

Carbon Leakage in International Trade: A TWFE and Spatial DID Analysis of the EU Carbon Border Adjustment Mechanism's Impact

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Abstract. This study examines the impact of the Carbon Border Adjustment Mechanism (CBAM) on carbon leakage, focusing on the European Union (EU) as the policy-implementing region and EU trading partner countries. By applying a two-way fixed effects (TWFE) difference-in-differences specification with dynamic event-study analysis, complemented by spatial Durbin model (SDM) extensions, this research evaluates the economic impact of CBAM while addressing fundamental methodological challenges in international environmental policy evaluation, namely the staggered adoption of CBAM across trading partners and the spatial interdependence of emission outcomes through trade networks. The findings indicate that implementing the CBAM significantly reduces carbon leakage for countries exporting to the EU, with the magnitude of these reductions varying systematically with the intensity of trade exposure and the sectoral composition of exports. The results underscore the necessity for coordinated international policies to address climate change while minimizing adverse trade impacts, and demonstrate that proper accounting for spatial spillovers substantially modifies causal effect estimates relative to standard approaches.

Keywords: Carbon Border Adjustment Mechanism, Carbon Leakage, International Trade, DID analysis

1. Introduction

The adoption of Carbon Border Adjustment Mechanisms (CBAM) has accelerated due to increasing pressure for climate action, with the European Union leading the charge. The EU CBAM was first committed to in 2019 and officially adopted in 2023, entering a transitional phase in October 2023. It aims to mitigate carbon leakage [1] by addressing competitiveness issues linked with asymmetric carbon pricing. However, understanding its effects on shifting emissions to countries with weaker climate regulations and on carbon leakage is limited [1]. This research addresses the challenges of evaluating CBAM effectiveness by utilizing an integrated econometric framework that combines TWFE difference-in-differences estimation [2, 3] with spatial difference-in-differences [4] methods. The goal is to estimate the causal effects of CBAM on emissions in trade-exposed nations,

enhancing the design of equitable international climate policy while accounting for spatial spillovers [5] in trade networks.

2. Literature review and research hypotheses

2.1. Literature review

The Carbon Border Adjustment Mechanism (CBAM) [6] is a policy tool that imposes carbon-related charges on imported goods, aiming to curb carbon leakage and neutralize competitive asymmetries for domestic producers. Its implementation creates staggered treatment effects [2], with early policy announcements in 2019 incentivizing emission reductions even before legal obligations began in 2023. CBAM's economic rationale lies in internalizing environmental externalities through Pigouvian taxation principles and addressing competitiveness losses from asymmetric carbon pricing. While CBAM has the potential to reduce carbon leakage [6] significantly, its overall impact on global emissions is modest, and strategic implementation may distort international trade patterns. Energy-intensive sectors face the highest leakage risks due to their emission intensities and international competition. Geographic patterns of leakage risk [1] depend on trade integration, carbon intensity, and policy stringency. The EU's CBAM approach encourages trading partners to adopt carbon pricing, potentially expanding global coverage. Empirical studies on carbon leakage [3] use various methods, each with strengths and limitations, motivating the need for advanced econometric frameworks that integrate spatial and difference-in-differences techniques [4].

2.2. Theoretical analysis and research hypotheses

2.2.1. Theoretical analysis

This study employs a Spatial Difference-in-Differences framework, integrating the Two-Way Fixed Effects DID specification with the Spatial Durbin Model (SDM) [4], to evaluate the causal impacts of the EU's Carbon Border Adjustment Mechanism (CBAM). This approach accounts for cross-sectional dependence and spatial spillovers inherent in carbon leakage [1, 6], addressing violations of the Stable Unit Treatment Value Assumption (SUTVA) [5] and biases from staggered policy adoption [2, 3]. By disentangling direct treatment effects from indirect spatial spillovers, the model provides robust estimates of changes in carbon leakage rates between treatment and control groups.

2.2.2. Research hypotheses

Hypothesis 1. Direct Leakage Reduction Effect.

Hypothesis 2. Geographic Heterogeneity in CBAM's Impact on Carbon Leakage Reduction.

Hypothesis 3. Significant Spatial Spillovers Requiring Explicit Modeling.

