FACTORS AFFECTING CARBON DIOXIDE EMISSIONS EMBODIED IN TRADE

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ABSTRACT

Trade encourages economic expansion and improves welfare based on international division of labor. However, trade also has an environmental footprint, particularly in the form of carbon dioxide (CO_2) and other emissions. This paper examines the impact of environmental regulation in exporter and importer economies on cross-border carbon flows. It uses pooled estimation, random effects, fixed effects, fixed effects with instrumental variables, and Poisson pseudo-maximum likelihood models to estimate the effect of more stringent environmental regulation, while controlling for scale, technique, and composition effects associated with CO_2 emissions. While stricter environmental regulations help reduce CO_2 emissions from domestic production, leading to lower CO_2 emissions embodied in exports, stricter regulations on the importing side lead to higher CO_2 emissions embodied in imports. More importantly, stricter environmental regulations could encourage further outsourcing of intermediate inputs by exporters, prompting carbon leakages in the upstream segment of global value chains.

Keywords: CO_2 emissions, carbon leakage, trade, global value chain

JEL codes: F1, F14, F18

1. Introduction

It is well recognized that trade promotes economic growth and helps increase welfare through job opportunities and income generation. International trade, however, entails environmental footprints, in particular due to the carbon dioxide (CO_2) and other harmful emissions associated with the production of goods and services that are traded both within and across borders. A growing number of economies have recognized this dilemma and strengthened efforts to reduce the environmental degradation caused by trade. From 2000 to 2018, the CO_2 emissions intensity of exports and imports declined in Asia, the European Union + United Kingdom (EU+UK), and North America. However, Asia still has the highest CO_2 emissions intensity embodied in exports and imports, which leaves ample room for improvement.

An inverse relationship between environmental regulations and CO_2 emissions embodied in exports and imports suggests that environmental policies have been effective in reducing environmental degradation from trade. The effect, however, is not straightforward and could have rather undesirable side effects by propagating carbon leakage: firms relocating production capacity from an economy with stringent environmental regulations to economies with laxer policies to capitalize on regulatory arbitrage. The positive relationship between environmental policies and CO_2 emissions embodied in imports and the negative relationship with respect to CO_2 emissions embodied in exports suggest that carbon leakage may be occurring. North America and EU+UK, with regulations more stringent than Asia, demonstrate higher CO_2 emissions embodied in their imports compared to exports, while Asia displays higher CO_2 emissions embodied in exports, which implies carbon leakages could be flowing from advanced to developing economies.

This paper aims to investigate the impact of environmental regulation on cross-border carbon flows. This is crucially related to the potential for carbon leakage through the impact of environmental regulations of both exporters and importers on CO_2 emissions embodied in trade. Previous literature has yielded mixed evidence in describing the effect of regulation on carbon leakage. This paper builds on the theoretical model of Copeland and Taylor (1994). It uses pooled estimation, random effects, fixed effects, fixed effects with instrumental variables, and Poisson pseudo-maximum likelihood models to estimate the effect of an environmental policy on CO_2 emissions embodied in exports, while controlling for scale, technique, and composition effects associated with CO_2 emissions.

Based on Fixed Effect and Poisson pseudo-maximum likelihood (PPML) regressions, results show that an increase in a partner (importer) economy's environmental policy stringency is associated with a reporter (exporter) economy's increase in domestic, foreign, and overall CO_2 emissions embodied in gross exports. This implies that importers with stricter environmental regulations might be relegating the production capacity of dirtier industries to exporters so as to import such products from their trade counterparts. Moreover, an increase in the reporter economy's environmental policy stringency is associated with a decrease in its domestic and overall CO_2 embodied in its gross exports and CO_2 embodied in its final goods exports. This supports the argument that stricter environmental regulations for different sectors help to green production procedures.

It is notable that the reporter's foreign CO_2 embodied in gross exports increases as its environmental policy becomes more stringent. This result suggests potential carbon leakage at upstream production segments and in downstream functions across borders because economies are inherently incentivized to outsource unclean production in both ways—upstream for exporters and downstream for importers—in the face of environmental regulations. This points to crucial drawbacks in the Carbon Border Adjustment Mechanism being contemplated by the European Union and other advanced economies in influencing exporters' production patterns through regulatory disciplines should the focus be on the final outcome of carbon leakage embodied in traded goods and services, without first considering the original source of emission productions embodied in the foreign value-added components of final exports. Likewise, the regulatory authorities need to consider the potential carbon leakages at the upstream of value chains in case the carbon intensity of intermediate products are not taken into account with environmental regulations.

A discussion and review of related literature on the relationship between trade, environment, and environmental policies is presented in Section 2, while Sections 3 and 4 present data and variables, and the paper's empirical strategy in testing its hypothesis. The results of the empirical analysis are discussed in Section 5, while Section 6 concludes the paper.

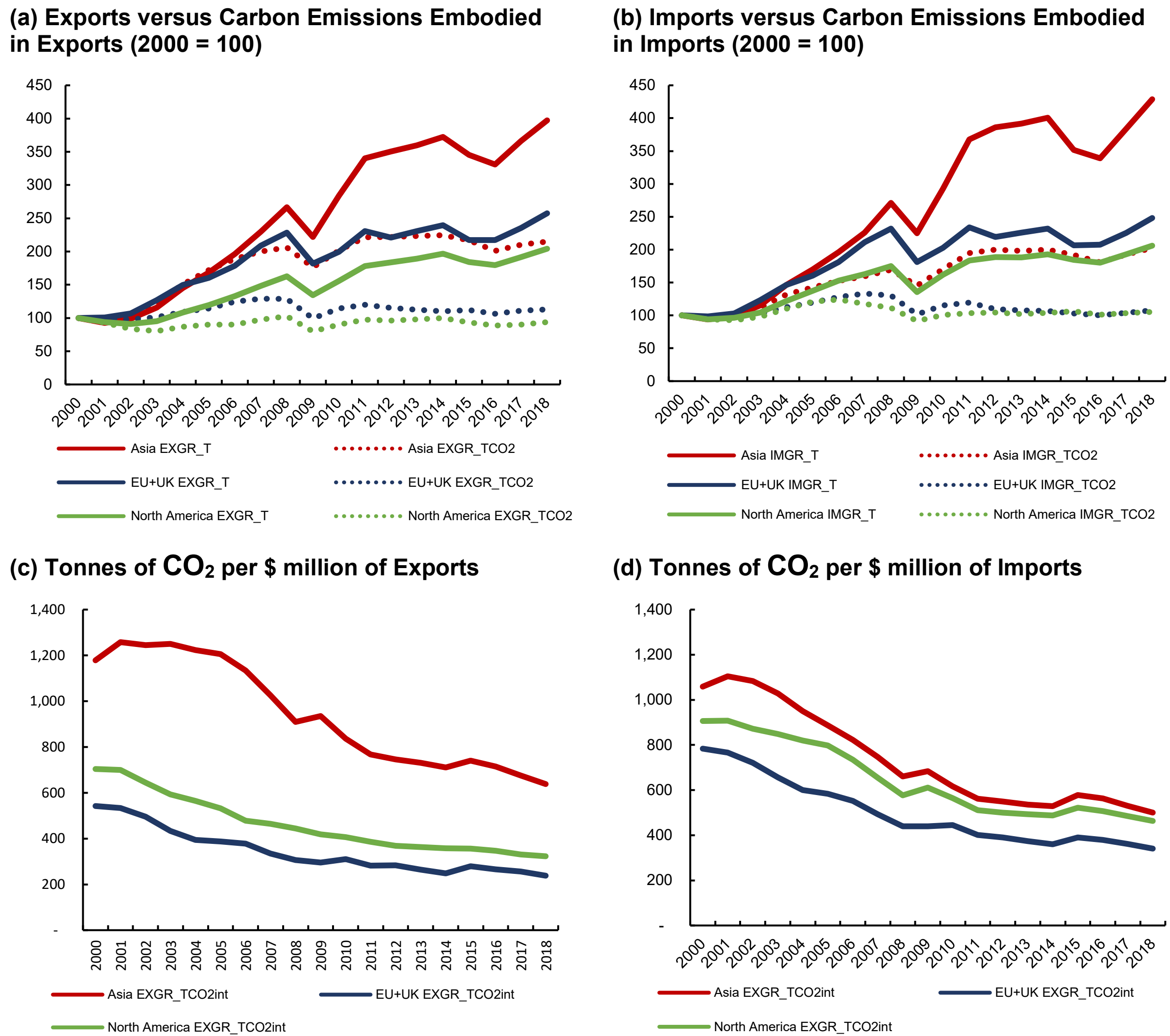
2. International Trade and the Environment

A. Background

International trade brings welfare improvements by supporting specialization of cross-border production and plugging gaps between domestic production and gross consumption at the economy level. However, these economic activities require, to varying degrees, significant fuel consumption and pursuant CO_2 emissions, which aggravate climate change and its adverse impacts. As an economy grows, it tends to emit more emissions because economic activities expand. Progress in economic growth and trade tends to increase carbon emissions (scale factor).

From 2000 to 2018, Asia's imports and exports quadrupled based on the $TECO_2$ data from the Organisation for Economic Co-operation and Development (OECD), while its carbon emissions embodied in trade only doubled. Meanwhile, although trade of EU+UK and North America doubled during the same period, their carbon emissions in trade stayed at the same level (Figure 1, panels a and b). Technical development could promote low carbon emissions for a given level of production (technology factor). The trend was of a decline in CO_2 emissions intensity (measured as tonnes of CO_2 per million US dollars of exports and imports) across all regions from 2000 to 2018. However, Asia still recorded higher CO_2 emissions intensity than EU+UK and North America in both exports and imports (Figure 1, panels c and d). This indicates although the region has progressed significantly in limiting CO_2 emissions from economic activities, it still has a lot of catching up to do with other parts of the world.

Figure 1: Carbon Emissions and International Trade over Time



CO_2 = carbon emissions, EU = European Union, EXGR_T = gross exports ($), EXGR_TCO2 = Tonnes of carbon emissions embodied in gross exports, EXGR_TCO2int = Tonnes of carbon emissions per $ million exports, IMGR_T = gross imports ($), IMGR_TCO2 = Tonnes of carbon emissions embodied in gross imports, IMGR_TCO2int = Tonnes of carbon emissions per $ million imports, UK = United Kingdom.

