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How Do Exchange Rates Affect Environmental Quality?

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Abstract: Exchange rates are integral to explaining the environmental consequences of globalization as they govern the prices of imported inputs and the price competitiveness of exports, and consequently, firms' production levels and emissions. We study how exchange rates, foreign input sourcing, and export orientation determine environmental outcomes across countries and industries. For industries relying intensively on foreign inputs and intermediate exports, a stronger domestic currency leads to lower emission intensities (emissions over output), while the opposite relationship holds with respect to an industry's reliance on final exports. Our findings suggest that exchange rates have environmental implications that have been heretofore unexplored

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1 Introduction

The world has become increasingly integrated through rising levels of trade and growing participation in global value chains (GVCs). As exchange rates govern the price of international commerce, the ever-expanding trade and supply chain linkages between economies have intensified their role in shaping international production, and the resulting generation of emissions, via their impacts on firms' foreign input sourcing and export sales. Despite the growing importance of these dynamics, the environmental consequences of exchange rate movements – particularly in the context of trade and GVC linkages – have received only limited attention from researchers.

The traditionally understood link between exchange rates, trade, and production emphasizes the impacts of exchange rate movements on the price competitiveness of a country's exports (see, for example, Amiti et al., 2014, Bems and Johnson, 2017, or the meta-analysis of McKenzie, 1999 for a review of the earlier literature). The appreciation of a foreign currency relative to the domestic currency raises the price competitiveness of a domestic industry, which (all else equal) leads to higher demand for its products, and consequently, higher output and sales. However, because the sourcing of inputs from abroad relies on foreign exchange, movements in exchange rates also have implications for firms' ability to obtain foreign intermediates, and thus, their efficiency in production. This last point implies that rising participation in GVCs has heightened the importance of this channel through which exchange rates affect trade, production, and industrial emissions of air pollution (Ahmed et al., 2017; Sato and Zhang, 2019; Patel et al., 2019).[1]

In this study we assess the effect of exchange rate variation on environmental quality, particularly through the lens of cross-border input-output linkages. To jointly assess the role of exchange rates, foreign input sourcing through GVCs, and export competitiveness in shaping environmental quality, we investigate the relationship between these factors and industrial emissions of global and local air pollutants across countries and industries. Specifically, we explore how real effective exchange rates determine industries' emission intensities (emissions generated per unit of sales) through the twin channels of (1) the extent of an industry's reliance on foreign-sourced interme-

[1] A large and growing literature has arisen in response to related issues at the intersection of globalization and the environment; for instance, work by Antweiler et al. (2001), Cole and Elliott (2003), and Cherniwchan (2017) on trade and pollution, and recent work by Dietzenbacher et al. (2012) and Brunel (2016) on production fragmentation and environmental quality. However, the role of exchange rates in these issues has been little-explored. Similarly, because efforts to systematically evaluate and quantify GVCs remain ongoing (e.g., work by Fally, 2012, Antràs et al., 2017, and Antràs and Chor, 2018), the literature in this area remains relatively young, particularly with respect to the relationship between international input-output relationships and environmental outcomes.

diates (a measure of backward participation in GVCs), and (2) the relative importance of the industry's export sales in its total sales, delineating between intermediate and final export goods (owing to factors we describe below).

Why is it necessary to investigate the link between exchange rates, GVCs, and environmental quality? Exchange rates are related to GVCs in that they reflect both the price of obtaining foreign intermediate goods and the price competitiveness of export goods. Movements in a currency's exchange rate will thus influence both the extent to which firms can efficiently source inputs from abroad, as well as the demand for their products from foreign customers. And because both factors directly shape the international distribution of production across countries and industries, they in turn influence the global distribution of polluting activities. Consequently, it is important to investigate this channel through which a major macroeconomic variable affects environmental quality in order to better understand the origins of pollution across countries and industries.

To this end we first develop an analytical framework that simultaneously incorporates exchange rates, foreign input sourcing, export orientation, and industry-level environmental accounts. This conceptual model characterizes (1) the behavior of a representative firm within a sector in choosing the optimal demand for production factors in a setting of international input-output linkages in response to an appreciation of the domestic currency, as well as (2) the dynamics of the total sales of the firm when selling its output both domestically and internationally, and (3) the resulting impacts of these factors on emission intensities.

The principal insight of the model is that the magnitude and direction of the relationship between the strength of a domestic currency and an industry's emission intensity depends on the degree of the industry's intermediate import orientation and its export orientation, which respectively refer to the relative importance of foreign-sourced intermediate inputs in the industry's production and the size of export sales relative to the industry's total sales. An exchange rate appreciation improves an industry's purchasing power for foreign inputs (which we denote as the *foreign content effect*), and thus its efficiency in production and profitability. In reality, these increases in efficiency are typically accompanied by emissions-reducing efforts by firms such as abatement investments, environmental technology adoption, or pollution outsourcing, which in turn reduces emission intensities.[2] Importantly, the greater is the extent of an industry's reliance on foreign-sourced factors of production, the more negative is the impact of a currency appreciation on emission intensity:

[2] Forslid et al. (2018), for example, analyze the way in which an increase in firms' production volumes and resulting ability to better absorb the costs of emissions-reducing efforts leads to improvements in emissions intensities.

the relationship between emission intensity and the appreciation is decreasing in intermediate import orientation.

The relationships on exports that we characterize are more nuanced, in that the impacts of exchange rate movements give rise to two distinct effects: one relating to the price competitiveness of exports (which we denote as the *export competitiveness effect*), and an additional effect originating from the foreign value-added content of the exports themselves. The former effect reduces profitability and sales, which leads to higher emission intensities owing to the aforementioned reaction of firms to changes in output levels in response to a domestic currency appreciation. However, the latter impact reflects the foreign content effect just described, in that an appreciation of the domestic currency improves an industry's ability to source foreign intermediates, and thus, the efficiency with which it is able to produce goods for export. In light of this, we delineate between an industry's intermediate export orientation (the importance of export sales of intermediate goods in total sales) and final export orientation (the importance of export sales of final goods in total sales). The two types of exports tend to differ with respect to the foreign value-added content that they embody, and thus, in the scope for one or the other effect to dominate the overall impact as mediated by export sales. An exchange rate appreciation therefore generates a positive export competitiveness effect on emission intensities, with the strength of this effect increasing in the relative degree of an industry's export orientation. Conversely, the impact originating from the embodied foreign value-added content of exports improves the industry's efficiency in production and profitability, thus reducing emission intensities.

Ultimately, because the two effects counteract one another, the overall relationship between exchange rates in determining emission intensities is theoretically ambiguous. In spite of this ambiguity, however, the model offers clear prediction that foreign input sourcing and export orientation jointly serve a central role in determining the overall environmental impacts of exchange rate movements. Importantly, we show that the environmental impacts of an exchange rate appreciation from embodied foreign content effects counteract those originating from the export competitiveness channel. We characterize this as a "mitigating effect" arising from backward participation in GVCs – the more intensive is an industry's use of foreign inputs, the more the emission-intensity-increasing aspect of the export competitiveness effect of a currency appreciation is offset.

