveness. Fourth, with the EU ETS extending to maritime transport and EU ETS 2 covering road transport, recent studies are examining carbon leakage risks in these newly regulated sectors. Fournier Gabela and Freund (2023) warn that transport, agriculture, forestry, and other land use (AFOLU) sectors may face higher leakage rate than traditional industries. Modelling studies (Dray & Doyme, 2019; Lagouvardou & Psaraftis, 2022) indicate that leakage in aviation and maritime sectors is highly sensitive to policy design, price levels, and routing flexibility. Flodén et al. (2024) stress that carbon and fuel prices significantly affect long-distance shipping and trade. Higher transportation costs could complicate the competitiveness channel of carbon leakage, particularly affecting industries with a high transport cost sensitivity, such as agriculture and cleaner final products.[7] However, most models do not take transport costs into account, which limits their ability to capture carbon leakage risks in trade-exposed sectors. These findings underscore that the magnitude and direction of carbon leakage are shaped by details of policy designs and sector-specific dynamics, which introduce distinct leakage pathways requiring tailored analysis and policy responses to ensure environmental effectiveness.

3.2. Ex-post evidence of carbon leakage

After excluding studies with medium and high risks of bias, the remaining ex-post studies were categorized into four clusters: international trade, interstate electricity trade, within-firm carbon transfer and investment. Due to the limited number of studies in each cluster, the analysis has low statistical power for exploring heterogeneity and factors influencing treatment effects. Thus, the emphasis is placed on categorizing and comparing leakage clusters rather than an in-depth exploration of heterogeneity or calculating an overall treatment effect. Within the electricity trade cluster, studies were further grouped based on changes in coal-based and non-coal-based electricity generation outside of regulated areas to better understand the treatment effect. The detailed data processing procedures are explained in Appendix B3.

(a) **Impact on international trade**: For the 13 effect sizes estimates from 3 empirical studies, the pooled effect size is 0.03, with a 95% confidence interval of −0.03 to 0.09, indicating that ETSs have no statistically significant impact on international trade (Figure 2(a))**.** Compared to the wide range of carbon leakage rates in modelling studies, empirical studies find little evidence of leakage in international trade. Only Wang and Kuusi (2024) report small leakage from the EU ETS using the recent OECD data on embodied carbon imports, whilst other studies conclude that carbon leakage does not occur. Most empirical studies focus on the first three phases of EU ETS, during which vulnerable industries were shielded from carbon pricing through generous free allocations (Naegele & Zaklan, 2019). Many authors argue that broader macroeconomic factors, such as recession (Healy et al., 2018), domestic and foreign demand (Branger et al., 2016) and electricity prices (Sartor, 2012), exert more influence on international trade than ETS policies.