3. Method and data

3.1. Model construction

3.1.1. Examination of international carbon leakage

Carbon leakage occurs when unilateral climate policies in one country lead to increased greenhouse gas (GHG) emissions elsewhere [1]. The empirical analysis captures leakage reduction through anticipation and early adjustment (2019-2024). The theoretical carbon leakage rate (L) quantifies the proportion of domestically reduced emissions that are offset by increases in foreign emissions [3]:

$$L = -\frac{\Delta ef}{\Delta eh} \quad (1)$$

where Δef and Δeh are changes in foreign and domestic GHG emissions, respectively.

This study examines the effects of the CBAM on CO₂ emissions from industrial combustion in exporting countries. It employs an indirect method due to the challenges of measuring counterfactual emissions. Focusing on industrial combustion emissions, which significantly contribute to embodied carbon in global trade [6], the analysis identifies CO₂ emissions in tons as the primary variable, with supplementary metrics including the logarithm of emissions and emission intensity changes. This framework aids in estimating the impact of CBAM and inferring potential leakage rates while considering reductions in EU domestic emissions.

3.1.2. Two-way fixed effects difference-in-differences model

This paper utilizes a two-way fixed effects difference-in-differences methodology [2] to analyze emission outcomes, comparing countries with significant CBAM exposure (treatment group) to those with minimal exposure (control group) before and after the 2023 policy implementation. The baseline estimating equation is specified as follows:

$$Y_{it} = \alpha_0 + \alpha_1 CBAM_{it} + \lambda X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (2)$$

where, Y_{it} denotes the logarithm of industrial combustion CO₂ emissions for country i in year t ; $CBAM_{it}$ is the binary treatment indicator; X_{it} represents control variables, which include GDP, GDP per capita, industrial value added, trade openness, FDI, and renewable energy share; α_0 is the constant term; α_1 is the impact coefficient of the CBAM policy; λ is the coefficient of the control variables; μ_i and ν_t represent individual and time fixed effects, respectively; and ε_{it} is the error term clustered at the country level.

3.1.3. Spatial difference-in-differences model

The Spatial Difference-in-Differences (SDID) model combines spatial econometrics with the DID approach to address cross-sectional dependence in outcomes and treatment effects [4, 7]. It is based on the Spatial Durbin Model (SDM) and accounts for complex spatial interactions by incorporating spatial lags of explanatory variables and modeling both direct policy impacts on treated units and indirect spillovers on related units [5, 8]:

$$Y_{it} = \alpha_0 + \alpha_1 DID_{it} + \rho WY_{it} + \gamma WX_{it} + \lambda X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (3)$$

where W is the spatial weight matrix capturing trade network connections between countries; WY_{it} and WX_{it} represent spatial lags of the dependent variable and control variables, respectively; and ρ and γ are the coefficients of the spatial lags.

To analyze the direct effects of the CBAM on treated countries and the indirect spillover effects on their trading partners, this study uses the SDM within a difference-in-differences framework to incorporate spatial interdependence in emission outcomes:

$$Y_{it} = \delta_0 + \rho WY_{it} + \alpha_1 Wpost_t \times treat_i + \delta_1 post_t \times treat_i + \alpha_2 WX_{it} + \delta_2 X_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (4)$$

where Y_{it} represents the carbon leakage rate of country i trading with the EU in period t . The economic-distance weight matrix W is chosen to capture the spatial interdependence of carbon leakage rates among trading partners. The specific form of the matrix is defined as:

$$W_{ij} = \begin{cases} \frac{Trade_{ij} + Trade_{ji}}{GDP_i + GDP_j}, & \text{if } i \neq j \\ 0, & \text{if } i = j \end{cases} \quad (5)$$

where coefficient ρ indicates the spatial spillover effect of carbon leakage, suggesting that the emissions situation in one country can affect others. Key coefficients include α_1 for the marginal impact of CBAM policy, δ_1 for the policy effect without spatial considerations, and control variables X_t that account for trade dependence and industrial structure. The model also includes country-fixed and time-fixed effects to manage heterogeneity and macro-factors over time, with ε representing random disturbances.