Source: Authors' estimates.

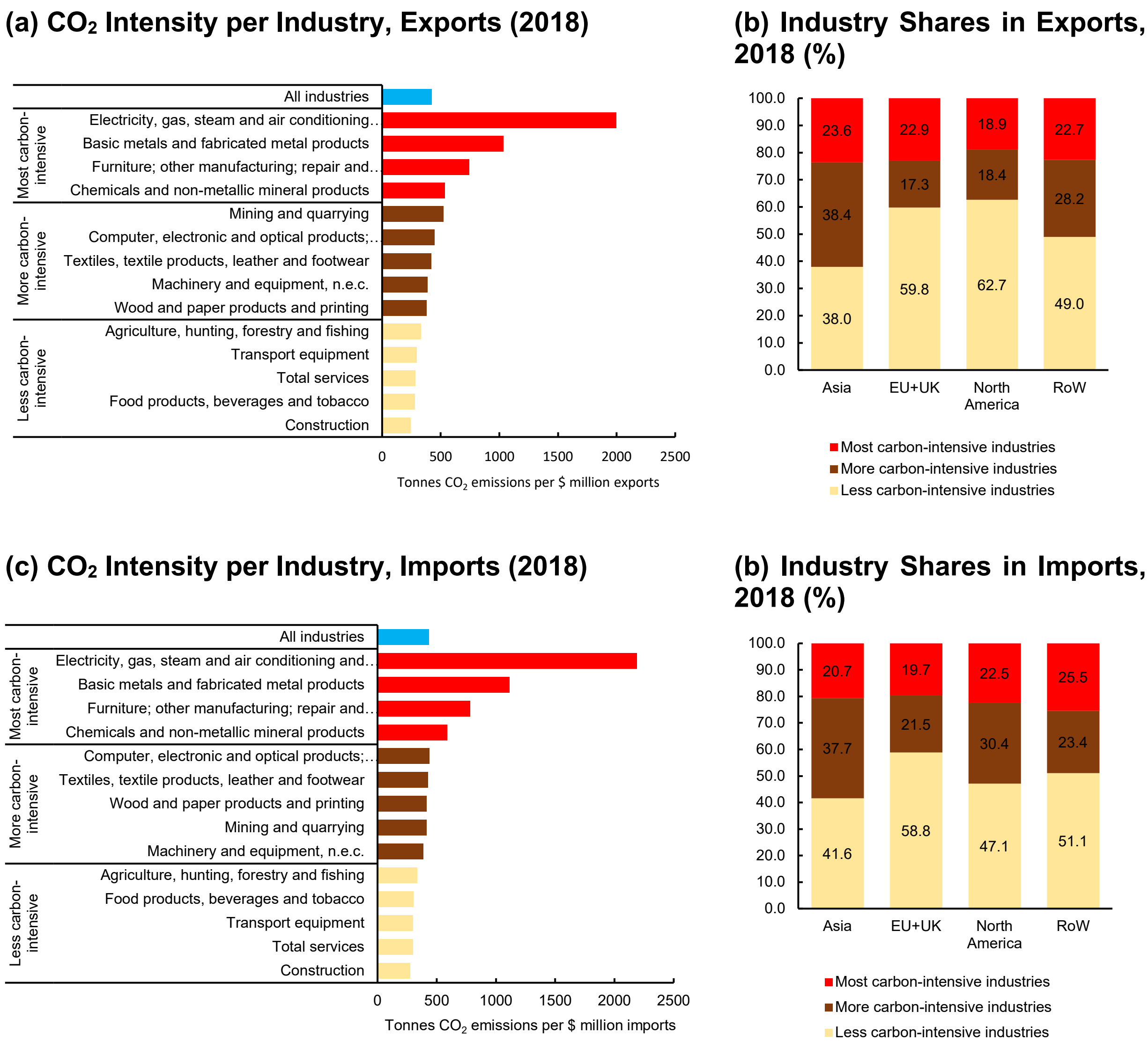
The OECD's TECO_2 data covers 68 industry groups with varying aggregation levels. A total of 14 non-overlapping industry groups were picked to cover all industries when aggregated. Carbon intensity of production is estimated according to these industrial groupings.

This estimation suggests the most carbon-intensive traded products are in industries such as (1) electricity, gas, steam and air conditioning and water supply; (2) basic metals and fabricated metal products; (3) Furniture, repair and installation, other manufacturing; (4) chemicals and non-metallic mineral products. The least carbon-intensive traded products are in (1) construction; (2)

food products, beverages and tobacco; (3) total services; (4) transport equipment; and (5) agriculture, hunting, forestry and fishing (Figure 2, panels a and c).

Overall, the high CO_2 intensity in Asian exports and imports might in part be due to the high shares of traded products coming from carbon intensive industries (the composition factor). In 2018, the share of carbon-intensive exports in Asia was 62%, while it was 40.2% in EU+UK and 37.3% in North America. Meanwhile, the share of carbon-intensive imports in Asia, at 58.4%, which is also higher than the shares of EU+UK and North America (Figure 2, panels b and d).

Figure 2: CO_2 Emissions Intensity per Industries and Trade Shares per Region

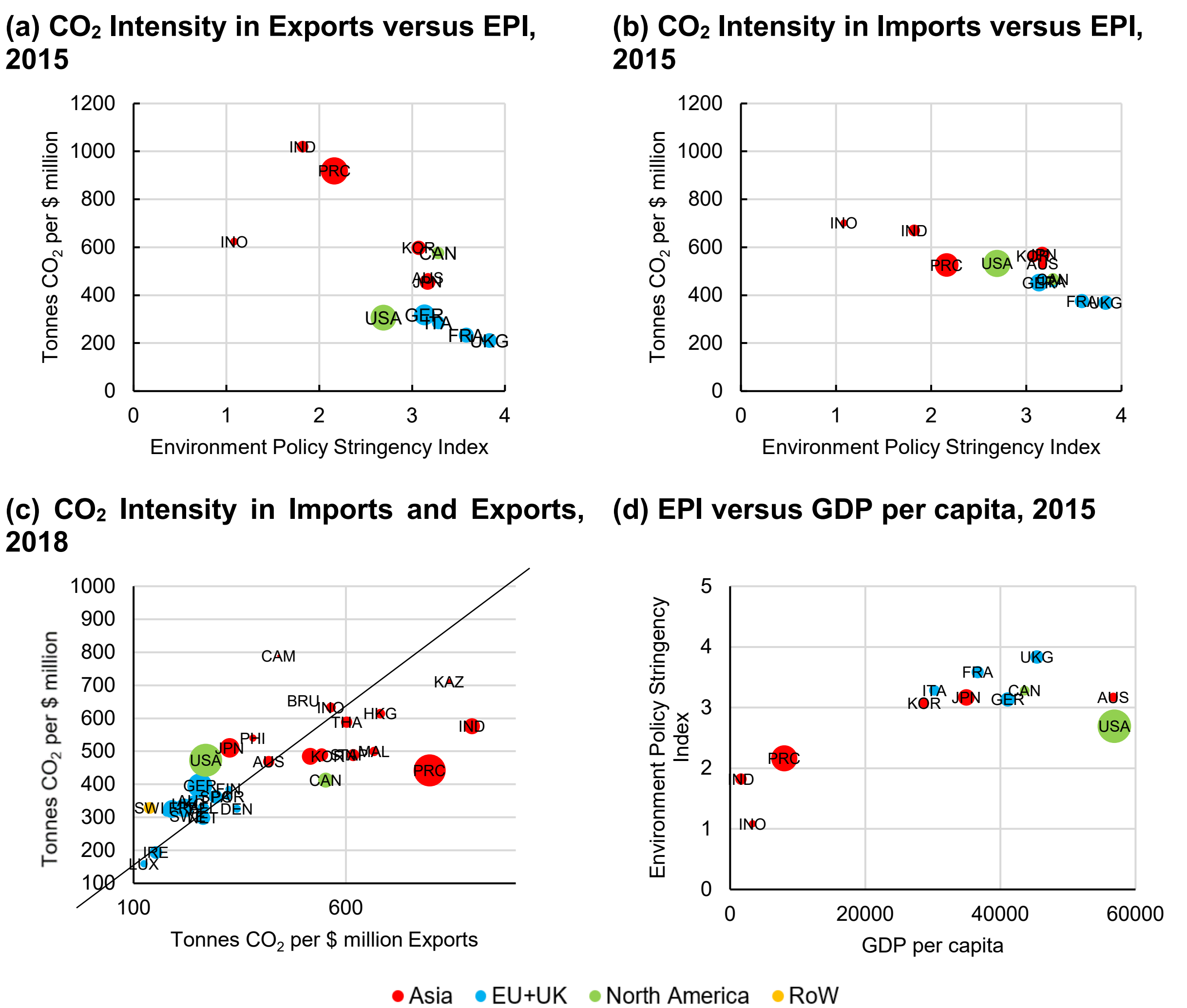


n.e.c. = not elsewhere classified, RoW = rest of the world.

Source: Authors' estimates.

The OECD Environmental Policy Stringency Index (EPI) is an economy-specific and internationally comparable measure According to the index, stringency is defined as the degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behavior.[1] The data indicates there is a steep negative correlation between CO_2 intensity in exports and EPI and a mild negative relationship between CO_2 intensity in imports and EPI. India, Indonesia, and PRC have lower EPI, while developed economies having higher EPI (Figure 3, panel a). It seems that higher income economies are more likely than lower income economies to employ stringent environmental policies (Figure 3, panel d).