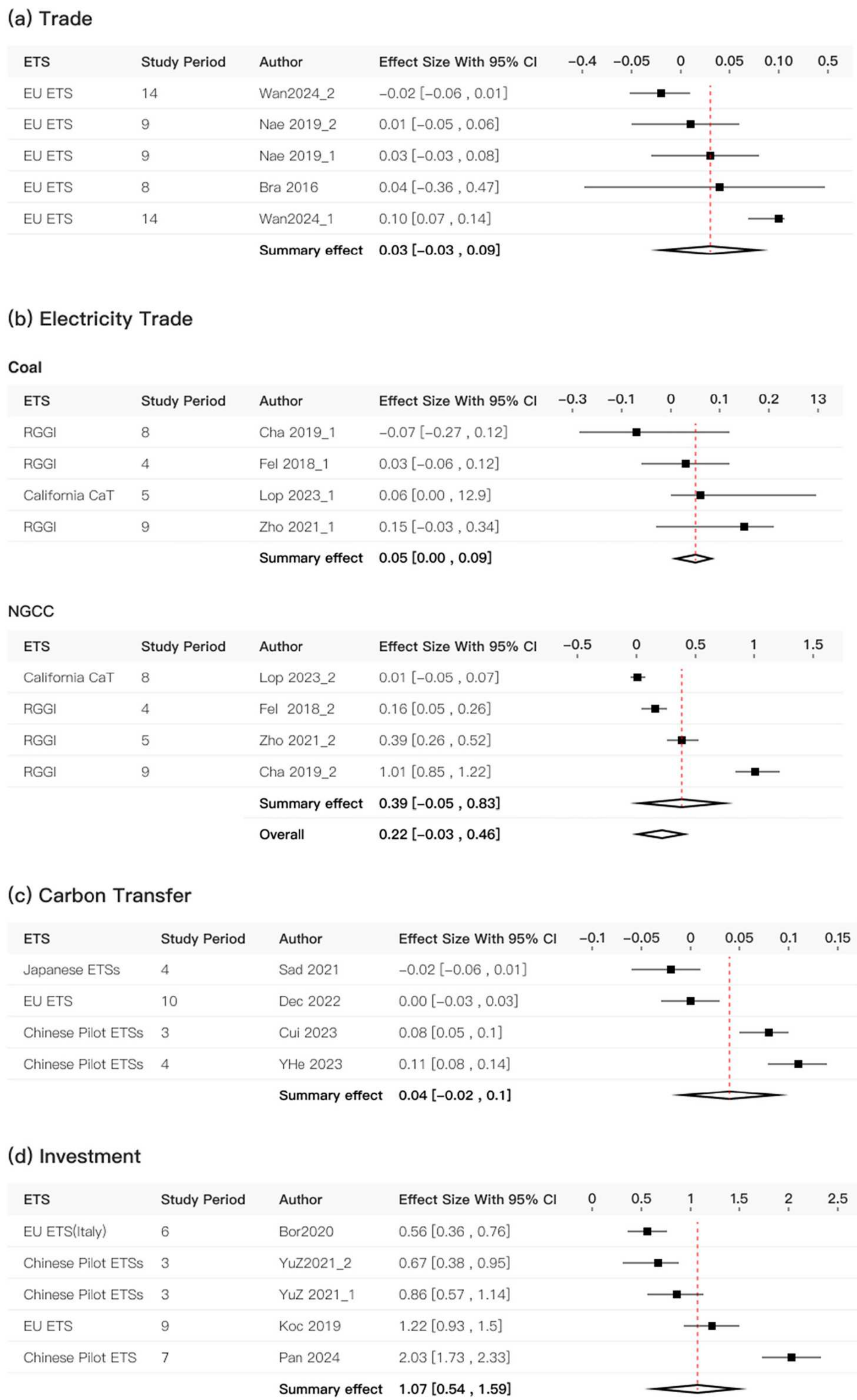

Figure 2. Forest plot in meta-analysis of empirical evidence on carbon leakage.

Note: NGCC stands for Natural Gas Combined Cycle power plant, a type of electricity generation facility which combines a gas turbine and a steam turbine to produce electricity. The study period refers to the timeframe examined following the implementation of ETSs. In cases where studies employed different measurements for the dependent variable, results were split into two effects. While similar measurement approaches were grouped into clusters, minor variations in methodology remain. As such, the findings should be interpreted with caution.

Joltreau and Sommerfeld (2019) provide a more detailed discussion on this topic. But Wang and Kuusi (2024) demonstrate that carbon leakage can occur under strict ETS designs when emission intensity is incorporated into international trade data. Studies in this cluster assess changes in international trade using measures such as trade flow in carbon content and monetary value (Naegele & Zaklan, 2019; Wang & Kuusi, 2024). While all effects were standardized as percentage changes, differences in measurement units and small sample size limit comparability across studies.

(b) **Impact on electricity trade:** The California CaT and RGGI only cover the electricity sector, with cross-regional electricity trade being the main source of carbon leakage. The meta-analysis finds an average effect size of 0.22, based on 60 estimates from 4 studies, with a 95% confidence interval (CI) ranging from −0.03 to 0.46. There is thus potential leakage effect in electricity trade, but the wide CI suggests high heterogeneity across studies and the result is not statistically significant. When coal and non-coal based electricity generation are analysed separately, a clearer picture emerges (Figure 2(b)). Coal based generation outside the regulated areas yields an average treatment effect of 0.05 (95% CI: 0.00 to 0.09), which is small but statistically significant. Non-coal based generation outside regulated area has a higher average treatment effect of 0.39, although the 95% CI (−0.05 to 0.83) is wide, indicating a high degree of uncertainty and heterogeneity. Notably, coal-to-gas substitution under the RGGI is observed across the three studies.