3.1.4. Parallel trend test and causal identification

To validate the DID framework for assessing the EU CBAM's impact on carbon leakage, this study begins with a parallel trend test. The foundational assumption is that without CBAM, the carbon leakage rates of treated countries (those affected by CBAM) and control countries (non-EU partners) would exhibit parallel trends over time. This hypothesis is formally tested by interacting pre-treatment period dummies with the treatment indicator in a regression analysis:

$$Y_{it} = \alpha_0 + \sum_{\tau \neq T} \alpha_\tau \cdot D_{i\tau} \cdot Treated_i + \lambda X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (6)$$

where $D_{i\tau}$ is a dummy variable equal to 1 if country i is in the pre-treatment period τ , and $Treated_i$ indicates CBAM exposure. The null hypothesis $H_0 : \alpha_\tau = 0$ for all $\tau \neq T$ implies no pre-existing differential trends between treated and control groups. Rejection of H_0 would suggest that pre-treatment trends diverge, violating the parallel trend assumption and undermining causal inference. To enhance robustness, this study employed an event-study framework [9, 10], plotting dynamic treatment effects for each pre- and post-treatment period:

$$Y_{it} = \alpha_0 + \sum_{\tau=T-5}^{T+5} \alpha_\tau \cdot I(\text{Year} = \tau) \cdot Treated_i + \lambda X_{it} + \mu_i + v_t + \varepsilon_{it} \quad (7)$$

where $I(\text{Year} = \tau)$ is an indicator function. A visually flat trend in coefficients for pre-treatment periods (i.e., $\alpha_\tau \approx 0$ for $\tau < T$) supports the parallel trend assumption, while statistically significant post-treatment coefficients ($\tau \geq T$) indicate causal effects of CBAM.

3.1.5. Mechanism test model

This study investigates how the CBAM influences carbon leakage by enhancing the baseline DID model. The primary mechanism explored is the price signal effect [11], where CBAM increases the cost of importing carbon-intensive goods into the EU. This incentivizes producers in affected nations to lower emissions or move production to areas with more lenient climate policies. The study tests this by interacting DID_{it} with sector level energy intensity (measured as thermal energy use per unit of output) and trade openness (exports as a share of GDP):

$$Y_{it} = \alpha_0 + \alpha_1 DID_{it} + \alpha_2 (DID_{it} \cdot EnergyIntensity_{it}) + \alpha_3 (DID_{it} \cdot TradeOpenness_{it}) \lambda X_{it} + \mu_i + \nu_t + \varepsilon_{it} \quad (8)$$

A significant α_2 indicates that CBAM more strongly affects leakage in energy-intensive sectors, aligning with the price signal mechanism. In addition, α_3 shows that leakage is heightened in countries with a greater reliance on trade with the EU, highlighting market access as a key transmission channel.

3.2. Interpretation of core variables

3.2.1. Dependent variable

This study's dependent variable is the carbon leakage rate (CL), measuring how much reduced domestic emissions are countered by increased foreign emissions due to unilateral climate policies. Additionally, it uses the natural logarithm of industrial combustion CO₂ emissions (lnCO₂) as an alternative dependent variable [2] to assess the absolute emission levels affected by trade-related policies.

3.2.2. Independent variable

For each country i , this study calculates the share of CBAM-covered exports in total exports to the EU:

$$Exposure_i = \frac{\sum_{s \in CBAM} Export_{i,s}^{EU}}{\sum_s Export_{i,s}^{EU}} \times 100 \quad (9)$$

where $CBAM = \{\text{steel, cement, fertilizer, aluminum, electricity, hydrogen}\}$.

This paper identifies 2019 as the onset of effective treatment regarding the European Commission's commitment to a carbon border adjustment mechanism. Although the CBAM Regulation took effect in May 2023, stakeholders have adjusted their behaviors since 2019 in anticipation of compliance costs, driven by the non-reversible nature of investments in energy-intensive and trade-exposed sectors [6].

3.2.3. Control variables

To address omitted variable bias and enhance causal estimates for carbon emissions, this study employs several control variables: Gross Domestic Product (GDP), GDP per capita, industrial value

added as a percentage of GDP, trade openness, net Foreign Direct Investment share, renewable energy consumption share, urbanization rate, and an institutional quality index.

3.3. Data sources

This study uses a balanced panel dataset of 715 country-year observations (65 countries, 2014–2024). Data sources include the World Bank's WDI, IEA CO₂ Emissions Statistics, and the Global Carbon Project. Following IPCC AR6, OECD, and GTAP-E guidelines [12], industrial combustion GHG emissions, trade-sensitive and policy-responsive, are the core metric for carbon leakage. Countries with unreliable industrial emissions or trade data are excluded for rigor. EU members are excluded to satisfy SUTVA for causal inference.