Figure 3: CO_2 Emissions Intensity versus EPI, and versus GDP Per Capita



AUS = Australia; AUT = Austria; BEL = Belgium; BRU = Brunei Darussalam; CAM = Cambodia; CAN = Canada; CO_2 = carbon dioxide; DEN = Denmark; EPI = Environmental Policy Stringency Index; FIN = Finland; FRA = France; GER = Germany; GDP = gross domestic product; HKG = Hong Kong, China; IND = India; INO = Indonesia; IRE = Ireland; ITA = Italy; JPN = Japan; KAZ = Kazakhstan; KOR = Republic of Korea; LAO = Lao People's Democratic Republic; LUX = Luxembourg; MAL = Malaysia; NET = Netherlands; NOR = Norway; NZL = New Zealand; PHI = Philippines; POR = Portugal; PRC = People's Republic of China;

[1] OECD Environment Statistics. https://www.oecd-ilibrary.org/environment/data/oecd-environment-statistics/environmental-policy-stringency-index_2bc0bb80-en

SIN = Singapore; SPA = Spain; SWE = Sweden; SWI = Switzerland; TAP = Taipei,China; THA = Thailand; TUR = Türkiye; UKG = United Kingdom; USA = United States.

Notes: The bubbles in panel a represents total exports, while those in panel b represent total imports, panel c is for total trade, and panel d bubbles represent GDP. Refer to Table 1A for economy descriptions.

Source: Authors' estimates.

With stricter environmental regulations in place for an economy, industries may try to avoid these by moving their production to economies with lenient environmental regulations. This is called carbon leakage.

EU+UK's share of carbon-intensive imports is 41.2% and North America's is 52.9%, with both higher than their shares on exports (Figure 2, panels b and d). On the other hand, Asia has higher CO_2 concentrations in its exports than its imports. Comparing CO_2 intensity in exports against imports, most Asian economies show more CO_2 intensity in their exports than their imports: many of them are below the 45-degree line in Figure 3, panel c. Meanwhile, economies in EU+UK and North America show more CO_2 intensity in their imports than their exports (Figure 3, panel c). With EU + UK and North America having more stringent environmental regulations than Asia, this again indicates the potential existence of carbon leakage across regions.

B. Review of Related Literature

Scale, Technique, and Composition Effects

Even as early as 1990s, awareness was increasingly over how international trade and environmental policies affect each other, at least in some ways. Copeland and Taylor (1994) recognized that changes in pollution levels can be decomposed into three effects: scale, technique, and composition effects. Their paper defined the scale effect as the increase in pollution brought by an increase in economic activity; the technique effect as the change in aggregate pollution arising from a switch to lesser pollution-intensive production techniques; and the composition effect as the change in pollution due to a change in the range of goods produced by an economy.

Investigation on the levels and dynamics of pollution and its decomposition are continuing. Levinson (2009) aimed to determine whether it was technological or compositional factors that caused the reduction of pollution levels in US manufacturing. The author found the technological factor accounted for most of the reductions in pollution. Similarly, Shapiro and Walker (2018), using a decomposition method and product-level emissions data, saw the technique effect as explaining most of the decline in emissions over time. While this decomposition exercise provides clear results, the study conceded that it lacked the ability to uncover primitive economic forces driving pollutions reduction. Moreover, Shahbaz et al. (2019) found that technique and composition effects reduce CO_2 emissions. They also observed that scale effect offsets some of the reductions caused by the two effects.

A number of papers studied the effectiveness of environmental policies. For instance, Ederington, Paraschiv, and Zanardi (2018) investigated how international environmental agreements (IEA) affect trade flows and the competitiveness of economies. Using a gravity framework and industry-level bilateral trade data, the authors found that IEA has a small negative effect on exports and competitiveness in the short term, although it eventually fades. This implies that IEAs are not to be majorly blamed where output and competitiveness decline. The study also found these agreements induce economies to shift from dirty industries toward cleaner industries, especially in the long term. Moreover, Shapiro and Walker (2018) found from running a quantitative model of pollution emissions that the observed reduction in pollution emissions was significantly attributable to stringent environmental regulations.

Theories and Evidence of Carbon Leakage

Carbon leakage has joined the list of budding concerns in the field of trade and environmental policy. As defined by Aichele and Felbermayr (2011), carbon leakage happens when stringent environmental regulations shift the production of CO_2-intensive goods to places with relatively lax environmental regulations. Branger and Quirion (2014) defined it as a scenario when third economies increase emissions after climate change mitigation measures are implemented in another region.

Copeland and Taylor (1994) theoretically found that if the sole motivation for trade between two economies is the income-induced differences in environmental policies, then trade always lowers pollution in rich regions, increases pollution in relatively poor regions, and increases pollution worldwide.

List et al. (2003), on the other hand, tried to examine the effect of air quality regulation on the location decision of firms. Using parametric and semi-nonparametric methods on a unique county-level panel data containing decisions of manufacturing plants in New York from 1980–1990, the authors found that regulations adversely affect the location decision of these plants, especially the pollution-intensive ones. This result suggests that areas with low levels of pollution and low regulatory stringency may become havens for polluters over time.

Jakob (2021a) classifies the papers studying carbon leakage into three theories: the energy-market effect, trade specialization, and free-riding. The energy-market effect, also known as the “green paradox”, happens when an unintended increase in demand for a carbon-intensive energy source is caused by environmental policies implemented in another economy or region. For instance, demand for fossil fuels may increase in regions with less stringent environmental policies as fossil fuel prices fall as a result of lower demand from regions with more stringent policies (Edenhofer and Kalkuhl 2011). Another example is when future environmental policies are expected to be implemented, current use of fossil fuels increase (Jensen et al. 2015).

Trade specialization, or “artificial” comparative advantage, happens when an economy with less environmental regulation gains increased exports of energy-intensive goods and services due to lower energy costs (Chichilnisky 1994; Markusen 1975). Carbon leakage can also increase when emissions permit and trading does not cover all sectors (Marschinski, Flachsland, and Jakob 2012).

Another issue is free-riding. This is where the first economies implementing strict environmental regulations will be the most disadvantaged as other economies take advantage of the public good provided by the first economies’ climate change mitigation efforts (Barrett 1994; Carraro and Siniscalco 1993). The late implementers may also adopt lower reduction commitments, which may undo emission reductions made by the early implementers (Buchholz and Konrad 1994). However, more recent studies suggest that in the presence of asymmetric information, an increased emission reductions commitment by one economy may be a strong signal of willingness to increase international cooperation through transfer payments (Jakob and Lessmann 2012) or the mitigation costs are low (Brandt 2004).

Aichele and Felbermayr (2011) claimed to have conducted the first evaluation of whether the Kyoto Protocol induced carbon leakage or not. Their paper developed a simple partial equilibrium model of bilateral trade in CO_2 emissions, using this as a basis for empirical analysis. Treating the Kyoto Protocol selection as endogenous and constructing a unique database that utilized input-output tables, sector CO_2 emissions coefficients, and bilateral trade data, the authors found that Kyoto protocol indeed induced carbon leakage. The paper also found some sectors, such as basic metals and other non-metallic mineral products, to be more prone to carbon leakage than others.

Misch and Wingender (2021) also found evidence for carbon leakage and noted variations across economies depending on their size and openness. Meanwhile, Ederington, Paracschiv, and Zanardi (2018) also found evidence for carbon leakage, although they noted that it may be weak.

Some studies that used computable general equilibrium (CGE) models to simulate carbon leakage saw leakage rates of up to 50% (Babiker and Rutherford 2005; Elliott et al. 2010, Felder and Rutherford 1993). Other CGE models predict lower leakage rates at 5% to 19% (Bohringer, Balistreri, and Rutherford 2012a, 2012b).

On the other hand, other papers found evidence for negative leakage in which emission reductions in one economy would reduce emissions in another. For instance, one economy implementing stricter environmental regulations may reduce its natural gas consumption and use cleaner alternatives instead. The demand reduction for natural gas would decrease its price, which would then incentivize other economies to use it as their energy source. This would then replace the more carbon-intensive energy sources such as fossil fuels and coal in those economies (Arroyo-Curras et al. 2013; Bauer et al. 2016). Another path for negative leakage is technology spillovers resulting in lower mitigation costs and encouraging economies to increase abatement of emissions (Baylis, Fullerton, and Karney 2013; Carbone 2013; Winchester and Rausch 2013).

Another strand of papers point to an ambiguous result of carbon leakages (Jakob 2021b) found the evidence for carbon leakage to be limited. The paper argues that this may be due to the system of CO_2 emissions accounting, several anti-leakage measures, and the importance of other factors in production. Moreover, Assogbavi and Dees (2021), using a standard gravity model in trying to determine the existence of carbon leakage, found no evidence for such. Their results even indicate that stringent environmental policy leads to a reduction in CO_2 emissions embodied in trade for both the exporter and importer.

Martin et al. (2014) found that firms subjected to the UK Climate Change levy did not exit and maintained their employment in the economy despite significant increase in energy costs. Likewise, Aldy and Pizer (2015) saw US firms' trade flows between US states did not change much despite changes in energy prices.

Some made simulations as well and found that leakage rates are limited. For instance, Sato et al. (2015) found that imports would only increase by 0.2% even after an increase of 10% in energy price difference between two economies.

Other papers provide mixed results. Ederington, Levinson, and Minier (2003) found that the effect of environmental regulations on trade between industrialized and developing economies is stronger than its effect on trade between industrialized economies. Hence, estimating the effect of environmental regulations over trade flows covering all economies may shadow carbon leakage. The paper also found that less mobile industries are more insensitive to differences in regulatory stringency, hence estimating the effect of environmental regulation on trade covering all industries may hide carbon leakage as well.

3. Data

This paper uses the CO_2 emissions embodied in trade data from the OECD.[2] Using OECD's Inter-Country Input-Output (ICIO) tables and International Energy Agency's (IEA) CO_2 emissions database, the emissions embodied in gross trade and final demand were calculated based on the vectors of production-based emissions and output multipliers (Yamano and Guilhoto 2020).

Following literature on environmental impact of trade and economic activities, this paper focuses on controlling scale, composition, and technique effects in estimating potential carbon leakage impact. For this, it uses real GDP (constant 2015 prices) from the World Bank's World Development Indicators as proxy for scale effect. The technique effect is proxied by CO_2 emissions embodied in production per capita from OECD. For composition effect, the share of the value added of clean industries to total value added was used as proxy.