In the regulated area, power plants favour imports, mainly from nearby natural gas combined cycle plants, over improving coal efficiency or switching to clean fuel, and cross-regional coal-to-gas substitution driven by RGGI can reduce emissions and lead to positive leakage (Fell & Maniloff, 2018). Zhou and Huang (2021) note that RGGI increases the share of natural gas in the energy mix, though falling gas prices also play a role – 2.98% of the heat share increase is attributed to RGGI, while 5.17% is attributed to lower gas prices in unregulated regions. The impact of carbon pricing on coal use outside regulated regions is small. Most authors find that RGGI led to increased coal-fired plant capacity in non-RGGI areas, only Chan and Morrow (2019) finding no significant change in coal use outside RGGI.

Empirical evidence indicates that carbon leakage occurs in the electricity sector, aligning with ex-ante modelling studies. Caron et al. (2015) estimate a 45% carbon leakage rate under the California CaT. Daubanes et al. (2021) estimate 42% rate but emphasize that coal-gas substitution has been accompanied by increased U.S. coal exports and greater global gas production, potentially pushing total carbon leakage above 100%. Since fossil fuels play a critical role in electricity generation, it is essential to incorporate fossil fuels as a traded input into carbon leakage models. Most models fail to do so, limiting their ability to capture leakage effects in the electricity sector.

The reviewed ex-post studies only focus on interstate leakage within the U.S. In modelling research, Bistline et al. (2020) highlight the potential for emissions leakage through cross-border electricity trade between the U.S. and Canada, whilst Fell and Maniloff (2018) suggest that this international leakage could be offset by increased hydropower generation in Canada, given its energy mix. Further empirical investigation is needed to assess the role of international electricity trade in carbon leakage.

(c) **Impact on within-firm carbon transfer[8]:** Seven studies assess whether firms transfer emissions to subsidiaries outside regulated areas, and four of them are included in the meta-analysis (Figure 2(c)). The average treatment effect is 0.04 (95% CI: −0.02 to 0.10), indicating no statistically significant effect. Carbon leakage within conglomerates is observed only in the Chinese ETS pilots. Cui et al. (2023) and He and Chen (2023) find evidence that regulated firms transfer emissions to unregulated sister firms. In contrast, Dechezleprêtre et al. (2022) find no significant evidence of within-firm leakage through multinational companies inside and outside the EU. Sadayuki and Arimura (2021) find that entities covered by the Saitama ETS and the Tokyo ETS reduce emissions at both regulated and unregulated facilities, suggesting that emission reductions can spill over to non-ETS entities within conglomerates. The contrasting findings across ETSs suggest country-specific heterogeneity and the need for further research to better understand firms' behaviour.

(d) **Impact on investment:** 25 effect size estimates were extracted from 4 studies on the impact of ETSs on investment. The average treatment effect is 1.07 (95% CI: 0.54 to 1.59) (Figure 2(d)), indicating a significant positive effect on investment leakage. Some studies use the number of subsidiaries as a proxy for carbon leakage. Pan and Yu (2024) and Yu et al. (2021) investigate changes in subsidiary distribution within China and abroad and find that Chinese ETS pilots drive investments to non-ETS regions domestically and internationally. Borghesi et al. (2020) and Koch and Basse Mama (2019) obtain similar findings on French and German firms and indicate that investment leakage is more pronounced in trade-intensive sectors and in industries that are more footloose or less capital-intensive. Chen et al. (2024a) find that investment decisions manifest an avoidance effect, steering away from regions with ETSs, particularly in carbon-intensive sectors. This result is consistent with the modelling research. D'arcangelo and Galeotti (2022) find evidence of investment leakage, particularly for pollution-intensive industries, though the overall leakage effect remains small.