Guided by the predictions from the theoretical framework, we then empirically investigate the model's fundamental hypotheses in an econometric setting. To do this we estimate the relationship between industry-level emission intensities across a sample of 26 countries as a function of real effective exchange rates (REER) as well as the extent of industries' intermediate import and export (intermediate versus final) orientations. As implied by our conceptual framework, it is the interaction of these factors which determines the magnitude and direction of the relationship between exchange rate movements and emission intensities, an implication which is borne out by our empirical findings. Specifically, we find that the marginal impact of a currency appreciation on an industry's emission intensity is negatively related to the extent of its reliance on imported intermediates. For the export effects, we find that the impacts are negatively related to an industry's reliance on intermediate export sales, but positively related to an industry's reliance on final export sales. As the former tend to rely more intensively on foreign value-added than the latter,[3] these findings are consistent with our analytical characterization of the competing impacts of embodied foreign content versus export competitiveness effects.

Our work contributes to several strands of the literature at the intersection of globalization and the environment. First, it aligns with previous research studying the various channels through which environmental quality is impacted by increasing international economic integration. Along these lines, the idea that globalization has contributed to improvements in environmental quality through the mechanism of firm sorting – a process whereby larger market shares are allocated towards large, productive, exporting firms after reductions in trade costs – has been well explored. Similarly, expanding trade and foreign investment creates competitive pressures for local firms, which in turn intensifies innovation efforts and encourages investment in abatement measures.[4] Our work departs from existing work, however, in that we explicitly account for the the role of GVC linkages, an increasingly prominent feature of international trade and production.

Second, this paper adds insights to the findings of several previous works studying the environmental consequences of global production networks. It has been shown that GVCs enable firms to outsource pollution to foreign destinations which directly reduces domestic pollution; furthermore, the international fragmentation of production has driven changes in industrial composition and expanded the scope for technological spillovers, which also affect domestic environmental quality.[5] Our work is in line with this recent literature in that we study the effect of industries' par-

[3]See Koopman et al. (2012) for detail.

[4]These so-called composition and technique effects induced by international integration have been well explored, for example by Antweiler et al. (2001), Cherniwchan et al., 2017, Cole and Elliott (2003), Grether et al. (2009), Levinson (2009), Forslid et al. (2011), Martin (2011), Baldwin and Ravetti (2014), Kreickemeier and Richter (2014), Cui et al. (2015), Holladay (2016), Barrows and Ollivier (2016), Cherniwchan (2017), Forslid et al. (2018), and many others.

[5]See, for example, Dean and Lovely (2010), Dietzenbacher et al. (2012), Meng et al. (2018), Li and Zhou (2017), Cole

ticipation in GVCs (as reflected by foreign intermediate input sourcing and intermediate export orientation) on environmental outcomes. In contrast to previous research, however, we investigate the role of production networks in shaping environmental quality in the presence of a macroeconomic shock – specifically, a change in the real effective exchange rate that affects an industry's price competitiveness in trade.

Lastly, our work is similar in spirit to previous studies exploring the effect of exchange rates on international trade in the context of GVCs. It is well known that supply chains buffer the direct impact of exchange rate variations on exporting activities (see, for example, the aforementioned Amiti et al., 2014, Ahmed et al., 2017, Sato and Zhang, 2019). However, little effort has been undertaken to assess the environmental consequences of movements in exchange rates in the context of international supply chains.

The remainder of the paper is organized as follows. Section 2 develops the conceptual framework which we use to analyze the underlying mechanisms through which exchange rates affect domestic environmental quality, specifically, vis-à-vis foreign input sourcing and export orientation. Section 3 describes the data and econometric approach used to estimate the key predictions of the model. Section 4 presents the empirical results and discusses the implications of our findings, and Section 5 offers concluding remarks.

2 Conceptual Framework

In this section we develop a theoretical framework to characterize the roles of exchange rates, foreign input sourcing, and export orientation – and importantly, the interaction of these factors – as determinants of industrial emission intensities. The purposes of this analysis are twofold. First, it allows us to formalize the intuition on the role of GVCs and trade as channels through which exchange rates affect an industry's environmental accounts. Second, the model generates testable empirical hypotheses on the relationship between these phenomena. We begin by describing a two-country (home, denoted by h, vs. foreign/rest-of-world, denoted by f), single-sector partial equilibrium setting. We assume the existence of a representative firm in the sector.

Notation For consistency of notation, we adopt the following structure to denote the amount of traded goods exported from the origin to destination and the price that the supplier charges to

et al. (2017), and Liu et al. (2018).

a consumer respectively as

$$X_{\text{destination, origin}}, \qquad p_{\text{customer, supplier}}.$$

Production We assume that there is a composite sector in the home country comprising of two sub-sectors: one producing intermediate inputs (I) and the other final goods (F). The representative firm s in each sub-sector, with $s \in \{I, F\}$, produces goods using a Cobb-Douglas constant-returns-to-scale technology combining a domestic primary factor (labor-capital-energy composites), denoted D_h^s, and intermediate input composites, denoted X_{hf}^{Is}, imported from the rest-of-world foreign country:

$$X_h^s = \left(D_h^s\right)^{1-\alpha^s} \left(X_{hf}^{Is}\right)^{\alpha^s}.$$

The parameter α^s reflects the share of foreign value-added content in each sub-sector, which will be a key determinant of the scope for foreign content effects to affect emission intensities.

Gross Output, Emissions, and Emission Intensity Gross output, GO_h, is the revenue generated from sales, either to domestic consumers or from export sales to foreign customers. Goods can be sold for either of three uses: (a) domestic final consumption, (b) exported intermediate goods, and (c) exported final goods. Thus, gross output (or alternatively, total sales) of a sector can be expressed as

$$GO_h \equiv p_h \left(X_{hh}^F + X_{fh}^I + X_{fh}^F\right),$$

where the price of output is denoted by p_h.[6] For simplicity, we assume that the (effective) prices of the three types of goods are identical – i.e., the prices faced by the intermediate and final good sectors are equivalent. We further assume that all intermediate goods produced in the home country are exported and utilized in the foreign country, while final goods are consumed both domestically and in the rest-of-world foreign country, i.e., $X_h^I = X_{fh}^I$ and $X_h^F = X_{hh}^F + X_{fh}^F$.

Manufacturing processes generate air pollution as a byproduct of production due to the use of the energy-embedded composite input. We introduce a generic pollution generation function given by

$$E_h = E\left(GO_h\right),$$

[6]Here, we do not model intermediate goods that are both produced and consumed domestically because we have assumed that firms only utilize foreign-produced intermediate inputs. The reason for this assumption is that the implication of a currency appreciation for the use of domestically consumed intermediate inputs is qualitatively similar to that for final goods, which we do explicitly model.

with $E' > 0$.