For the environmental policy variable, this paper uses "stringency of environmental regulations" from World Economic Forum's Executive Opinion Survey. In this survey, respondents were asked "How do you assess the stringency of your country's environmental regulations?", They rated "1" as "very lax", and "7" as "among the world's most stringent".

As a robustness check to minimize potential endogeneity problem and address the missing data problem and heteroscedasticity of error terms, we introduce fixed effect model with instruments, and Poisson pseudo-maximum likelihood (PPML) regression respectively. For the share of the value added of clean industries to total value added for both reporter and partner, we use reporter and partner's share of research and development (R&D) to GDP as instruments. Following studies of Ederington, Paraschiv, and Zanardi (2018) and Ederington and Minier (2003), which argued that environmental regulations should be treated endogenously to obtain accurate estimates of its effects, we use the number of international environmental agreements for both reporter and partner as instruments for environmental regulations.

Variables used in the empirical estimation can be grouped into three categories: (i) non-bilateral and non-sectoral variables, (ii) bilateral and sectoral variables, and (iii) bilateral and non-sectoral variables. Non-bilateral and non-sectoral variables are variables that are economy-specific—these are real GDP, stringency of environmental regulations, share of research and development (RND) expenditures to GDP, share of labor force with advanced education to total working-age population, international environmental agreements, CO_2 embodied in production per capita, and the share of the five cleanest industries to total production. Bilateral and sector variables are reporter-partner-industry-specific and these include total CO_2 emissions embodied in exports, domestic CO_2 emissions embodied in exports and foreign CO_2 emissions embodied in exports.

[2] Carbon dioxide emissions embodied in international trade (2021 edition). https://stats.oecd.org/Index.aspx?DataSetCode=IO_GHG_2021

Finally, a bilateral and non-sector variable is reporter-partner-specific and is the preferential trade agreements between two economies.

GDP data is expressed in real terms using 2015 as the base year and it averaged $1 trillion from 2008–2018 with 715 observations (Table 1). Standard deviation is notably high at about $2,514 billion, indicating erratic values for real GDP. Stringency of environmental regulations variable is a scale variable with a value of 7 indicating the most stringent score. Data are available for 2008–2018 and averaged at 4.73 with a standard deviation of 0.93. Share of R&D expenditures to GDP variable spans for 2008–2018 and averaged 1.45%, a notably low share. International environmental agreements entered upon by economies averaged 17 agreements, indicating stronger environmental cooperation among economies. CO_2 embodied in production per capita averaged 7.6 tonnes during 2008–2018. Finally, the share of total production for the economies' five cleanest industries averaged around 32% for 2008–2018.

All bilateral and sectoral variables covered 2008–2018. Total CO_2 emissions embodied in exports averaged 111,000 tonnes. Domestic CO_2 emissions embodied in exports accounted for most of this at an average of 78,000 tonnes, while foreign CO_2 emissions embodied in exports only averaged 33,000 tonnes. On the other hand, total CO_2 emissions of intermediate goods, on average, is higher than the CO_2 emissions of final goods. Lastly, the preferential trade agreements between economies variable is a binary variable with a value of 1 indicating the existence of such for an economy-pair. For 2008–2018, the variable averaged 0.9, indicating that most of the economy-pairs have trade agreements between them during that period.

Table 1: Descriptive Statistics

Variables	No. of Observations	Mean	Standard Deviation	Minimum Value	Maximum Value
Non-Bilateral Non-Sectoral Variables					
Real GDP (constant 2015, $ billion)	715	1,006.6	2,514.1	8.07	19,551.98
Stringency of environmental regulations (7 = most stringent)	702	4.73	0.93	2.51	6.62
Share of research and development expenditures to GDP	605	1.45	1.03	0.03	4.94
International environmental agreements	715	16.76	5.30	2.00	26.00
CO_2 embodied in production per capita (tonnes per capita)	726	7.64	5.39	0.15	29.90
Share of top five cleanest industries to total production	726	32.16	15.98	6.21	83.04
Bilateral Non-Sectoral Variables					
Preferential trade agreements between economies	24,288	0.92	0.27	0	1.00
Bilateral Sectoral Variables					
Total CO_2 emissions embodied in exports (million tonnes)	388,608	0.111	0.865	0	63.296
Domestic CO_2 emissions embodied in exports (million tonnes)	388,608	0.078	0.686	0	59.452
Foreign CO_2 emissions embodied in exports (million tonnes)	388,608	0.033	0.259	0	23.902
Total CO_2 emissions embodied in exports of intermediate goods (million tonnes)	388,608	0.072	0.663	0	63.142
Total CO_2 emissions embodied in exports of final goods (million tonnes)	388,608	0.038	0.314	0	27.467

CO_2 = carbon dioxide.

Source: Authors' estimates.

4. Identification Strategy

Appendix A.1 summarizes papers that empirically analyzed the effects of environmental regulations on trade and CO_2 embodied in trade. Papers mostly used imports or exports (and their corresponding CO_2 emissions) as dependent variables. Others utilized the location decision of firms as dependent variable. Various models, both parametric and nonparametric, were employed to identify the determinants of CO_2 emissions and examine potential carbon leakages.

This paper follows the approaches of Ederington, Paraschiv, and Zanardi (2018), Assogbavi and Dees (2021), and Misch and Wingender (2021). It utilizes CO_2 emissions embodied in exports as a dependent variable and runs various models such as ordinary least squares (OLS), fixed effects, random effects, fixed effect with instrumental variables, and PPML models to determine the effects on CO_2 emissions of environmental policy and of scale, composition, and technique effects. Time-invariant fixed effects such as variables for distance, common language, and contiguity are added in the analysis, similar to the gravity model approach of Assogbavi and Dees (2021).

(1) Pooled OLS Model Estimation

Following Assogbavi and Dees (2021), this paper estimates the model initially using pooled OLS. One key new feature is the attempt to explicitly control scale, composition, and technique effects, which are believed to affect carbon footprints of production and the international trade thereof based on theories and literature.

$$\begin{aligned}\ln CO2_{ijst} = {} & \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{jt} + \beta_3 \ln carb_{it} + \beta_4 \ln carb_{jt} + \beta_5 clean_{it} \\ & + \beta_6 clean_{jt} + \rho_1 str_{it} + \rho_2 str_{jt} + \rho_3 pta_{ijt} + \mu_1 \ln dist_{ij} + \mu_2 cont_{ij} \\ & + \mu_3 lang_{ij} + \mu_4 col_{ij} + \epsilon_{ijst}\end{aligned} \quad (4.1)$$

Where $CO2_{ijst}$ can either be: total, domestic, or foreign CO_2 emissions embodied in gross exports; or CO_2 emissions embodied in intermediate or final goods exports depending upon model specifications. GDP is the gross domestic product of an economy, $carb$ is CO_2 emissions embodied in production per capita, $clean$ is the share of the top cleanest industries to total production, str is environmental policy stringency index, and pta is the presence of preferential trade agreement between reporter and partner economies. Time invariant variables are also included: $dist$ is the distance between reporter and partner, $cont$ identifies if reporter and partner share a border, $lang$ identifies if reporter and partner share a common language, and col identifies if reporter and partner have colonial ties.

(2) Random Effects Model Estimation

Random effects model assumes that there is unobserved heterogeneity across economy pairs and sector captured by a_{ijs}.

$$\begin{aligned}\ln CO2_{ijst} = {} & \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{jt} + \beta_3 \ln carb_{it} + \beta_4 \ln carb_{jt} \\ & + \beta_5 clean_{it} + \beta_6 clean_{jt} + \rho_1 str_{it} + \rho_2 str_{jt} + \rho_3 pta_{ijt} + \mu_1 \ln dist_{ij} \\ & + \mu_2 cont_{ij} + \mu_3 lang_{ij} + \mu_4 col_{ij} + a_{ijs} + \varepsilon_{ijst}\end{aligned} \quad (4.2)$$

(3) Fixed Effects Model Estimation

The fixed effects model is less restricted than the random effects model as it allows the economy-pair-sector-specific effects a_{ijs} to be correlated with the regressors.

$$\begin{aligned}\ln CO2_{ijst} = {} & \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{jt} + \beta_3 \ln carb_{it} + \beta_4 \ln carb_{jt} + \beta_5 clean_{it} \\ & + \beta_6 clean_{jt} + \rho_1 str_{it} + \rho_2 str_{jt} + \rho_3 pta_{ijt} + \mu_1 \ln dist_{ij} + \mu_2 cont_{ij} \\ & + \mu_3 lang_{ij} + \mu_4 col_{ij} + \sum_i^I \sum_j^J \sum_s^S a_{ijs} dummy_{ijs} + \varepsilon_{ijst} \end{aligned} \quad (4.3)$$

(4) Fixed Effects Model Estimation with Instrumental Variables

To minimize the potential endogeneity with the variables of industrial composition, $clean$, and policy stringency, str, we use R&D share to GDP, res, and number of international environmental agreements, $inter$ as instruments respectively. R&D may not directly affect the CO_2 emissions embodied in exports while it is correlated with industrial structure of an economy and international environmental agreements may have a direct impact on environmental policy stringency while it may not directly affect CO_2 emissions embodied in exports. The validity of these instruments are described through various statistics in the Appendix. IV test results show rejection of null hypothesis that the independent variables, "*clean*" and "*str*" are exogenous. Moreover, the null hypothesis that the instrument variables are under-identified and weakly identified were rejected in all estimates.

The first stage of this model can be written as:

$$\begin{aligned} instru = {} & \eta_0 + \eta_1 res_{it} + \eta_2 res_{jt} + \eta_3 inter_{it} + \eta_4 inter_{jt} + \gamma_1 \ln GDP_{it} \\ & + \gamma_2 \ln GDP_{jt} + \gamma_3 \ln carb_{it} + \gamma_4 \ln carb_{jt} + \gamma_5 pta_{ijt} + \gamma_6 dist_{ij} \\ & + \gamma_7 cont_{ij} + \gamma_8 lang_{ij} + \gamma_9 col_{ij} + \sum_i^I \sum_j^J \sum_s^S \gamma_{ijs} dummy_{ijs} + \varepsilon_{ijt} \end{aligned} \quad (4.4)$$

Where the vector $instru' = [clean_{it} \;\; clean_{jt} \;\; str_{it} \;\; str_{jt}]$.