4. Discussion

To better understand the complexities of carbon leakage research, the discussion begins by distinguishing between ex-ante and ex-post studies (section 4.1). Section 4.2 then assesses how country-level heterogeneity influences leakage, followed by a closer look at the evidence on the competitiveness channel of carbon leakage (section 4.3). Finally, section 4.4 evaluates the role of complementary anti-leakage measures.

4.1. The difference between ex-ante and ex-post studies

Ex-ante studies report economy-wide or sector-specific estimates of carbon leakage, while ex-post studies offer more granular insights at the firm or plant level. These approaches are complementary. Ex-ante studies allow researchers to more easily isolate the impact of carbon pricing by controlling for other factors. However, they are often criticized for relying on strong assumptions. In contrast, ex-post studies are based on observed data but are more susceptible to confounding factors, making it difficult to disentangle the effects of carbon pricing from those of other policy or economic changes (Ward et al., 2015).

In our analysis, studies of interstate electricity trade report relatively consistent results between ex-ante and ex-post approaches, whereas there are more inconsistencies between ex-ante studies and ex-post studies on carbon leakage in the other clusters. Ex-ante studies report a wide range of leakage estimates depending on factors such as policy coverage, modelling approach, and the presence of anti-leakage measures. In contrast, aside from a subset of ex-post studies that identify significant carbon leakage in interstate electricity trade under the California CaT and RGGI, most ex-post evidence points primarily to investment leakage across several ETSs. Previous reviews provide partial explanations for the discrepancy between ex-ante and ex-post findings, often focusing on the competitiveness channel of carbon leakage. Joltreau and Sommerfeld (2019) argue that the design of the EU ETS such as allowance overallocation, firms' ability to pass through costs, and a relatively low energy-cost share help explain why empirical studies find limited evidence of carbon leakage and competitiveness losses. However, this may not be the case with the Chinese ETSs and in investment leakage in this analysis. The modelling literature suggests that the broad exemption criteria and current leakage risk metrics can also weaken the effectiveness of ETSs (Fowlie & Reguant, 2021; Kurz, 2024). Focusing on why estimated leakage rates are often small, Caron (2022) points out that ex-post econometric studies are unable to estimate economy-wide leakage, while leakage rates in ex-ante CGE models are heavily constrained by historically estimated trade elasticities. In addition, the interaction of different leakage channels in models may mask the underlying drivers.

Given the limited scope of the available evidence, the findings raise several concerns about research on carbon leakage in ETSs. First, many ex-ante studies focus on the EU ETS, which may not be representative for all ETSs if there is substantial country-specific heterogeneity in policy design or economic structures (see the discussion in section 4.2). Second, although the meta-regression does not find a statistically significant effect of jurisdictional level on leakage rates in ex-ante estimates, it remains a concern for the implementation of regional ETSs. McCallum (1995) suggests that national boundaries significantly impact trade flows. Accordingly, carbon leakage might be more pronounced under regional ETSs than national ones. The substantial leakage in interstate electricity trade under the RGGI, and California CaT and investment leakage in Chinese ETS pilots, provides an empirical basis for this concern. On the other hand, studies of other sub-national systems, such as those in Tokyo and Saitama, indicate that energy efficiency spillovers can mitigate emissions and reverse leakage. The impact of jurisdictional level on carbon leakage remains unclear and needs further investigation. Third, firm- and plant-level adjustments require granular, firm-level modelling approaches, ideally validated against empirical evidence. For instance, investment leakage – often ignored in modelling studies due to the assumption of capital immobility – has been observed in ex-post analyses. Intra-firm carbon transfers are one type of firm-level adjustment, though empirical findings remain inconclusive. Other adjustments, such as carbon-intensive task offshoring and domestic strategic outsourcing, are also plausible pathways for leakage but challenging to explore in quantitative models (Dussaux et al., 2023).