Only limited explicit evidence exists to inform us on the expected curvature of the function E. Recent work by Empora et al. (2020) offers empirical support for a positive non-linear relationship between emissions of sulfur dioxide (SO_2) and nitrogen oxide (NO_x), and further argues that abatement efforts that accompany higher output levels give rise to a concave relationship between output and emissions. While definitively quantifying the exact relationship between output and emissions is beyond our scope, there is robust support in the literature for the notion that firms' environment-saving efforts such as abatement investments, technology adoption, and research and development efforts maintain an increasing relationship with sales (see, for example, Cui, 2017 and Forslid et al., 2018). These factors are each associated with broader technique effects that limit firms' emissions via practices such as the capture of end-of-pipe gases or reductions in the energy-intensiveness of manufacturing processes (see, for example, Copeland et al., 2021). Hence, we assume that marginal emissions are diminishing in output, i.e., that $E'' < 0$.

From the emissions generation function, we define (country-sectoral) emission intensity in the home country as the amount of air pollution emitted per (nominal) unit of gross output:

$$e_h \equiv \frac{E\left(GO_h\right)}{GO_h}.$$

Profit Maximization The firm in each sector chooses the optimal amount of production factors which maximizes profits:

$$\max_{D_h^s, X_{hf}^{Is}} \quad p_h X_h^s - w D_h^s - p_{hf} X_{hf}^{Is}, \quad s = I, F,$$

where p_h is the price of output, w is the price of the domestic composite input, and p_{hf} is the (import) price of the foreign-produced composite intermediate input in the home country. Before any change in the exchange rate takes place, assume that the price of home's imports from foreign, p_{hf}, is equal to the price of goods produced and consumed in foreign (denoted p_f). The profit maximization and zero-profit conditions together yield the optimal factor demands

$$\left(D_h^s\right)^* = \frac{(1-\alpha^s) p_h X_h^s}{w},$$
$$\left(X_{hf}^{Is}\right)^* = \frac{\alpha^s p_h X_h^s}{p_{hf}}.$$

The above relationships together indicate that the optimal use of production factors is directly and positively related to the level of production.[7] Applying the same logic, the foreign demand for goods produced in the home country can be expressed as

$$\left(X_{fh}^{Is}\right)^* = \frac{\beta^s p_f X_f^s}{p_{fh}}, \quad s = I, F,$$

where

$$X_f^s = \left(D_f^s\right)^{1-\beta^s} \left(X_{fh}^{Is}\right)^{\beta^s},$$

and β^s governs the weight of intermediate inputs sourced from the home country used in foreign production. We denote the total amount of intermediate goods exported from home to the foreign intermediate and final goods sectors as $X_{fh}^I = X_{fh}^{II} + X_{fh}^{IF}$ $(= X_h^I)$.

Domestic Currency Appreciation We next consider an exogenous appreciation of the home country's currency which alters the effective prices of internationally traded goods as

$$p_{fh} = \varepsilon_h p_h,$$
$$p_{hf} = \varepsilon_h^{-1} p_f,$$

where $\varepsilon_h > 1$ describes the magnitude of the appreciation. These relationships indicate that the currency appreciation raises the effective price of home's exports to the foreign country (p_{fh}) and reduces the effective price of home's imports from the foreign country (p_{hf}) relative to domestic prices p_h and p_f.

Currency Appreciation and Total Sales To see the effect of the currency shock on emission intensity, we next disentangle its respective effects on emissions and total sales. There are several factors that together determine the effect of the domestic currency appreciation shock on sales, and the net effect is determined by the relative importance of each of these channels:

$$\frac{\partial GO_h}{\partial \varepsilon_h} = p_h \left[\frac{\partial X_{hh}^F}{\partial \varepsilon_h} + \frac{\partial X_{fh}^I}{\partial \varepsilon_h} + \frac{\partial X_{fh}^F}{\partial \varepsilon_h} \right].$$

The terms in brackets comprise, in order, the impact of the currency appreciation on (1) home's

[7] From the Cobb-Douglas function form, we implicitly assume that the share of expenditures on imported intermediate inputs in the total sales of sub-sector s is fixed to α^s in the home country; in other words, this share does not change in response to movements in exchange rates. We address this assumption later on in our empirical analysis.

production of final goods for the home market, (2) home's exports of intermediate goods to foreign, and (3) home's exports of final goods to foreign, and the sign of each term in the bracket is influenced by both supply-side and demand-side reactions to the appreciation of the domestic currency. After substituting in the optimal factor demands from above, we depict the elements of each of these terms in Table 1. We refer to these respective aspects of the reaction to the shock that originate from import versus export effects as foreign content and export competitiveness effects since, as shown in Table 1, these impacts are largely mediated by countries' trade openness in importing versus exporting (i.e., the relative importance of embodied foreign content and export sales for a firm or industry). In the former dimension, the currency appreciation impacts the price at which a domestic firm is able to source inputs from abroad for use in production, and thus its overall economic efficiency in production. The latter effect, on the other hand, reflects the price competitiveness of the firm's exports, which deteriorates with the appreciation of the domestic currency, thus reducing foreign demand for the firm's output.

We delineate these latter effects between intermediate versus final exports since the two types of export goods are distinguished by both the degree of foreign value-added that each embodies (reflected by the parameter α for each sub-sector, which determines the magnitude of $\partial X^F_{hh}/\partial X^{IF}_{hf}$, $\partial X^I_{fh}/\partial X^{II}_{hf}$, and $\partial X^F_{fh}/\partial X^{IF}_{hf}$), as well as the sensitivity of foreign demand to changes in the effective prices of intermediate versus final goods ($\partial X^I_{fh}/\partial p_{fh}$ and $\partial X^F_{fh}/\partial p_{fh}$). Thus, exported goods that are foreign value-added-intensive (i.e., which have a higher value of α) are likely to manifest a foreign content effect larger than that for exported goods which possess comparatively less foreign value-added. The second component of this effect indicates that export competitiveness effects will be larger in goods for which foreign demand is most sensitive to price changes.

The comparative statics in Table 1 demonstrate the ambiguity in the sign of the overall relationships in (2) and (3) arising from the offsetting forces of the foreign content and export competitiveness effects: the domestic currency appreciation reduces the price competitiveness of home-produced goods in foreign markets (reducing output and sales); however, it raises the purchasing power of the home country in obtaining foreign-produced intermediate inputs for production activities (increasing output and sales). The two countervailing forces make the overall effect of a currency shock on the home industry's total sales ambiguous:

$$\frac{\partial GO_h}{\partial \varepsilon_h} = p_h \left[\underbrace{(+)}_{(1)} + \underbrace{[(+) + (-)]}_{(2)} + \underbrace{[(+) + (-)]}_{(3)} \right] \lesseqgtr 0.$$