We then conduct the second stage using the estimates $\widehat{instru}' = [\widehat{clean}_{it} \;\; \widehat{clean}_{jt} \;\; \widehat{str}_{it} \;\; \widehat{str}_{jt}]$.

$$\begin{aligned}\ln CO2_{ijst} = {} & \beta_0 + \beta_1 \ln GDP_{it} + \beta_2 \ln GDP_{jt} + \beta_3 \ln carb_{it} + \beta_4 \ln carb_{jt} \\ & + \beta_5 \widehat{clean}_{it} + \beta_6 \widehat{clean}_{jt} + \rho_1 \widehat{str}_{it} + \rho_2 \widehat{str}_{jt} + \rho_3 pta_{ijt} + \mu_1 \ln dist_{ij} \\ & + \mu_2 cont_{ij} + \mu_3 lang_{ij} + \mu_4 col_{ij} + \sum_i^I \sum_j^J \sum_s^S a_{ijs} dummy_{ijs} + \varepsilon_{ijst} \end{aligned} \quad (4.5)$$

(5) PPML Model Estimation

Poisson pseudo-maximum likelihood (PPML) estimation allows observations with zero values. This paper uses the PPML regression with multiple high-dimensional fixed effects (HDFE) by Correia et al. (2020).

$$CO2_{ijst} = \exp\begin{pmatrix} \beta_1 GDP_{it} + \beta_2 GDP_{jt} + \beta_3 clean_{it} + \beta_4 clean_{jt} \\ + \beta_5 carb_{it} + \beta_6 carb_{jt} + \rho_1 str_{it} + \rho_2 str_{jt} \\ + \rho_3 pta_{ijt} + \mu_1 dist_{ij} + \mu_2 cont_{ij} + \mu_3 lang_{ij} \\ + \mu_4 col_{ij} + \theta_s + \theta_t + \theta_{ijst} \end{pmatrix} + \varepsilon_{ijst} \quad (4.6)$$

Where θ_s denotes sector fixed effects, θ_t denotes time fixed effects, and θ_{ijs} denotes economy-pair-sector fixed effects.

5. Results

Results show that FE and PPML regressions are consistent across the board with the impact of reporters' environmental policies exerting negative impact on CO_2 emissions embodied in gross exports and a generally positive impact of partners' policies on CO_2 emissions embodied in gross imports at economy bilateral, sectoral level. The former suggests that the stricter the environmental regulations, the fewer CO_2 emissions are embodied in production, which leads to equally less dirty exports at the bilateral sectoral level. The latter could imply the existence of carbon leakage by letting others produce carbon intensive products and import those under stricter environmental regulations.

The results on the reporter's policy impact were further investigated by using domestic and foreign CO_2 emissions embodied in gross exports. The model for foreign CO_2 emissions also shows a positive sign from PPML while the domestic CO_2 emissions model has the same results as that of the total CO_2 emissions model. It is likely that that the negative impact on total CO_2 emissions embodied in gross exports in FE and part of PPML models stems from the regulatory impact of domestic CO_2 production, and at the same time economies might be simply bypassing foreign produced CO_2 emissions to others through exports.

A. CO_2 Emissions Embodied in Total Exports

Economic size works in the direction of raising CO_2 emissions embodied in both exports and imports, corroborating the conventional theory that the larger the economy, the greater CO_2 emissions produced, that are then embodied in both exports and imports. Technique effect points to a positive impact of CO_2 emissions on production per capita for both exporters and importers, except in the FE model with instruments for the importers. This implies that less carbon efficient production procedures lead to greater CO_2 emissions embodied in exports and imports. Composition effect also largely points to the expected direction except for the FE models. Looking at the policy variables when using a pooled model, which has the most restrictive assumptions, the higher stringency index entails lower CO_2 emissions embodied in trade for both the reporter and partner. However, using the random effects estimator, the coefficients' magnitude decreases while partners' policy stringency now entails higher CO_2 emissions embodied in imports. Moreover, using the fixed effects model after rejecting the null hypothesis in the Hausman test[3], both reporter and partners' stringency index gained positive coefficients. The signs of the coefficients in the fixed effects model change depending on the instrument variables used. On one hand, if the stringency of environmental regulations for both reporter and partner were instrumented using the number of international environmental agreements, both reporter and

[3] Hausman Test determines whether random effects or fixed effects estimation fits the model better. Meanwhile Breusch-Pagan Lagrange Multiplier Test checks the significance of random effects in the panel data model.

partner coefficients become negative. On the other hand, when all instruments mentioned are used simultaneously, the reporter's policy stringency coefficient turns negative while partner's stays positive.

Now using the PPML model, the reporter's increase in policy stringency would be associated with decreasing CO_2 emissions embodied in its total exports. Meanwhile, the partner's increase in policy stringency would be associated with increasing CO_2 emissions embodied in total imports at bilateral economy, sectoral level. Results show that a 1-percentage-point increase in the reporter's stringency of environmental regulation is associated with 4% decrease in CO_2 emissions embodied in its total exports. And then a 1-percentage-point increase in partner's stringency of environmental regulation is associated with 15% increase in CO_2 emissions embodied in its total imports.[4] Adding sector and year fixed effects in the PPML does not significantly change the results (Table 2).

[4] Using PPML estimation, the effect on the dependent variable is (EXP(coefficient) – 1) × 100.

Table 2: CO_2 Emissions Embodied in Total Exports

					Fixed Effects IV Regression			PPML Regression		
	Dependent Variable: Natural log of CO_2 emissions embodied in Total Exports except for PPML model Independent Variables:	**Pooled OLS** (1)	**RE Panel Regression** (2)	**FE Panel Regression with economy-pair-sector FE** (3)	Instrumented: Stringency of Environmental regulation (4)	Instrumented: Industrial composition (5)	Instrumented: Both (6)	No fixed effects (7)	with fixed effects: sector, year, sector-year (8)	with fixed effects: sector, year, sector-year, economy-pair-sector (9)
Scale Effect	Natural log of reporter economy's real GDP (base year = 2015)	0.576***	0.408***	-0.225***	-0.200***	-0.736***	-0.763***			
		(0.00270)	(0.00632)	(0.0152)	(0.0193)	(0.0688)	(0.0815)			
	Reporter's Real GDP (base year = 2015)							0.000175***	0.000177***	1.96e-05***
								(2.55e-06)	(2.43e-06)	(6.05e-06)
	Natural log of partner economy's real GDP (base year = 2015)	0.566***	0.506***	0.803***	0.776***	1.414***	1.452***			
		(0.00266)	(0.00621)	(0.0152)	(0.0182)	(0.0749)	(0.0814)			
	Partner's Real GDP (base year = 2015)							0.000189***	0.000191***	8.59e-05***
								(2.84e-06)	(2.66e-06)	(6.00e-06)
Technique Effect	Natural log of reporter economy's CO_2 embodied in production per capita	0.219***	0.374***	0.770***	0.891***	1.282***	1.553***			
		(0.00645)	(0.00949)	(0.0131)	(0.0213)	(0.0717)	(0.103)			
	Reporter's CO_2 embodied in production per capita							0.0507***	0.0491***	0.0577***
								(0.00327)	(0.00319)	(0.00422)
	Natural log of partner economy's CO_2 embodied in production per capita	0.0284***	0.223***	0.232***	0.280***	-0.210***	-0.478***			
		(0.00626)	(0.00922)	(0.0126)	(0.0214)	(0.0703)	(0.0912)			
	Partner's CO_2 embodied in production per capita							0.0106***	0.00898***	0.0403***
								(0.00339)	(0.00320)	(0.00459)
Composition Effect	Reporter's share of top five cleanest industries to total production	-0.00973***	-0.00721***	0.00120***	0.000106	0.0466***	0.0480***	-0.0273***	-0.0269***	-0.00792***
		(0.000274)	(0.000300)	(0.000351)	(0.000473)	(0.00556)	(0.00658)	(0.00101)	(0.000951)	(0.00131)
	Partner's share of top five cleanest industries to total production	-0.00349***	-0.00189***	0.00144***	-0.00104**	-0.0428***	-0.0518***	-0.0158***	-0.0154***	-0.00150
		(0.000268)	(0.000281)	(0.000327)	(0.000453)	(0.00565)	(0.00590)	(0.000892)	(0.000833)	(0.00104)

	Dependent Variable: Natural log of CO_2 emissions embodied in Total Exports except for PPML model	Pooled OLS	RE Panel Regression	FE Panel Regression with economy-pair-sector FE	Fixed Effects IV Regression: Instrumented: Stringency of Environmental regulation	Instrumented: Industrial composition	Instrumented: Both	PPML Regression: No fixed effects	with fixed effects: sector, year, sector-year	with fixed effects: sector, year, sector-year, economy-pair-sector
Policy Variables	Reporter's stringency of environmental regulation (7 = most stringent)	-0.223***	-0.0115***	0.0188***	-0.498***	-0.00523	-1.052***	-0.0437***	-0.0412***	-0.0204*
		(0.00553)	(0.00406)	(0.00419)	(0.0669)	(0.00657)	(0.103)	(0.0149)	(0.0139)	(0.0110)
	Partner's stringency of environmental regulation (7 = most stringent)	-0.0775***	0.00601	0.0200***	-0.269***	0.0271***	0.470***	0.135***	0.136***	-0.00628
		(0.00565)	(0.00407)	(0.00420)	(0.0691)	(0.00629)	(0.0971)	(0.0157)	(0.0144)	(0.0117)
	1 = Preferential trade agreement between economies is present	0.131***	-0.0261***	-0.00557	0.0384***	-0.00693	0.00986	-0.124**	-0.0979**	-0.0107
		(0.0161)	(0.00602)	(0.00612)	(0.00794)	(0.00794)	(0.0111)	(0.0483)	(0.0486)	(0.0174)
Time-invariant variables	Natural log of distance	-0.428***	-0.290***							
		(0.00412)	(0.0110)							
	distance							-0.0875***	-0.0870***	
								(0.00376)	(0.00357)	
	Contiguity	0.961***	1.336***					1.143***	1.140***	
		(0.0147)	(0.0440)					(0.0356)	(0.0328)	
	Common Language	0.213***	0.169***					0.152***	0.153***	
		(0.0134)	(0.0401)					(0.0367)	(0.0334)	
	Same colony	0.0489**	0.101					0.0348	0.0405	
		(0.0204)	(0.0626)					(0.0359)	(0.0290)	
	Constant	-30.04***	-27.32***	-21.68***	-17.91***	-24.46***	-21.55***	-2.079***	-1.583***	-0.258**
		(0.103)	(0.212)	(0.324)	(0.519)	(2.329)	(2.922)	(0.113)	(0.106)	(0.104)
	Observations	229,535	229,535	229,535	229,535	190,245	190,245	371,840	371,840	264,754
	R-squared	0.329		0.051						
	Number of id		24,797	24,797	24,797	23,672	23,672			

CO_2 = carbon dioxide; FE = fixed effects; GDP = gross domestic product; IV = instrumental variables; OLS = ordinary least squares; PPML = Poisson pseudo-maximum likelihood; RE = random effects.