4.2. Country heterogeneity in ETS and carbon leakage

Our analysis relies heavily on leakage evidence from the EU, US, and China ETSs, with more sparse evidence from other schemes such as those in Japan, South Korea, the UK, and Canada. ETSs also differ substantially across countries in terms of their jurisdictional level, sector coverage, allocation methods, and carbon prices (see Table A2). This heterogeneity, combined with the uneven distribution of evidence, makes direct comparisons across ETSs challenging, but still provides useful insights into the global implementation of ETSs.

One might expect the level of carbon price to play a key role in carbon leakage. However, the meta-regression analysis suggests otherwise. China's ETS pilots, for example, exhibit investment leakage and within-firm carbon transfer, despite the low average carbon price of $5 per t$CO_2$e and a relatively short study period of four years. Paroussos et al. (2015) argue that countries with higher energy and carbon inefficiency tend to be more responsive to carbon pricing. This does not imply that carbon price levels are irrelevant, but that they may be less important in driving leakage dynamics than other factors.

ETSs also vary in sectoral scope and enforcement, reflecting countries and regions' unique social, economic, and political considerations. Economic structures and energy mixes also shape carbon leakage in goods and electricity trade. For instance, China's electricity system includes regulated monopolies in transmission and distribution, making carbon leakage in electricity trade less likely. Cao et al. (2021) find that the shift away from coal-fired electricity is largely government-driven, meaning that institutional factors influence ETS implementation. The heterogeneity in institutional effects across jurisdictions can complicate the effectiveness of carbon markets and introduce distortions in carbon market outcomes. This may also explain why studies on within-firm carbon transfer under three ETSs showed contradictory results.

In contrast, the U.S. power sector operates in a market-driven, profit-maximizing environment, where significant carbon leakage is observed in interstate electricity trade. Due to abundant natural gas reserves, coal-to-gas substitution is economically and environmentally preferable. The current regional ETS policies may favour natural gas as a transition fuel, potentially delaying the expansion of renewable energy generating capacity. Thus, variations in electricity sector structures across countries shape how ETSs function, particularly in terms of carbon cost pass-through to consumers and firms, which in turn influences the extent of carbon leakage.

This phenomenon extends beyond the electricity sector. For example, Oh (2022) finds that carbon leakage risks are particularly high in South Korea's manufacturing, as most firms are heavily engaged in international trade. This economic structure might make ETS implementation in Korea challenging, with only 3% of allowances auctioned. Cross-country heterogeneity highlights the need for more sophisticated ETS designs, including country- and sector-level leakage risk metrics, rather than a one-size-fits-all approach. Further research is also needed on underrepresented ETSs, including both newly implemented schemes and those currently under development.

4.3. Trade-related and investment leakage

International trade and FDI are key components of the global value chain, underpinning the competitiveness channel of carbon leakage. Leakage in either of these areas undermines the effectiveness of the ETSs. We find that investment leakage is more pronounced than trade-related carbon leakage and the main leakage channel. One explanation is that trade-related research relies on aggregated and sectoral data, making it difficult to capture subtle firm-level shifts, such as investment leakage. Sectoral exposure to foreign competition also varies, e.g. while the chemical industry is more vulnerable to international competition, much of its export consists of non-energy-intensive goods, such as pharmaceuticals. These products are substantially influenced by non-price competitiveness factors, such as innovation (David et al., 2025). Such complexities make trade-related carbon leakage harder to detect. More importantly, trade dynamics are influenced by many other factors than costs (as discussed in the previous section), which may buffer short-term impacts of carbon cost (Sartor, 2012). As carbon pricing in the transport sector is expected to influence international trade, a more detailed investigation into trade-related leakage is needed.