Table 1: Components of the Effect of a Currency Appreciation on Sales

	Term		Foreign Content Effect	Export Competitiveness Effect	Net Effect
(1)	$\frac{\partial X^F_{hh}}{\partial \varepsilon_h}$	=	$\underbrace{\frac{\partial X^F_{hh}}{\partial X^{IF}_{hf}}}_{(+)} \cdot \underbrace{\frac{\partial X^{IF}_{hf}}{\partial p_{hf}}}_{(-)} \cdot \underbrace{\frac{\partial p_{hf}}{\partial \varepsilon_h}}_{(-)}$		$(+)$
(2)	$\frac{\partial X^I_{fh}}{\partial \varepsilon_h}$	=	$\underbrace{\frac{\partial X^I_{fh}}{\partial X^{II}_{hf}}}_{(+)} \cdot \underbrace{\frac{\partial X^{II}_{hf}}{\partial p_{hf}}}_{(-)} \cdot \underbrace{\frac{\partial p_{hf}}{\partial \varepsilon_h}}_{(-)}$	$+ \underbrace{\frac{\partial X^I_{fh}}{\partial p_{fh}}}_{(-)} \cdot \underbrace{\frac{\partial p_{fh}}{\partial \varepsilon_h}}_{(+)}$	$(+/-)$
(3)	$\frac{\partial X^F_{fh}}{\partial \varepsilon_h}$	=	$\underbrace{\frac{\partial X^F_{fh}}{\partial X^{IF}_{hf}}}_{(+)} \cdot \underbrace{\frac{\partial X^{IF}_{hf}}{\partial p_{hf}}}_{(-)} \cdot \underbrace{\frac{\partial p_{hf}}{\partial \varepsilon_h}}_{(-)}$	$+ \underbrace{\frac{\partial X^F_{fh}}{\partial p_{fh}}}_{(-)} \cdot \underbrace{\frac{\partial p_{fh}}{\partial \varepsilon_h}}_{(+)}$	$(-/+)$

It is important to be clear on why the magnitude of this offsetting effect will be heterogeneous across the two types of export goods. If we assume that intermediate exports are relatively more intensive in their use of foreign value-added than final export goods (owing to such goods' increased prominence in GVCs and processing trade), the foreign content effect for the former will be larger than for the latter. Therefore, while the sign of the net effects in (2) and (3) is ultimately ambiguous (and also depends on the sensitivity of foreign demand to changes in international prices), the net effect of the appreciation on intermediate production and exports is conceivably less negative (or more positive) than for final goods, an assertion whose validity we test in our empirical analysis.

Despite its ambiguity, the above relationship offers several important insights. To illustrate, consider a simple case in which the home country mostly utilizes primary (domestic) factors and only participates in final good export activities (no domestic sales or intermediate exports). In this setting, the impact on output of a currency appreciation via input sourcing effects is minimal, and is largely manifested through the export competitiveness effects. In this case, the limited role of embodied foreign content in the industry's production implies that the magnitude of channel (1) is negligible, and that the impact of the foreign content effects in channel (3) is also very small. In this scenario, then, total sales will likely decline ($\partial GO_h/\partial \varepsilon_h < 0$) as a consequence of the loss in export competitiveness due to the currency appreciation.

If we instead consider a situation in which the home country intensively relies on foreign intermediate inputs while undertaking minimal exports of any kind, then the negative effect of the currency appreciation on foreign sales in this example will be attenuated relative to a country that sells mostly final goods abroad. In this scenario for which the import effects are comparatively strong, the sign on the relationship between total sales and the currency shock is likely to be positive ($\partial GO_h/\partial \varepsilon_h > 0$). Simply put, the relationship between output and the appreciation of the home country's currency in this case is positive due to its intensive reliance on imported inputs, and this relationship is increasing in the degree of the country's intermediate import orientation. Because most industries do not occupy either of these extremes in their trade orientations, deducing the true nature of these relationships between exchange rate movements and output (and thus emission intensities) becomes an empirical question.

Currency Appreciation and Emission Intensity Because emissions are increasing in total output, the ambiguous relationship between the currency appreciation shock and output means that the relationship between emission intensity and the currency appreciation is also ambiguous. This can be illustrated by considering the comparative static for the marginal effect of a currency shock on emission intensity, which is given by

$$\begin{aligned} \frac{\partial e_h}{\partial \varepsilon_h} &= \left[\frac{\partial E\left(GO_h\right)}{\partial GO_h} - \frac{E\left(GO_h\right)}{GO_h} \right] \cdot GO_h^{-1} \cdot \frac{\partial GO_h}{\partial \varepsilon_h} \\ &= \underbrace{\left[ME_h - AE_h\right]}_{(-)} \cdot GO_h^{-1} \cdot \underbrace{\frac{\partial GO_h}{\partial \varepsilon_h}}_{(+/-)}, \end{aligned}$$

where ME_h and AE_h respectively indicate the marginal and average emissions with respect to output. The assumption of diminishing marginal emissions implies that average emissions strictly outweigh marginal emissions, and therefore, that any increase in total output will lead to a comparatively smaller proportional increase in total emissions which results in a decrease in emission intensity (with analogous logic for a decrease in total output). Thus, as with the relationships for gross output, the effect of a domestic currency appreciation on emission intensity is ambiguous for the same reasons that give rise to uncertainty in the sign of the relationship between the currency appreciation and output; however, the same implications of the foreign content and export competitiveness effects as they relate to trade orientation which allows us to qualify the anticipated magnitude and direction of the relationship.

Predictions Based on the discussion so far, we make the following claims:

Claim 1. *Changes in exchange rates affect emission intensities through an industry's use of imported intermediate inputs and its export sales, which give rise to the foreign content and export competitiveness effects.*

Claim 2. *The relationship between emission intensity and an appreciation of the domestic currency (as mediated by the foreign content effect) is negative and decreasing in the extent of an industry's intermediate import orientation, defined as the value of the industry's use of imported intermediates relative to its total sales.*

Claim 3. *The relationship between emission intensity and an appreciation of the domestic currency (as mediated by the export competitiveness effect) is positive and increasing in the extent of an industry's intermediate and final export orientations, defined respectively as the share of an industry's intermediate and final exports in its total sales.*

Claim 4. *The overall effect of a change in exchange rates on output, and thus emissions and emission intensities, is ambiguous due to the offsetting impacts of the foreign content and export competitiveness effects.*

Claim 1 derives from the relationship between output and movements in the exchange rate due to the forces described above. We advance claim 2 based on the logic that industries for which embodied foreign content is more important in production will exhibit larger effects on output and emissions from a change in the value of the domestic currency relative to industries with little reliance on imported intermediates. The second claim particularly emphasizes the role of GVC activities (i.e., the sourcing and sale of intermediate goods across borders) in determining the effect of exchange rate movements on environmental quality. More specifically, it is clear that any consideration of the link between exchange rates and environmental outcomes that omits this aspect of trade would omit one of the key factors that underpins this relationship. Claim 3 originates from the supposition that industries for which export markets comprise a large share of sales are likelier to see larger changes in trade from changes in the effective foreign price of their output than industries that sell most of their output domestically. In conjunction with this, goods for which foreign demand is more sensitive to changes in the effective price of a source country's exports will also see larger export competitiveness effects. The final claim results from the offsetting forces of the respective import- and export-driven mechanisms that we describe, and while the relationship is a priori ambiguous, we will explore empirically how the two effects that we highlight interact to determine the sign of the relationship.

Having established the formal intuition that characterizes the relationships between exchange rates, foreign input sourcing and exports, and emission intensities, we now turn to estimating these relationships empirically.