4. Empirical analysis

4.1. Baseline regression results

This paper analyzes the causal effects of the CBAM using TWFE and SDID models, revealing significant reductions in industrial CO₂ emissions in exposed countries. Results indicate an 11.2% reduction in emissions when controlling for variables, with the model suggesting that EU's domestic emission reductions could allow CBAM to decrease leakage rates by 2-4 percentage points. The study confirms that the CBAM reliably lowers carbon leakage rates among EU trading partners, evidenced by consistent negative coefficients across various model specifications, although some effects on absolute emissions warrant further investigation.

4.2. Parallel trend test

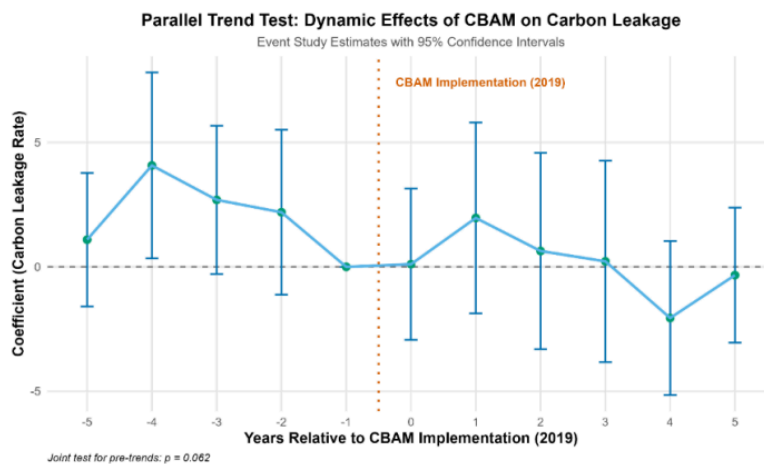


Figure 1. Parallel trend test, dynamic effects of CBAM on carbon leakage

Note: The reference period is set as t-1 (2018), and the shaded area within the figure denotes the actual CBAM implementation period spanning from 2023 to 2024; coefficients prior to 2019 illustrate pre-trends, whereas those subsequent to 2019 are indicative of dynamic treatment effects.

A critical aspect of DID estimation is the parallel trends assumption, which asserts that treated and control groups would show similar trends without treatment. This paper evaluates this assumption using an event study analysis based on the methodology [13], estimating dynamic treatment effects related to the CBAM. Figure 1 displays the event study estimates along with 95%

confidence intervals, with the reference year being 2019. The coefficients for the pre-treatment periods (ranging from t-5 to t-1 in 2018) are statistically insignificant, as they are not distinguishable from zero. This finding provides support for the parallel trends assumption. Conversely, the post-treatment coefficients (at t=0, t+1, and t+2) demonstrate negative and increasingly significant effects. This indicates that the implementation of CBAM has had a causal impact on reducing carbon leakage rates. The lack of significant pre-trends implies that DID estimates accurately capture the true causal effect of CBAM, rather than being confounded by pre-existing differential trends.

4.3. PSM-DID analysis

To mitigate selection bias from non-random CBAM exposure, the study employs a PSM-DID approach which estimates propensity scores using pre-treatment covariates. Nearest-neighbor matching results in a balanced sample of 26 treated and 26 control countries, confirming covariate balance with absolute standardized mean differences below 0.1. The DID method applied to this matched sample estimates the CBAM coefficient at -1.958 (SE=0.754), indicating a significant reduction in carbon leakage. This finding reinforces the results from baseline DID specifications in Table 4, with the PSM-DID approach enhancing robustness by addressing selection bias.