Carbon pricing has a clear impact on investment leakage. Compared to trade shifts and within-firm carbon transfer, long-term capital reallocation may have far-reaching impact, as it involves structural changes in production capacity, supply chains, and global carbon transfer (Zhang et al., 2020b). While investment leakage is considered a medium- to long-term response to carbon pricing, studies of Chinese ETS pilots, conducted just 3 years after implementation, already found significant carbon leakage through the investment channel even with a low carbon price. Investment decisions can thus respond quickly to carbon price signals, particularly in the context of developing regulatory frameworks. Investment location decisions can be confounded by macroeconomic factors. For example, Yu et al. (2021) show that the Belt and Road Initiative (BRI) reduces costs and risks associated with overseas investments by Chinese firms. Thus, BRI facilitates investment leakage through outward foreign direct investment (OFDI), although non-ETS countries outside the BRI are even more attractive investment destinations for ETS-covered firms. Carbon pricing lowers future profitability and discourages investment (Chen et al., 2024a), but it can also attract cleaner investment in low-carbon technologies and drive innovation in green products (Chen et al., 2024b). However, empirical evidence on the technology channel of carbon leakage is not included in the reviewed studies, as it may involve a time dimension that affects each step of technology spillover (Calel, 2020). More nuanced analyses are needed to better understand the implications of investment leakage and its potential heterogeneity across different types of investment.

4.4. Mitigating external and internal carbon leakage

Both ex-ante and ex-post studies suggest that ETSs contribute to carbon leakage risk. Meta-regression results also indicate that the expanding climate coalitions and implementation of anti-leakage policies can significantly reduce this risk. This analysis does not explore in detail the effectiveness of OBS and BCA, since a considerable literature already examines them (Branger & Quirion, 2014b Cameron & Baudry, 2023; Xie & Rousseau, 2024). However, previous reviews have paid limited attention to how to affect other carbon leakage channels. Monjon and Quirion (2011) conclude that neither BCA nor OBS can fully prevent carbon leakage, as their anti-leakage effects are limited to the competitiveness channel. They do not address the energy channel or promote the technology channel of carbon leakage. Given the significant carbon leakage observed in interstate electricity trade, Daubanes et al. (2021) emphasize that carbon pricing may accelerate domestic and global gas exploitation, potentially pushing leakage rates above 100%. This underscores the need for specific supply-side policies to complement demand-side carbon pricing measures. Supply-side policies could include reducing fossil fuel supply and increasing green production (Grubb et al., 2022; Harstad, 2012), for example, by introducing a tax on fossil fuel extraction and by implementing green public procurement. To counteract the energy channel, policies should target domestic fossil fuel production while also targeting foreign emissions. In particular, policies should aim to make the foreign fossil fuel supply more inelastic (Harstad, 2012). Governments often adopt a cautious approach when implementing carbon pricing, complementing them with support for cleaner energy and green technologies. Long-term structural changes in the energy sector are leading to decreasing carbon costs associated with electricity generation (IEA, 2020). Complementary policies to increase the demand of carbon-neutral products, such as green public procurement, can promote the technology channel of carbon leakage. It can also change the elasticity of substitution between clean and dirty goods in the long term, diminishing the competitiveness channel of carbon leakage (Sapir et al., 2022). It would be important to analyse the interaction effects of carbon pricing with policies promoting energy transitions and technological innovation, and dynamically adjusted factors such as the elasticity of substitution.

This analysis emphasizes the importance of internal carbon leakage, which is often overlooked in empirical research. Internal leakage can distort the domestic market competition and resource allocation, necessitating sector-specific analysis. For example, Kurz (2024) argues that ETS exemption criteria favour smaller and more polluting firms in a one-sector Melitz model, which is characterized by monopolistic competition. Other studies examine resource allocation across sectors, but their findings remain inconclusive. Market structures vary significantly by industry. Certain regulated sectors, such as cement and chemicals, are highly concentrated oligopolies with substantial markups, which reduces internal leakage risks (Cludius et al., 2020). This also shows the need for sector-specific complementary policies to support industrial transitions under carbon pricing (Zhang et al., 2020a).