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

Sources: Authors' estimates.

B. Domestic CO_2 Emissions Embodied in Gross Exports

Results using domestic CO_2 emissions embodied in gross exports are similar to CO_2 embodied in total exports when using pooled and random effects estimation. However, since this model rejects the null hypothesis in both Breusch-Pagan and Hausman tests, the fixed effects models are estimated. Compared to the previous result, the reporter's stringency of environmental regulation becomes not significant, while the partner's policy stringency remains positive and significant. Adding instrumental variables would change the signs of the coefficients. When policy stringency is instrumented for both reporter and partner, the reporter coefficient becomes negative and significant while the partner coefficient become negative but not significant. In contrast, when industrial composition is instrumented, the partner coefficient becomes positive and significant while the reporter coefficient remains negative and significant. When all instrumental variables were used, the reporter coefficient remains negative while that for the partner remains positive; in both cases, the coefficients were significant and larger in magnitude.

Using PPML, which accounts for observations with zero values, the results are similar to CO_2 embodied in total exports: an increase in the reporter's policy stringency is associated with decreasing domestic CO_2 embodied in its gross exports, while an increase in the partner's policy stringency entails increasing domestic CO_2 embodied in the reporter's gross exports. The difference is that reporter coefficient is higher in magnitude than in the previous result, while partner coefficient is lower. Results show that a 1-percentage-point increase in the reporter's stringency of environmental regulation is associated with 7% decrease in domestic CO_2 emissions embodied in its total exports. And then a 1-percentage-point increase in partner's stringency of environmental regulation is associated with 9% increase in domestic CO_2 emissions embodied in its total imports (see footnote 4). This suggests that the production procedures of domestic value-added are more directly and greatly influenced by environmental regulations. Adding sector and year fixed effects preserves the results.

Table 3: Domestic CO_2 Emissions Embodied in Gross Exports

					Fixed Effects IV Regression			PPML Regression		
	Dependent Variable: Natural Log of Domestic CO_2 emissions embodied in Gross Exports except for PPML model	**Pooled OLS**	**RE Panel Regression**	**FE Panel Regression with economy-pair-sector FE**	Instrumented: Stringency of Environmental regulation	Instrumented: Industrial composition	Instrumented: Both	No fixed effects	with fixed effects: sector, year, sector-year	with fixed effects: sector, year, sector-year, economy-pair-sector
	Variable Description	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Scale Effect	Natural log of reporter economy's real GDP (base year = 2015)	0.552***	0.395***	-0.230***	-0.182***	-0.728***	-0.770***			
		(0.00280)	(0.00648)	(0.0157)	(0.0219)	(0.0722)	(0.0917)			
	Reporter's Real GDP (base year = 2015)							0.000189***	0.000190***	9.50e-06
								(2.95e-06)	(2.83e-06)	(6.66e-06)
	Natural log of partner economy's real GDP (base year = 2015)	0.525***	0.477***	0.810***	0.771***	1.396***	1.440***			
		(0.00276)	(0.00636)	(0.0157)	(0.0202)	(0.0755)	(0.0923)			
	Partner's Real GDP (base year = 2015)							0.000187***	0.000189***	9.37e-05***
								(3.01e-06)	(2.71e-06)	(6.38e-06)
Technique Effect	Natural log of reporter economy's CO_2 embodied in production per capita	0.222***	0.391***	0.828***	0.925***	1.318***	1.706***			
		(0.00671)	(0.00985)	(0.0138)	(0.0221)	(0.0816)	(0.133)			
	Reporter's CO_2 embodied in production per capita							0.0457***	0.0441***	0.0722***
								(0.00383)	(0.00373)	(0.00513)
	Natural log of partner economy's CO_2 embodied in production per capita	0.0302***	0.195***	0.179***	0.190***	-0.318***	-0.688***			
		(0.00648)	(0.00948)	(0.0131)	(0.0223)	(0.0751)	(0.117)			
	Partner's CO_2 embodied in production per capita							0.0193***	0.0180***	0.0348***
								(0.00382)	(0.00359)	(0.00539)
Composition Effect	Reporter's share of top five cleanest industries to total production	-0.0138***	-0.00984***	-0.000974***	-0.00109**	0.0476***	0.0591***	-0.0380***	-0.0376***	-0.00790***
		(0.000290)	(0.000321)	(0.000375)	(0.000515)	(0.00643)	(0.00874)	(0.00135)	(0.00128)	(0.00177)
	Partner's share of top five cleanest industries to total production	-0.00295***	-0.00202***	0.00107***	-0.000859*	-0.0481***	-0.0604***	-0.0159***	-0.0155***	-0.00159
		(0.000279)	(0.000296)	(0.000347)	(0.000492)	(0.00609)	(0.00754)	(0.00103)	(0.000962)	(0.00125)

					Fixed Effects IV Regression			PPML Regression		
	Dependent Variable: Natural Log of Domestic CO_2 emissions embodied in Gross Exports except for PPML model	**Pooled OLS**	**RE Panel Regression**	**FE Panel Regression with economy-pair-sector FE**	Instrumented: Stringency of Environmental regulation	Instrumented: Industrial composition	Instrumented: Both	No fixed effects	with fixed effects: sector, year, sector-year	with fixed effects: sector, year, sector-year, economy-pair-sector
Policy Variables	Reporter's stringency of environmental regulation (7 = most stringent)	-0.270***	-0.0351***	0.000748	-0.402***	-0.0288***	-1.133***	-0.0722***	-0.0683***	-0.0249**
		(0.00570)	(0.00414)	(0.00427)	(0.0716)	(0.00681)	(0.133)	(0.0166)	(0.0155)	(0.0127)
	Partner's stringency of environmental regulation (7 = most stringent)	-0.0857***	0.00957**	0.0244***	-0.0575	0.0382***	0.802***	0.0850***	0.0869***	-0.00499
		(0.00582)	(0.00420)	(0.00434)	(0.0723)	(0.00672)	(0.124)	(0.0181)	(0.0166)	(0.0141)
	1 = Preferential trade agreement between economies is present	0.118***	-0.0194***	-0.00491	0.0191**	-0.00895	-0.00357	-0.169***	-0.146***	0.0223
		(0.0168)	(0.00630)	(0.00639)	(0.00793)	(0.00825)	(0.0123)	(0.0525)	(0.0533)	(0.0173)
Time-invariant variables	Natural log of distance	-0.340***	-0.202***							
		(0.00424)	(0.0112)							
	distance							-0.0846***	-0.0841***	
								(0.00427)	(0.00400)	
	Contiguity	0.932***	1.285***					1.110***	1.107***	
		(0.0147)	(0.0435)					(0.0402)	(0.0371)	
	Common Language	0.203***	0.130***					0.223***	0.223***	
		(0.0136)	(0.0402)					(0.0390)	(0.0356)	
	Same colony	0.0363*	0.0858					0.0667	0.0737**	
		(0.0205)	(0.0621)					(0.0412)	(0.0336)	
Constant		-28.95***	-27.01***	-21.88***	-19.93***	-24.13***	-22.49***	-1.812***	-1.293***	-0.506***
		(0.107)	(0.218)	(0.331)	(0.499)	(2.404)	(3.316)	(0.125)	(0.116)	(0.123)
Observations		206,191	206,191	206,191	206,191	171,001	171,001	371,840	371,840	241,905
R-squared		0.307		0.055						
Number of id			22,655	22,655	22,655	21,604	21,604			

CO_2 = carbon dioxide; FE = fixed effects; GDP = gross domestic product; IV = instrumental variables; OLS = ordinary least squares; PPML = Poisson pseudo-maximum likelihood; RE = random effects.

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

Source: Authors' estimates.

C. Foreign CO2 Emissions Embodied in Gross Exports

Similar to CO_2 embodied in total exports and domestic CO_2 emissions embodied in exports, the pooled OLS and random effects models reject the null hypothesis in both Breusch-Pagan and Hausman tests, which prompts the use of the fixed effects model. The results are somewhat different from those for total exports and the domestic portion of CO_2 emissions in gross exports. When the stringency of environmental regulation for both the reporter and partner are instrumented in particular, their coefficient signs flip from positive to negative. Whereas the negative signs of the partners' environmental policy are largely preserved, the sign of reporters' environmental policy regulation becomes positive and the magnitude of the positive coefficients for partners' environmental policy regulation becomes smaller.

Estimating the model using PPML, estimates now differ from domestic CO_2 embodied in exports; the reporter's increase in regulatory stringency is associated with an increase in foreign CO_2 embodied in gross exports, while partner's increase in regulatory stringency is also associated with an increase in foreign CO_2 embodied in gross imports. Results show that a 1-percentage point increase in reporter's stringency is associated with 6% increase in foreign CO_2 emissions embodied in its total exports (see footnote 4). Adding sector and year fixed effects preserves the results although both the coefficients become insignificant when economy-pair-sector fixed effects are used. The results indicate stricter environmental regulations in exporting economies might lead to carbon leakages in the upstream segment of global value chains, through economies outsourcing the dirtier segments of productions to other economies.