3 Empirical Approach and Data

To test the key claims developed in the theoretical framework, we estimate a reduced-form econometric model of country-industry-level emission intensities as a function of annualized real effective exchange rates, as well as country- and industry-specific measures of intermediate import and intermediate versus final export orientations. We introduce these trade orientation variables to account for the foreign content and export competitiveness effects that give rise to the relationship between exchange rates and emission intensities, and to assess the degree to which these effects are increasing in the extent of industries' trade openness in either direction as implied by our modeling framework. In extending our setting to a multi-county, multi-industry analysis, we henceforth refer to country-industry combinations (for example, the U.S. automobile sector) as simply "industries."

Our estimating equation is given by

$$\begin{aligned} \ln e_{ikt} = {} & \beta_1 \ln REER_{it} + \beta_2 IIO_{ikt} + \beta_3 IEO_{ikt} + \beta_4 FEO_{ikt} \\ & + \beta_5 \ln REER_{it} \times IIO_{ikt} + \beta_6 \ln REER_{it} \times IEO_{ikt} + \beta_7 \ln REER_{it} \times FEO_{ikt} \\ & + \boldsymbol{X}_{ikt}\boldsymbol{\gamma} + \delta_{ik} + \eta_t + \kappa_i t + \varepsilon_{ikt}, \end{aligned} \tag{1}$$

where e_{ikt} is the emission intensity (total emissions of a particular pollutant per million nominal dollars of output) for either carbon dioxide (CO_2), sulfur oxides (SO_x), or nitrogen oxides (NO_x) in country i's industry k in year t.[8] Emissions and output data are based on country- and industry-level environmental accounts and output data obtained from the World Input-Output Database (WIOD; Genty, 2012). The data in our analysis cover 26 countries,[9,10] and the 16 goods sectors in

[8] We also estimate a version of Equation (1) using industries' emissions per dollar of value added (rather than gross output) as the left-hand-side variable. In addition, we perform an alternative estimation of Equation (1) that excludes the coke, refined petroleum, and nuclear fuel sector, as this sector's emissions (as well as its intermediate import orientation) are significantly higher than the other sectors. Our findings are largely unchanged in these alternative specifications.

[9] See Table A1 for the list of countries in the analysis.

[10] 11 of the 26 countries in our analysis were in the Eurozone for most or all of the sample period, and thus have effec-

the WIOD data (see Table 3 below) for the years 1999 to 2009.

$REER_{it}$ is the annualized average value of country i's real effective exchange rate index based on trade-weighted bilateral exchange rates. We consider a standard measure of REER calculated based on trade in goods (from the IMF's International Financial Statistics data; IMF, 2020). As described both by Bayoumi et al. (2013) and Bems and Johnson (2017), however, this and other standard measures of REER based on partner-weighted trade mixes might be limited by incompletely accounting for the structure of fragmented production tasks and input-output linkages between countries, a relevant factor when considering the interaction between exchange rates and GVC participation. We thus also consider an alternative measure of "REER-in-tasks" (from Bayoumi et al., 2013) that takes these factors into account, a robustness exercise the results of which are presented in Table A5 in the appendix.

Information on intermediate imports and exports are obtained from the 2016 version of the OECD's Trade in Value Added (TiVA) and Inter-Country Input-Output (ICIO) databases. We define intermediate import orientation (IIO) as

$$IIO_{ikt} = \frac{\text{Imports of intermediate inputs by industry } ik \text{ in year } t}{\text{Gross output of industry } ik \text{ in year } t},$$

where intermediate inputs represent the industry's use of foreign content in production (including from foreign service sectors). Similarly, the export orientation measures (IEO and FEO for intermediate and final exports, respectively) are defined as

$$IEO_{ikt} = \frac{\text{Intermediate export sales of industry } ik \text{ in year } t}{\text{Gross output of industry } ik \text{ in year } t}$$

and

$$FEO_{ikt} = \frac{\text{Final export sales of industry } ik \text{ in year } t}{\text{Gross output of industry } ik \text{ in year } t}.$$

The objects of primary interest in Equation (1) are the expressions relating to the REER, IIO, IEO, and FEO terms. Because both emission intensity and REER are expressed in logarithms, the associated coefficients offer an elasticity interpretation. Consequently, the elasticity of emission intensity with respect to REER (which we denote as θ_{ikt}) is a function of the main effect of REER (β_1), as well

tive exchange rates that are strongly correlated with those of other Eurozone countries. Accounting for this feature of the data by controlling for Eurozone status, or clustering our standard errors by currency group, does not meaningfully change our results.

as the interaction effects with intermediate import and export orientations (reflected by β_5, β_6, and β_7):

$$\theta_{ikt} \equiv \frac{\partial \ln e_{ikt}}{\partial \ln REER_{it}} = \beta_1 + \beta_5 IIO_{ikt} + \beta_6 IEO_{ikt} + \beta_7 FEO_{ikt}. \tag{2}$$

In essence, Equation (2) indicates that the relationship between emission intensity and exchange rates is a function of the industry's trade exposure in the three included dimensions. The interactions between the trade measures and REER are thus direct empirical analogues to the elements that constitute the foreign content and export competitiveness effects in the theoretical model. The nature of the direct relationship between emission intensities and REER represented by β_1 is not obvious, as both intuition and the analytical framework above suggest intermediate import orientation and export orientation as the primary channels through which REER should have any effect on emission intensities; we therefore expect β_1 to be zero. We thus focus our discussion on the trade orientation channels as reflected by β_5, β_6, and β_7.[11]

Based on the claims derived from the theoretical framework above, we should anticipate intermediate import orientation to negatively affect the relationship between emission intensities and exchange rates ($\beta_5 < 0$). The foreign content effect implies that industries which rely intensively on imported intermediates will see their efficiency in production rise when foreign inputs become comparatively more affordable after an increase in the industry's foreign purchasing power, expanding the scope for reductions in emission intensity from the adoption of emissions-reducing efforts and technique effects (which are implicitly associated with pollution outsourcing as well as environment-saving efforts).[12]

On the other hand, as detailed above, the export orientation effects do not offer a straightforward interpretation, as they embody both foreign content and export competitiveness effects. The export competitiveness effect on its own should lead to a more-negative impact of REER on emission intensity (i.e., the rise in REER causes emission intensity to increase), as the change in the terms of trade spurs a reduction in foreign demand for the industry's output, which in isolation would

[11]We also emphasize that we are considering the direct causal relationship between REER and emission intensities as mediated by the trade orientation measures, rather than the potential effect that REER would have on the trade orientation measures themselves. To assess the extent to which our results represent the former relationship versus the latter, we will also estimate a version of Equation (4) that fixes the trade orientation measures at their start-of-sample levels.