5. Conclusions and policy implications

This study reports a comprehensive assessment of carbon leakage in ETSs globally and synthesizes both ex-ante modelling results and ex-post empirical evidence. Ex-ante models are typically static, and due to their macro-economic orientation, often fail to capture firm-level adjustments and technological shifts. Ex-post evidence is based on observed outcomes but is more vulnerable to confounding factors and captures only a limited portion of carbon leakage at the firm level. Despite their respective limitations, both bodies of research offer valuable insights into the dynamics of carbon leakage in ETSs and highlight its continued relevance as a policy concern. At the same time, the existing evidence base is concentrated in small number of major schemes; accordingly, the mechanisms identified here are informative across contexts, while the magnitude of estimated effects may vary in ETSs that differ in design and economic structure. The concerns highlighted below are intended to inform policy discussions, particularly for ETSs beyond the major schemes.

First, ex-ante studies generally estimate positive carbon leakage rates, with values ranging widely from −8% to 90%. This variation is shaped by factors such as the scope of emissions covered, the design of anti-leakage measures, and the modelling approaches used. A key finding from ex-post studies is that investment leakage is more dominant in the competitiveness channel than trade-related leakage. Firms respond to carbon pricing signals by shifting investments, even under low carbon prices, as seen in Chinese ETS pilots. In contrast, trade-related leakage remains limited. It is worth noting, however, that carbon pricing in the transport sector could alter trade patterns, affecting competitiveness and leakage risks across industries. The energy sector, particularly interstate electricity trade under the California CaT and RGGI, remains a significant source of carbon leakage. Carbon pricing can incentivize emission shifts through coal-to-gas replacement, which may, in turn, exacerbate global gas extraction. Second, these two bodies of research are complementary and provide valuable insights for designing effective anti-leakage measures. The meta-regression analysis highlights that expanding climate coalitions and implementing anti-leakage policies significantly reduce the risk of carbon leakage. This analysis also emphasizes the importance of complementary policies targeting the energy supply side and boosting demand for clean goods to further limit leakage risks. Third, jurisdictions considering mitigation policies should design ETSs that reflect context-specific factors to minimize carbon leakage. More research is needed on understudied country- or region- specific ETSs. Future ex-ante research could focus on newly implemented or emerging ETSs, such as Vietnam's and Indonesia's schemes, which may differ in economic structure from ETSs in advanced economies. Ex-post research could continue to monitor the performance of operational ETSs and investigate a broader set of mechanisms that explain why leakage occurs in some contexts but not in others.

Notes

1. IPCC (2022) identifies eight carbon leakage channels. Some classifications align with ours: the scale and terms of trade effects can be considered part of the income channel, and the intertemporal channel a form of energy channel. Paroussos et al. (2015) refer to the competitiveness channel as the industry channel and intertemporal leakage is associated with the 'green paradox' (Eichner & Pethig, 2011; Sinn, 2012).
2. The systematic review by An et al. (2023) focuses on the application of CGE models in low-carbon policy analysis, while Pan et al. (2020) employ meta-analysis to assess magnitude of carbon leakage in energy and forest sectors.
3. Available at osf.io/mns8a, published at Open Science Framework website.

4. Access from https://sites.google.com/site/riskofbiastool/.
5. The mean leakage rate presented here is an illustrative average effect derived from the included ex-ante studies; it does not reflect any single study and should not be interpreted as generalizable to other ETSs.
6. Paroussos et al. (2015) identify key determinants of carbon leakage rates in CGE models, including market structure, Armington elasticity, energy supply adjustment and technology spillover. Other important factors include sectoral and regional aggregation, transportation costs, and policy design elements such as permit allocation, coverage, and revenue recycling.
7. Cristea et al. (2013) find that carbon-intensive commodities are typically transported via maritime shipping, in contrast, cleaner products such as electronics heavily depend on carbon-intensive air freight. Also, nearby trade partners tend to use cleaner rail and road transport, whereas distant trade relies more on polluting transport.
8. Within-firm carbon transfer is proxied by the emissions from production in subsidiaries located in regulated areas and unregulated areas, while investment leakage is proxied by the number and value of investments, such as FDI, in both regulated areas and unregulated areas.

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Author contributions

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Disclosure statement

No potential conflict of interest was reported by the author(s).

Data availability statement

The dataset used in this study was constructed by the authors. The data and replication code are publicly available in a Zenodo repository (doi:10.5281/zenodo.18108255).

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