Table 4: Foreign CO_2 Emissions Embodied in Gross Exports

	Dependent Variable: Natural Log of Foreign CO_2 emissions embodied in gross exports, except for PPML model	Pooled OLS	RE Panel Regression	FE Panel Regression with economy-pair-sector FE	Fixed Effects IV Regression: Instrumented: Stringency of Environmental regulation	Instrumented: Industrial composition	Instrumented: Both	PPML Regression: No fixed effects	with fixed effects: sector, year, sector-year	with fixed effects: sector, year, sector-year, economy-pair-sector
		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Scale Effect	Natural log of reporter economy's real GDP (base year = 2015)	0.453***	0.328***	-0.186***	-0.150***	-0.563***	-0.685***			
		(0.00266)	(0.00613)	(0.0152)	(0.0203)	(0.0607)	(0.0868)			
	Reporter's Real GDP (base year = 2015)							0.000140***	0.000142***	5.09e-05***
								(2.31e-06)	(1.98e-06)	(4.85e-06)
	Natural log of partner economy's real GDP (base year = 2015)	0.494***	0.446***	0.718***	0.669***	1.184***	1.320***			
		(0.00262)	(0.00607)	(0.0153)	(0.0198)	(0.0692)	(0.0907)			
	Partner's Real GDP (base year = 2015)							0.000199***	0.000202***	6.67e-05***
								(3.57e-06)	(3.39e-06)	(7.44e-06)
Technique Effect	Natural log of reporter economy's CO_2 embodied in production per capita	0.246***	0.386***	0.712***	0.887***	1.119***	1.570***			
		(0.00634)	(0.00934)	(0.0131)	(0.0229)	(0.0636)	(0.120)			
	Reporter's CO_2 embodied in production per capita							0.0571***	0.0554***	0.0335***
								(0.00287)	(0.00276)	(0.00362)
	Natural log of partner economy's CO_2 embodied in production per capita	0.0439***	0.237***	0.266***	0.327***	-0.00760	-0.430***			
		(0.00619)	(0.00921)	(0.0128)	(0.0225)	(0.0685)	(0.114)			
	Partner's CO_2 embodied in production per capita							-0.0143***	-0.0167***	0.0522***
								(0.00304)	(0.00271)	(0.00445)
Composition Effect	Reporter's share of top five cleanest industries to total production	-0.00155***	-0.00293***	0.00344***	0.00204***	0.0383***	0.0496***	-0.0108***	-0.0103***	-0.00702***
		(0.000265)	(0.000296)	(0.000352)	(0.000488)	(0.00490)	(0.00738)	(0.000712)	(0.000674)	(0.000941)
	Partner's share of top five cleanest industries to total production	-0.00443***	-0.00276***	0.000420	-0.00277***	-0.0315***	-0.0553***	-0.0157***	-0.0152***	-0.00129
		(0.000264)	(0.000285)	(0.000336)	(0.000492)	(0.00553)	(0.00735)	(0.000794)	(0.000733)	(0.000906)

	Dependent Variable: Natural Log of Foreign CO_2 emissions embodied in gross exports, except for PPML model	Pooled OLS	RE Panel Regression	FE Panel Regression with economy-pair-sector FE	Fixed Effects IV Regression: Instrumented: Stringency of Environmental regulation	Fixed Effects IV Regression: Instrumented: Industrial composition	Fixed Effects IV Regression: Instrumented: Both	PPML Regression: No fixed effects	PPML Regression: with fixed effects: sector, year, sector-year	PPML Regression: with fixed effects: sector, year, sector-year, economy-pair-sector
Policy Variables	Reporter's stringency of environmental regulation (7 = most stringent)	-0.152***	0.00401	0.0271***	-0.639***	0.0123*	-1.212***	0.0569***	0.0562***	-0.00850
		(0.00539)	(0.00405)	(0.00420)	(0.0690)	(0.00642)	(0.125)	(0.0144)	(0.0133)	(0.0112)
	Partner's stringency of environmental regulation (7 = most stringent)	-0.0805***	-0.00375	0.00976**	-0.314***	0.0126**	0.412***	0.258***	0.258***	-0.00938
		(0.00551)	(0.00404)	(0.00419)	(0.0698)	(0.00585)	(0.120)	(0.0132)	(0.0118)	(0.0113)
	1 = Preferential trade agreement between economies is present	0.0948***	-0.0515***	-0.0398***	0.0125	-0.0428***	-0.0253**	-0.0475	-0.00848	-0.104***
		(0.0163)	(0.00618)	(0.00629)	(0.00829)	(0.00779)	(0.0121)	(0.0463)	(0.0455)	(0.0221)
Time-invariant variables	Natural log of distance	-0.393***	-0.277***							
		(0.00404)	(0.0105)							
	distance							-0.0996***	-0.0990***	
								(0.00383)	(0.00370)	
	Contiguity	0.748***	1.043***					1.212***	1.209***	
		(0.0137)	(0.0402)					(0.0377)	(0.0339)	
	Common Language	0.118***	0.101***					-0.0413	-0.0385	
		(0.0127)	(0.0374)					(0.0468)	(0.0409)	
	Same colony	-0.00350	-0.00609					-0.0299	-0.0252	
		(0.0192)	(0.0576)					(0.0336)	(0.0273)	
	Constant	-26.30***	-24.41***	-20.95***	-16.09***	-23.68***	-19.61***	-4.687***	-4.139***	-1.431***
		(0.102)	(0.207)	(0.322)	(0.533)	(2.113)	(3.119)	(0.110)	(0.102)	(0.101)
	Observations	191,193	191,193	191,193	191,193	158,857	158,857	371,840	371,840	227,230
	R-squared	0.297		0.054						
	Number of id		21,246	21,246	21,246	20,278	20,278			

CO_2 = carbon dioxide; FE = fixed effects; GDP = gross domestic product; IV = instrumental variables; OLS = ordinary least squares; PPML = Poisson pseudo-maximum likelihood; RE = random effects.

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

Source: Authors' estimates.

6. Conclusions

This paper finds that although the environmental footprints of international trade have been studied in the literature, the existence of carbon leakages remains elusive. The potential impact of different factors on cross-border carbon flows adds complication. In investigating the carbon leakage argument, this paper uses the economy bilateral sectoral gravity model approach, and attempts to control for economic, composition, and technique effects that could influence the carbon footprint of international trade through the production mechanism of goods and services.

The OECD's TECO$_2$ data provides practical data sources to test the key hypotheses of this research: (i) whether stricter environmental regulations promote cleaner production procedures, leading to lower exports of CO_2 emissions across the borders, (ii) whether importers with stricter environmental regulations tend to import greater CO_2 emissions, which could suggest they relegate dirtier productions to other economies to import those goods instead, implying potential existence of carbon leakages, and (iii) whether the potential carbon leakage exists in the upstream segment of the global value chain when exporters face stricter environmental regulations.

Various empirical approaches have been engaged in testing these hypotheses, and the results point to the general significant, positive impact of environmental regulations on greening production procedures, resulting in a reduction of CO_2 emissions exported. Importers with stricter environmental regulations display greater imports of CO_2 emissions embodied in goods and services, corroborating the necessary condition of carbon leakage. Nevertheless, stricter environmental regulations of exporting economies could lead to increased CO_2 emission exports embodied in foreign value added portion of gross exports. This implies that even as stricter environmental regulations help reduce the CO_2 emissions of domestic production, they may induce greater outsourcing to other economies of dirty industries in the upstream segment of value chains. This suggests potential carbon leakages upstream. For example, while stringent environmental regulations might curb the production of emission-intensive diesel vehicles, and their export, such tougher rules may induce the outsourcing of emissions-intensive parts and components in a way that allows automobile firms to avoid violating the environmental requirements of production. Whereas this may help reduce environmental footprint of domestic production, it adds to the environmental cost for other economies which produce emission-heavy parts and components.

The implications for the ongoing discussions of Border Carbon Adjustment (BCA) mechanism could be significant. Insofar as the BCA is based on the carbon intensity of final goods, it may not take into account the emissions embedded along the entire supply chain. Although the BCA may help reduce carbon emissions from final products by prompting trade partners to introduce stringent environmental regulations and carbon pricing, it may not contribute to greening supply chains since it could incentivize exporters to outsource more the production of intermediate goods abroad in order to bypass the constraints in the domestic market. While attempting to reduce downstream carbon leakages, the BCA would instead lead to carbon leakages in the upstream segment of global value chains.

Environmental regulations can exert significant impact on production patterns and supply chain evolution in terms of CO_2 emissions. However, unless such policies are harmonized across economies, their intended policy outcomes may not be achieved. This calls for renewed attention to cross-border harmonization of environmental policies in dealing with the global public good nature of cross-border carbon emissions.