[12]To be clear, we do not explicitly quantify the extent to which firms alter their emissions-reducing activities, such as abatement efforts, environmental technology adoption, pollution offshoring, etc., in response to exchange rate movements, as the lack of availability of suitable data constrains our ability to assess such outcomes. Rather, our analysis seeks to quantify the extent to which our hypotheses are consistent with the relationships depicted in the preceding section, which, in line with the literature in this area, could plausibly arise because of such efforts.

cause β_6 and β_7 to be positive. However, this effect is counteracted by the foreign content effect arising from the value-added content of the exports: when exported goods embody large amounts of foreign value-added, the appreciation of the domestic currency improves the efficiency with which the industry is able to source the inputs used to produce exports. Because intermediate versus final exports are likely to differ in their respective foreign value-added content, we can anticipate that the impacts of the appreciation will be different for the two types of exports, and as a result, that β_6 and β_7 might be differently signed. Ultimately, the sign of θ_{ikt} (and thus whether exchange rate movements improve, have no effect on, or detract from environmental quality) hinges on which effect dominates as a function of the parameter values and the extent of an industry's trade orientation in these three dimensions.

Table 3 presents summary statistics for the three trade orientation measures and emission intensities for each of the goods sectors in the WIOD data. The industries with the highest levels of intermediate import orientation (such as chemicals, basic metals and fabricated metal products, and transport equipment) are those that rely intensively on intermediate inputs sourced from upstream foreign suppliers. Conversely, industries with low levels of intermediate import orientation (such as agriculture, food and beverages, or wood and wood products) are those whose output does not depend significantly on foreign inputs; generally, primary commodity and basic manufacturing sectors. Similar variation is evident in export orientation across industries: primary sectors tend to be comparatively more reliant on intermediate export sales given the nature of the goods produced (e.g., the agricultural and resource sectors, whose output is used intensively by downstream sectors), whereas industries located closer to final consumption (such as textiles and apparel or transport equipment) tend to have relatively higher levels of final export orientation. We also compute the sample correlation matrix for the three variables (Table 2), which suggests that each of the three measures maintain a weakly positive correlation with one another, i.e., industries with high (low) levels of exposure to trade in one dimension tend to demonstrate high (low) levels of trade exposure in the other dimensions.

Table 2: Sample Correlations between Trade Orientation Measures

	IIO	IEO	FEO
IIO	1.00		
IEO	0.42	1.00	
FEO	0.41	0.27	1.00

Table 3: Industry Descriptions and Summary Statistics

	IIO		IEO		FEO		CO_2 int.		SO_x int.		NO_x int.	
Industry	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
Agriculture, Hunting, Forestry and Fishing	0.09	0.05	0.07	0.05	0.04	0.03	0.23	0.13	1.58	4.69	3.35	3.47
Mining and Quarrying	0.12	0.08	0.21	0.15	0.02	0.02	0.69	1.05	1.29	2.41	1.57	1.54
Food, Beverages and Tobacco	0.11	0.05	0.07	0.05	0.12	0.08	0.11	0.11	0.32	0.46	0.36	0.50
Textiles and Textile Products	0.20	0.09	0.13	0.06	0.29	0.14	0.09	0.06	0.22	0.30	0.32	0.30
Leather, Leather Products, and Footwear	0.19	0.09	0.13	0.06	0.29	0.15	0.05	0.04	0.11	0.15	0.22	0.23
Wood and Products of Wood and Cork	0.12	0.05	0.18	0.12	0.03	0.02	0.14	0.36	0.39	1.16	0.65	1.18
Pulp, Paper, Paper Products, Printing and Publishing	0.13	0.06	0.15	0.10	0.05	0.04	0.15	0.14	0.98	1.54	0.90	1.21
Coke, Refined Petroleum and Nuclear Fuel	0.46	0.19	0.17	0.10	0.10	0.06	0.58	0.47	3.36	3.88	0.95	0.84
Chemicals and Chemical Products	0.20	0.08	0.29	0.15	0.12	0.07	0.42	0.47	1.53	2.03	0.80	0.89
Rubber and Plastics	0.19	0.08	0.27	0.14	0.06	0.03	0.08	0.11	0.27	0.85	0.24	0.42
Other Non-Metallic Mineral Products	0.17	0.07	0.16	0.08	0.02	0.01	1.29	0.71	2.12	2.45	3.34	3.40
Basic Metals and Metal Products	0.22	0.09	0.28	0.12	0.03	0.02	0.49	0.42	1.57	2.17	0.91	1.10
Machinery, n.e.c.	0.20	0.08	0.23	0.09	0.21	0.08	0.05	0.06	0.15	0.32	0.19	0.21
Electrical and Optical Equipment	0.18	0.10	0.28	0.1	0.22	0.08	0.03	0.05	0.08	0.22	0.10	0.13
Transport Equipment	0.27	0.12	0.22	0.09	0.29	0.12	0.04	0.05	0.12	0.29	0.15	0.19
Manufacturing, n.e.c.; Recycling	0.19	0.11	0.12	0.08	0.24	0.14	0.09	0.12	0.11	0.21	0.25	0.26
All Industries	*0.19*	*0.12*	*0.18*	*0.13*	*0.13*	*0.13*	*0.27*	*0.51*	*0.89*	*2.18*	*0.90*	*1.74*

Notes: IIO indicates "intermediate import orientation," IEO indicates "intermediate export orientation," and FEO indicates "final export orientation," all expressed as the value of an industry's trade in each respective dimension relative to its gross output. Emission intensities are defined as kilotons (for CO_2) or tons (for SO_x and NO_x) of emissions per million dollars of output.

The vector $\boldsymbol{X}_{ikt}$ includes a set of controls that are plausibly associated with both emission intensity and either REER or the trade orientation measures. Following the broader literature linking industrial emissions with trade and globalization, we include five controls reflecting several relevant socioeconomic and policy factors. These include (1) each industry's capital-labor ratio (defined as capital expenditures over wages by sector; from OECD), to capture differences in production techniques, (2) countries' GDP per capita (in logarithms; taken from World Bank) to account for differences in environmental quality along the income distribution (i.e., environmental Kuznets curve effects), (3) a numerical measure of country-level environmental policy stringency (ranging from 0 to 4 and increasing in a country's policy stringency; from OECD) to account for potential pollution haven effects, (4) the number of environment-related patent applications filed under the Patent Cooperation Treaty (by applicant's country of origin; from OECD) to reflect technological differences across countries, and (5) country-level FDI inflows as a percentage of GDP (from UNCTAD) to capture potential productivity differences in industries or pollution offshoring activities as reflected by a high degree of foreign ownership.[13]

The fixed effects δ_{ik} and η_t account for unobserved country-industry and time-specific factors. The inclusion of the former ensures that our identification derives purely from exchange rate variation in conjunction with within-industry variation in trade orientation, rather than from variation across countries and industries which might be driven by other unobserved factors. We also incorporate country-specific linear time trends $\kappa_i t$ to account for secular changes in emission intensities across countries over time, for instance due to technological progress or environmental and macroeconomic policy efforts.[14] Finally, ε_{ikt} is a mean-zero error term, which we cluster by country-year to account for within-country, cross-industry correlation in the observations of REER.

4 Empirical Results

Based on the empirical strategy and data outlined above, we now turn to estimating the key relationships relating industry-level emission intensities to exchange rates and trade orientation. This analysis is comprised of three components. First, we explore the empirical relationships

[13]Country-level summary statistics on these variables are presented in Appendix Table A2.