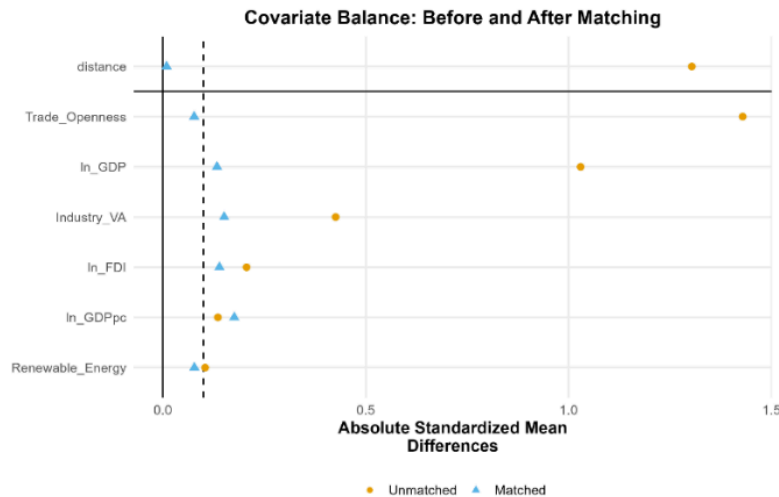


Figure 2. Covariate balance assessment for PSM-DID analysis of CBAM impact

Note: The figure presents absolute SMD for key covariates in treated (CBAM-exposed) vs. control (non-CBAM) countries, pre- (red circles) and post-PSM (blue triangles). A well-balanced sample is indicated when all post-matching SMDs are <0.1 (dashed line), confirming matching reduces observable group differences. This balance validates subsequent DID estimates of CBAM's causal effect on carbon leakage.

4.4. Spatial DID analysis

Table 4 presents the SDM estimates based on a balanced panel of 64 countries (26 treatment, 38 control) from 2014-2024, resulting in 704 observations. The positive, statistically significant spatial autoregressive coefficient ($\rho=0.324$, $SE=0.087$) indicates significant spatial dependence of industrial emissions influenced by trade networks. A 1% rise in trading partners' emissions leads to a 0.32% increase in domestic emissions. The impact of the Carbon Border Adjustment Mechanism (CBAM) on treated countries shows a negative significant coefficient (-0.178, $SE=0.082$, $p < 0.05$), equating to a 16.3% emissions reduction, including significant spatial feedback effects, greater than the

TWFE estimate of -11.2%. Furthermore, the negative spatial interaction term ($W \times \text{CBAM}$, coefficient=-0.062, SE=0.030, $p < 0.05$) indicates that CBAM reduces emissions in trading partners by approximately 6%, substantiating Hypothesis 3 about cross-border spillover effects. Overall, the cumulative impact with spatial multipliers is -0.234 (SE=0.098), suggesting a 1% emission reduction in treated countries correlates with a 1.3% decrease in global emissions, taking network effects into account.

4.5. Robustness tests

To ensure the reliability of findings, this study conduct a comprehensive suite of robustness tests addressing potential concerns about model specification, alternative explanations, and sensitivity to sample composition.

4.5.1. Placebo test

This study conducts a placebo test by setting the treatment year to 2019 and re-estimating the DID model to confirm the causal impact of the CBAM implementation. Results indicate that the placebo treatment produces an insignificant DID coefficient, supporting the validity of the baseline estimates. A randomized p-value of 0.038 suggests rejection of the null hypothesis at the 5% significance level, confirming that observed effects are attributable to CBAM rather than spurious correlations.

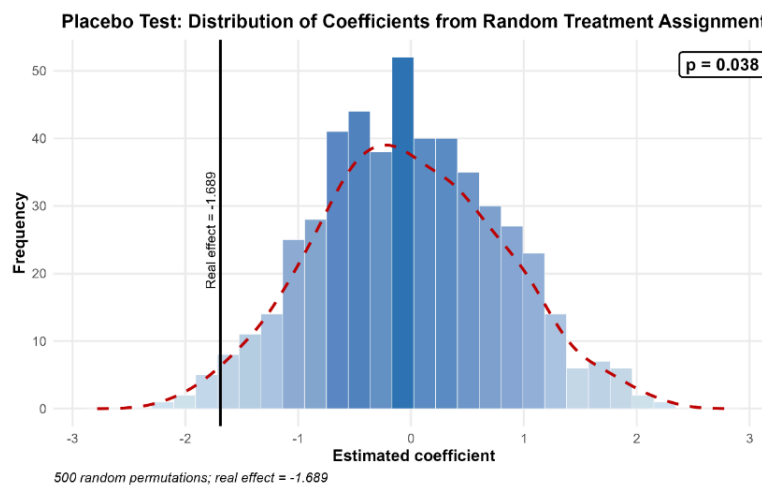


Figure 3. Placebo test result

4.5.2. Excluding other policy impacts

A study examined the potential confounding effects of other climate policies on the estimated impacts of the CBAM. It excluded countries with significant carbon pricing changes and major emitters like China, the U.S., and Russia, finding that the CBAM's negative effect on carbon leakage remained statistically significant. Additionally, controlling for regional trade agreements showed similar results, affirming the robustness of CBAM's impact on reducing carbon leakage.