Appendix

A.1: Summary of Econometric Models Used in the Literature

Paper/Author	Dependent Variable	Independent Variables	Econometric Model	Coverage	Results
"Footloose and Pollution-Free." Ederington, Levinson, and Minier (2003).	Net imports by industry	(1) Industry's environmental cost; (2) Trade barriers; (3) Factor intensity variables; (4) Industry and time-specific fixed effects; (5) Mobility variables (plant, product transport, agglomeration)	Fixed effects model by adding fixed effects variables	US trade 1978–1992	The effect of environmental regulations on trade between industrialized and low-income economies is stronger than its effect when trade occurs between industrialized economies. The second finding is that less geographically mobile industries will be less sensitive to differences in regulatory stringency.
"Is Environmental Policy a Secondary Trade Barrier? An Empirical Analysis." Ederington and Minier (2003).	(1) Net imports scaled by domestic production; (2) Environmental regulation in an industry	(1) Level of environmental regulation; (2) Trade barriers; (3) Factor intensity variables; (4) Industry- and time-specific effects; (5) Net imports; (6) Political economy variables	OLS, 2SLS, and 3SLS	US manufacturing industries 1978–1992	When treated endogenously, environmental protection will have strong adverse effects on trade flows (competitive disadvantage).
"Effects of Environmental Regulations on Manufacturing Plant Births: Evidence from a Propensity Score Matching Estimator." List et al. (2003).	(1) In PSM: treatment and control group classification are based on attainment status. Computes the average treatment effect of the independent variables based on the said grouping); (2) In parametric estimates: count of new plants	(1) Attainment status dummy (= 1 if out of attainment); (2) Log of employment, wage, population, and property tax	(1) Semi-non-parametric propensity score matching; (2) Parametric models for comparison	Manufacturing firms located in New York, US, 1980–1990	Environmental regulations have larger than previously reported adverse effects on new-plant formation, especially the pollution-intensive ones.
"Unmasking the Pollution Haven Effect." Levinson, and Taylor (2004).	Net imports	(1) Time-, industry- fixed effects; (2) Pollution abatement operating costs per dollar of value added; (3) Tariffs	Fixed effect model; 2SLS fixed effect model	US trade 1977–1986	Higher abatement cost translates to more imports. Evidence for pollution haven effect.
"Kyoto and Carbon Leakage: An Empirical Analysis of the Carbon Content of Bilateral Trade." Aichele and Felbermayr (2011).	(1) Log of imports (in $); (2) Log of CO_2 intensity of imports; (3) Log of carbon imports	(1) Kyoto membership dummy variable of reporter/partner; (2) GDP of reporter/partner; (3) Common WTO, FTA, EU membership dummy variables; (4) Bilateral multilateral resistance: distance, common language, contiguity, colonial ties; (5) Country-pair, year, economy-year dummies	(1) Fixed-effects model; (2) First-differencing model; (3) Fixed effects variables are added to address the endogeneity of Kyoto protocol membership variable	40 economies 1995–2007 covering 12 sectors	Carbon leakage exist. Carbon imports of committed economy from an uncommitted economy are higher than when the economy had no commitments. Some sectors are more prone to carbon leakage.
"The Short and Long-Run Effects of International Environmental Agreements on Trade." Ederington, Paraschiv, and Zanardi (2018).	Exports	(1) Difference in the number of ratified international environmental agreements (IEA); (2) Interaction of IEA and sectoral emission intensity; (3) Trade and economic integration variable; (4) Time-varying economy fixed effects, time-invariant fixed	(1) Fixed effects model; (2) Fixed effects variables are added to address the endogeneity of IEA variable and to consider unobserved determinants of trade flow.	163 economies 1976–2011	The study finds that IEA membership only has a small negative effect on exports in the short-run and this effect disappears in the long-run. Moreover, IEAs tend to induce a shift away from the dirty industries towards the clean industries and this becomes stronger

Paper/Author	Dependent Variable	Independent Variables	Econometric Model	Coverage	Results
		effects (distance, common language, sector-specific transport costs), industry-time fixed effects			in the long-run. Saw some evidence for pollution leakage (economy importing more pollution-intensive goods from abroad).
"Environmental Policy and the CO_2 Emissions Embodied in International Trade." Assogbavi and Dees (2021).	CO_2 embodied in exports	(1) Environmental Policy Stringency Index; (2) Environmental Performance Index; (3) GDP per capita; (4) Trade costs; (5) Common language; (6) Contiguity; (7) Energy use; (8) Electricity production; (9) Country fixed-effects	Fixed effect model; OLS; PPML	33 to 56 economies 2005–2015	Finds no evidence for carbon leakage. The higher the environmental standards, the lower is carbon embodied in trade for both importer and exporter.
"Revisiting Carbon Leakage." Misch and Wingender (2021).	(1) Carbon embodied in exports from sector *s* in economy *i* to the rest of the world; (2) Carbon embodied in imports of economy *i* originating from sector *s* in the rest of the world; (3) Carbon embodied in domestic final demand of economy *i* originating from sector *s*; (4) Domestic carbon emissions of sector *s* and economy *i*	(1) Sectoral energy price; (2) Country-sector, economy-year, and sector-year fixed effects	Fixed effects model by adding fixed effects variables (to determine the effect of energy price on carbon trade). Then from the results of the regression, utilized an accounting framework to estimate carbon leakage rates	38 economies 2005–2015 covering 21 sectors	Carbon leakage rates vary across economies, and this can be big for small open economies.

2SLS = two-stage least squares; 3SLS = three-stage least squares; CO_2 = carbon dioxide; FTA = free trade agreement; GDP = gross domestic product; IEA = international environmental agreements; OLS = ordinary least squares; PPML = Poisson pseudo-maximum likelihood; PSM = propensity score matching; WTO = World Trade Organization; EU = European Union.

Source: Authors' compilation.

A.2: IV Test Results for CO_2 Embodied in Gross Exports

Table A.2.1: Each Instrumented Variable

Variable	Anderson-Rubin Wald test F(4,166564)	P-val	Under-identification test Sanderson-Windmeijer Chi-sq(1)	P-val	Weak identification test Sanderson-Windmeijer F stat (1,166564)
Reporter's share of top five cleanest industries to total production	449.71	0.0000	391.69	0.0000	391.67
Partner's share of top five cleanest industries to total production	383.20	0.0000	482.79	0.0000	482.76
Reporter's stringency of environmental regulation (7 = most stringent)	293.62	0.0000	329.11	0.0000	329.09
Partner's stringency of environmental regulation (7 = most stringent)	291.50	0.0000	363.48	0.0000	363.46

Source: Authors' estimates.

Table A.2.2: Overall Results

Under-identification test Ho: under-identified	Anderson canon. corr. LM statistic	Chi-sq(1)=275.51 P-val=0.0000
Weak identification test Ho: equation is weakly identified	Cragg-Donald Wald F statistic	68.99
Tests of joint significance of endogenous regressors B1 in main equation Ho: B1=0 and orthogonality conditions are valid	Anderson-Rubin Wald test	F(4,166564)= 59.37 P-val=0.0000 Chi-sq(4)= 237.51 P-val=0.0000
	Stock-Wright LM S statistic	Chi-sq(4)= 237.17 P-val=0.0000
Over-identification test of all instruments	Sargan statistic	0.000 (equation exactly identified)

Source: Authors' estimates.

A.3: IV Test Results for CO_2 Embodied in Domestic Value-added Exports

Table A.3.1: Each Instrumented Variable

Variable	Anderson-Rubin Wald test F(4,166564)	P-val	Under-identification test Sanderson-Windmeijer Chi-sq(1)	P-val	Weak identification test Sanderson-Windmeijer F stat (1,166564)
Reporter's share of top five cleanest industries to total production	383.09	0.0000	232.79	0.0000	232.78
Partner's share of top five cleanest industries to total production	347.98	0.0000	282.13	0.0000	282.12
Reporter's stringency of environmental regulation (7 = most stringent)	254.54	0.0000	199.41	0.0000	199.39
Partner's stringency of environmental regulation (7 = most stringent)	259.03	0.0000	218.86	0.0000	218.85

Source: Authors' estimates.

Table A.3.2: Overall Results

Under-identification test Ho: under-identified	Anderson canon. corr. LM statistic	Chi-sq(1) = 171.60 P-val = 0.0000
Weak identification test Ho: equation is weakly identified	Cragg-Donald Wald F statistic	42.95
Weak-instrument-robust inference tests of joint significance of endogenous regressors B1 in main equation Ho: B1=0 and orthogonality conditions are valid	Anderson-Rubin Wald test	F(4,149388)= 45.26 P-val=0.0000 Chi-sq(4)= 181.07 P-val=0.0000
	Stock-Wright LM S statistic	Chi-sq(4)= 180.85 P-val=0.0000
overidentification test of all instruments	Sargan statistic	0.000 (equation exactly identified)

Source: Authors' estimates.

A.4: IV Test Results for CO_2 Embodied in Foreign Value-added Exports

Table A.4.1: Each Instrumented Variable

Variable	Anderson-Rubin Wald test F(4,166564)	P-val	**Under-identification test** Sanderson-Windmeijer Chi-sq(1)	P-val	**Weak identification test** Sanderson-Windmeijer F stat (1,166564)
Reporter's share of top five cleanest industries to total production	442.79	0.0000	234.82	0.0000	234.81
Partner's share of top five cleanest industries to total production	354.13	0.0000	242.93	0.0000	242.91
Reporter's stringency of environmental regulation (7 = most stringent)	266.52	0.0000	195.67	0.0000	195.66
Partner's stringency of environmental regulation (7 = most stringent)	248.93	0.0000	202.80	0.0000	202.79

Source: Authors' calculations.

Table A.4.2: Overall Results

Under-identification test Ho: under-identified	Anderson canon. corr. LM statistic	Chi-sq(1)= 164.72 P-val=0.0000
Weak identification test Ho: equation is weakly identified	Cragg-Donald Wald F statistic	41.23
Weak-instrument-robust inference Tests of joint significance of endogenous regressors B1 in main equation Ho: B1=0 and orthogonality conditions are valid	Anderson-Rubin Wald test	F(4,138570)= 66.47 P-val=0.0000 Chi-sq(4)= 265.91 P-val=0.0000
	Stock-Wright LM S statistic	Chi-sq(4)= 265.40 P-val=0.0000
overidentification test of all instruments	Sargan statistic	0.000 (equation exactly identified)

Source: Authors' estimates.

A.5: Stock-Yogo Weak ID F Test: Critical Values for Single Endogenous Regressor

5% maximal IV relative bias	16.85
10% maximal IV relative bias	10.27
20% maximal IV relative bias	6.71
30% maximal IV relative bias	5.34
10% maximal IV size	24.58
15% maximal IV size	13.96
20% maximal IV size	10.26
25% maximal IV size	8.31

Note: Critical values are for Sanderson-Windmeijer F statistic.

Source: Stock-Yogo (2005). Reproduced by permission.

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Factors Affecting Carbon Dioxide Emissions Embodied in Trade

This paper examines the impact of environmental regulation in exporter and importer economies on cross-border carbon flows. While stricter environmental regulations help reduce carbon dioxide (CO_2) emissions from domestic production, leading to lower CO_2 emissions embodied in exports, stricter regulations on the importing side lead to higher CO_2 emissions embodied in imports. Moreover, stricter environmental regulations could encourage further outsourcing of intermediate inputs by exporters, prompting carbon leakages in the upstream segment of global value chains.

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