[14]We also estimate another specification with country-time fixed effects in place of the country-specific time trends; however, this specification precludes the identification of the direct effect of REER. The coefficients on the other variables of emphasis in this specification are qualitatively unchanged.

described above by estimating how exchange rates and the trade orientation measures jointly influence emission intensities. Second, we use these findings to calculate θ_{ikt}, the REER elasticity of emission intensity, and characterize how this measure relates to the various trade orientation measures. Third and finally, we provide empirical support for our assertion from the theoretical framework that these relationships are indeed driven by changes in industries' total sales arising from the interaction of the REER and trade orientation variables.

4.1 Exchange Rates, Trade Orientation and Emission Intensity

Before estimating Equation (1) in full, we first estimate a version of Equation (1) for each of the three pollutants that only considers the main effects of the REER, IIO, and EO (intermediate versus final) measures. The purpose of this exercise is to characterize the effects (or lack of effects) of the variables of interest when failing to account for their interactive effects, the results for which are presented in columns 1, 3, and 5 of Table 4.[15]

The generally insignificant results on REER suggest that exchange rates are, on their own, uninformative about emission intensities. This is to be expected, as movements in exchange rates per se should have little effect on emission intensities having already conditioned on the level of intermediate import and export orientation. The coefficient on the IIO variable is estimated to be negatively related to emission intensities, but only significantly so for the estimates on SO_x and NO_x. This result conforms to other findings in the literature (e.g., Shapiro, 2021) demonstrating an association between backward participation in GVCs and emission intensity because of factors unrelated to exchange rates (such as trade policy that penalizes imports of dirty intermediate inputs). We also find consistently negative effects on emission intensities for the intermediate export orientation measure and positive effects from the final export orientation measure, suggesting that industries focused on the former type of exports tend to maintain lower emission intensities than those focused on the latter, even after having controlled for long-run country-by-industry features.

As discussed, the degree to which exchange rates matter for emission intensities depends fundamentally on the degree of an industry's import and export orientations because of the foreign content and export competitiveness effects. These relationships are explicitly accounted for in the specifications of columns 2, 4, and 6, which allow for differential marginal impacts of changes

[15]The other controls of secondary interest are also included in the estimation, but for brevity are not presented in the table of results. We present the results for these variables in Appendix Table A4.

Table 4: Impacts of REER and Trade Orientation on Industry-Level Emission Intensities

	CO_2		SO_x		NO_x	
	(1) Direct Effects	(2) Baseline	(3) Direct Effects	(4) Baseline	(5) Direct Effects	(6) Baseline
REER	–0.048	0.089[b]	–0.172	0.094	–0.171	–0.078
	(0.039)	(0.044)	(0.106)	(0.127)	(0.099)	(0.115)
IIO	–0.021	6.189[a]	–0.381[a]	13.665[a]	–0.169	6.819[a]
	(0.059)	(0.677)	(0.147)	(2.097)	(0.086)	(1.344)
REER × IIO		–1.380[a]		–3.121[a]		–1.553[a]
		(0.152)		(0.468)		(0.299)
IEO	–0.139[a]	2.947[a]	–0.535[a]	4.897[a]	–0.400[a]	3.807[a]
	(0.051)	(0.417)	(0.112)	(1.260)	(0.094)	(0.854)
REER × IEO		–0.677[a]		–1.192[a]		–0.929[a]
		(0.091)		(0.279)		(0.187)
FEO	0.052	–8.195[a]	0.289[b]	–18.004[a]	0.219[b]	–13.287[a]
	(0.051)	(0.611)	(0.114)	(1.284)	(0.091)	(0.895)
REER × FEO		1.828[a]		4.054[a]		2.998[a]
		(0.136)		(0.282)		(0.199)
Other controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,558	4,558	4,558	4,558	4,558	4,558
R^2	0.940	0.948	0.879	0.887	0.931	0.937

Notes: Dependent variables are the (log) industry-level emission intensities for the indicated pollutants. Each specification includes country-industry and year fixed effects as well as country-specific time trends. "Other controls" includes capital-labor ratio, GDP per capita, policy stringency, environmental patents, and FDI inflows. Robust standard errors clustered by country-year are reported in parentheses. a: $p < 0.01$, b: $p < 0.05$.

in REER as a function of an industry's intermediate-import and intermediate versus final export orientations.[16]

The results for the three pollutants are qualitatively similar in sign and significance, and we therefore focus principally on the results for CO_2, one of the the most common industrial air pollutants. In the results of column 2, we find significant evidence that trade orientation matters for explaining the marginal impact of exchange rates on industries' environmental accounts. The direct effect of the IIO variable (β_2 from Equation (1)) is estimated to be positive, and the direct effects of the IEO and FEO variables (β_3 and β_4, respectively) are estimated to be positive for the former and

[16]To account for potential simultaneity between REER, intermediate-import sourcing, and export sales, we also estimate Equation (1) while fixing the levels of the trade orientation measures at their start-of-sample (1999) levels, which allows us to isolate the pure effect of variation in exchange rates on emission intensity, rather than in conjunction with any effects of exchange rate movements on the trade orientation variables themselves. These results are presented in appendix Table A3. Because these and the baseline results convey similar findings, we focus on the baseline findings in our discussion.

negative for the latter, but the interpretation of these variables' overall impacts also depends on the specific value of REER.

We first observe that a higher intermediate import orientation causes the effect of REER on emission intensity to become more negative (as demonstrated by the interaction between REER and IIO), which accords with Claim 2 above: as a currency appreciates, the emission intensity of an industry improves in a way that is increasing in the industry's reliance on foreign intermediate inputs. This finding is consistent with the notion that a currency appreciation, by raising the industry's purchasing power in sourcing foreign inputs, enhances its efficiency in production and causes output to expand, strengthening the scope for emissions-reducing efforts and technique effects that contribute to lower emission intensities.

The roles of the two export orientation measures are more subtle, owing to the two offsetting forces that they reflect. The REER $\times$ IEO enters with the same negative sign as the REER $\times$ IIO interaction (though smaller in magnitude), which similarly implies that industries highly engaged in intermediate exports tend to see a currency appreciation improve their emission intensity. This is consistent with the foreign content effect dominating the export competitiveness effect for this dimension of exports, though whether this arises purely because of high levels of foreign content relative to final exports, weak foreign demand effects, or some combination of the two is not readily apparent. Conversely, the interaction REER $\times$ FEO has a strongly positive relationship with emission intensities: industries which rely heavily on final export sales see their emission intensities increase under a currency appreciation, suggesting that the export competitiveness effect dominates the foreign content effect in this dimension of trade. However, while we emphasize that these findings are consistent with the theorized relationships, owing to the multiple factors at play in determining these effects (i.e., the degree of embodied foreign content in intermediate versus final exports and the price sensitivity of foreign demand, factors which our data are only partly able to account for) it is difficult to definitively attribute these findings to a single source.[17]

[17]With regard to differences in foreign content by types of exports, there exists limited empirical evidence on the breakdown of foreign content between exports of intermediate versus final goods. While not overlapping perfectly with our analysis, Koopman et al. (2012) show that foreign-intermediate-intensive processing trade embodies a significantly larger share of foreign content than "normal" exports, i.e., export goods produced primarily using domestic value-added. One obstacle to computing the foreign-content shares of different types of exports lies in the uniform manner with which such values are generally calculated from cross-country input-output tables. Specifically, the value-added shares and input coefficients (for instance, those in our ICIO data) from upstream supplier industries are typically assumed to be the same for intermediate versus final production in the downstream demanding industry, and thus, automatically impose the assumption that intermediate and final exports embody the same shares of foreign value added. Similar limitations characterize the evidence on the sensitivity of import demand across broad product types, a factor that determines the size of the export competitiveness effect. Ghodsi et al. (2016) estimate the import demand elasticity for intermediate versus final goods and find that elasticities for the former tend to be larger than for the latter.