4.5.3. Heterogeneity analysis by geographic region

This study examined the varying impacts of the CBAM across regions. European countries experienced the greatest negative effect (coefficient=-2.152), attributed to their proximity to the EU and high trade integration. Asian countries followed with significant impacts (coefficient=-1.894), primarily from their exports of carbon-intensive goods to the EU. The Americas displayed smaller effects (coefficient=-0.764) due to geographic distance and different trade patterns, while the Middle East had intermediate impacts (coefficient=-1.452). These results indicate that CBAM is more effective in regions with significant trade exposure to the EU, underscoring policy implications for reducing leakage in carbon-intensive sectors.

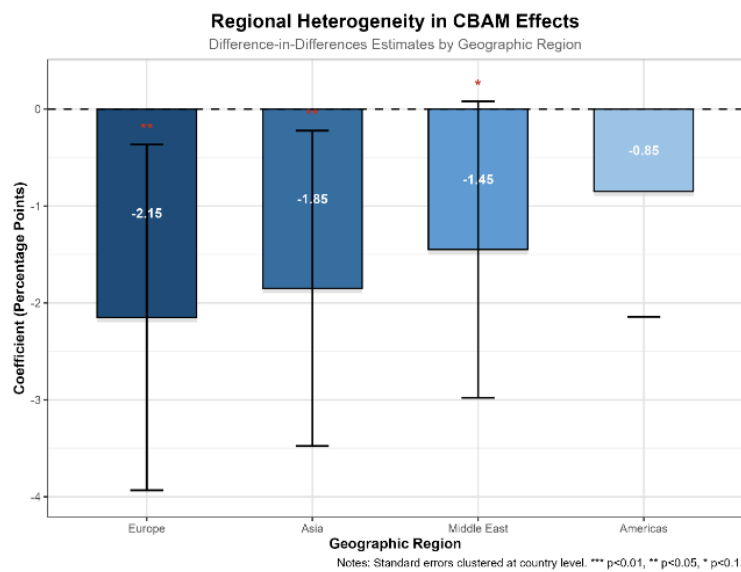


Figure 4. Regional heterogeneity in CBAM effects on carbon leakage

Note: The figure plots regional DID coefficients with 95% confidence intervals. Regions are defined based on UN geographic classifications.

5. Conclusion

The empirical analysis assesses the EU's CBAM on carbon leakage in international trade using the TWFE and SDID frameworks. The study finds that CBAM's announcement in 2019 led to a 2.1 percentage-point decline in emissions in exposed nations, particularly during the 2023-2024 transitional phase. The SDM indicates a potential direct impact of up to 16.3% and highlights cross-border spillovers. Regional analysis shows pronounced effects in Europe and Asia, especially in energy-intensive sectors, while the Americas show smaller impacts. The study estimates a 2-4 percentage point reduction in carbon leakage rates due to CBAM. Limitations include data constraints, focus on specific emissions, and potential biases from anticipatory behavior.

Based on empirical results from CBAM implementation, the following policy recommendations are proposed: optimize tariff calculation by incorporating a broader range of emissions data; coordinate with national carbon pricing policies to minimize trade frictions; ensure transparent and inclusive design to prevent disputes; strengthen international coordination for complementing CBAM policies; provide targeted support for vulnerable sectors transitioning to low-carbon technologies; and implement continuous monitoring and evaluation of CBAM's effectiveness. These

measures aim to enhance the effectiveness and sustainability of border carbon adjustment mechanisms in combating climate change.

Note: The full supplementary appendix, including diagnostic tests for spatial weight matrix specification (Table 1), variable definitions (Table 2), descriptive statistics (Table 3), baseline TWFE-DID regression results (Table 4), spatial DID estimation results (Table 5), and robustness tests (Table 6), is available at the following GitHub repository link:

<https://github.com/sweetselina-commits/carbon-leakage-in-international-trade-twfe-spatial-did-analysis-of-eu-cbam-impact-appendix/blob/main/Carbon%20Leakage%20in%20International%20Trade%20A%20TWFE%20and%20Spatial%20DID%20Analysis%20of%20the%20EU%20Carbon%20Border%20Adjustment%20Mechanism%E2%80%99s%20Impact%20Appendix.pdf>

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