In summary, we emphasize two key findings from this analysis: first, that foreign content effects typically lead to a stronger negative relationship between emission intensities and REER (as reflected by the findings on IIO and IEO), and second, that export competitiveness effects tend to cause a more positive relationship between the two (reflected by the finding on FEO). We next turn to exploring how these offsetting effects interact to determine the relationship between emission intensity and REER as captured by the REER elasticity of emission intensity θ_{ikt}.

4.2 The Exchange Rate Elasticity of Emission Intensity

From our estimates, we evaluate the joint relationship between emission intensities, exchange rates, and the trade orientation measures using Equation (2) to compute θ_{ikt} (i.e., the REER elasticity of emission intensity). Based on our estimates in column 2 at the sample average values of IIO, IEO, and FEO, we calculate an elasticity for CO_2 emission intensity of –0.055, which with a standard error of 0.042 (obtained by the delta method) is statistically insignificant. This implies that for an industry with average levels of each trade orientation measure, changes in REER have no statistically meaningful effect on emission intensities. While this result supports the logic of Claim 4 regarding the ambiguous relationship between REER and emission intensities, this calculation at the average masks several important aspects of the findings.

To facilitate interpretation of the results, we consider the implied estimates of θ_{ikt} for CO_2 emission intensities evaluated at the quartiles of the trade orientation measures, which we present in Table 5. Because θ_{ikt} is a function of three variables, in order to compute how its value changes as a function of two particular trade orientation measures we fix the value of the third measure at its median value (e.g., each cell in the upper left panel of Table 5 gives the value of θ_{ikt} evaluated at the respective percentiles of IIO and IEO while fixing FEO at its median value).

Focusing first on the upper left panel, we see a clear relationship between the sign of θ_{ikt} and an industry's trade orientation in intermediate imports and exports. For industries with low levels of each measure (i.e., with low levels participation in GVCs), changes in REER have limited (or even positive) effects on emission intensities; however, as an industry's exposure in either (or both) dimension(s) grows larger, increases in REER have increasingly negative impacts on emission intensity, which we attribute to increasingly strong foreign content effects. The upper right panel that depicts quartiles of final export orientation illustrates a different story: industries with comparatively high levels of FEO, but low levels of IIO, exhibit a significantly positive relationship

Table 5: REER Elasticity of CO_2 Emission Intensity (θ_{ikt})
Evaluated at Sample Percentiles of IIO, IEO, and FEO

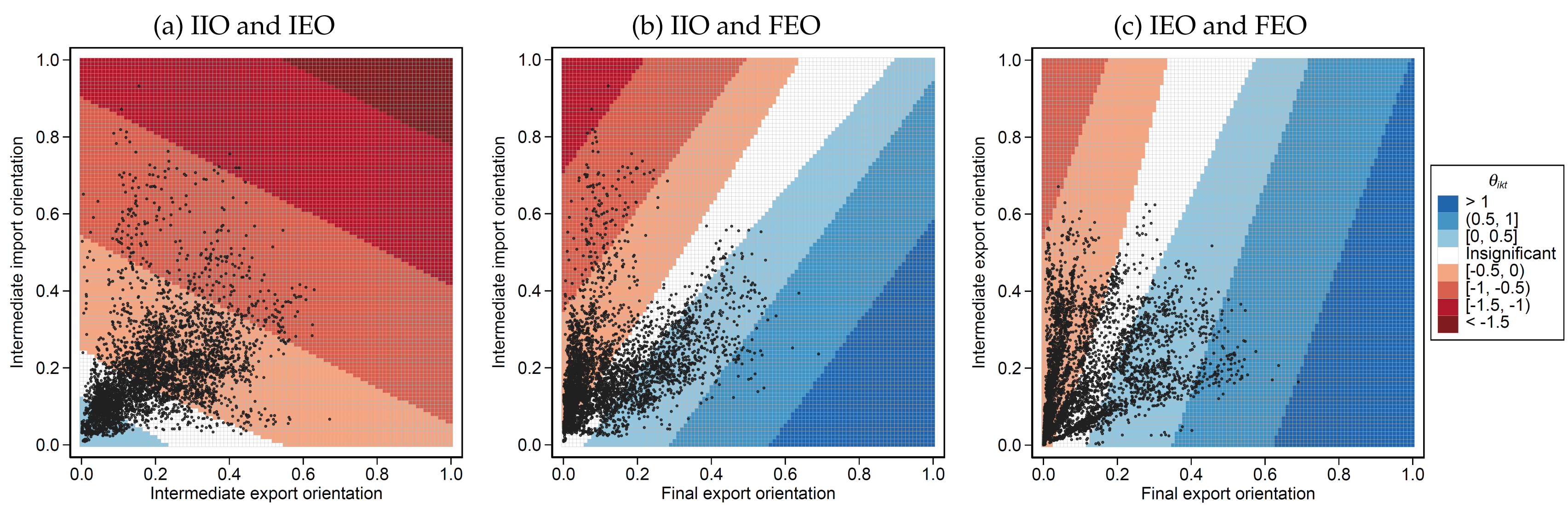
		IEO			FEO		
		$p_{25} = 0.08$	$p_{50} = 0.16$	$p_{75} = 0.24$	$p_{25} = 0.03$	$p_{50} = 0.08$	$p_{75} = 0.21$
IIO	$p_{25} = 0.11$	0.042	–0.012	–0.087	–0.118[a]	–0.026	0.211[a]
		(0.040)	(0.040)	(0.043)	(0.042)	(0.040)	(0.041)
	$p_{50} = 0.16$	–0.027	–0.081	–0.156[a]	–0.187[a]	–0.095[b]	0.142[a]
		(0.041)	(0.041)	(0.044)	(0.044)	(0.042)	(0.041)
	$p_{75} = 0.24$	–0.137[b]	–0.192[b]	–0.266[a]	–0.297[a]	–0.206[a]	0.032
		(0.046)	(0.046)	(0.047)	(0.049)	(0.046)	(0.043)
FEO	$p_{25} = 0.03$	–0.137[a]	–0.191[a]	–0.266[a]			
		(0.045)	(0.044)	(0.046)			
	$p_{50} = 0.08$	–0.046	–0.100[b]	–0.174[a]			
		(0.042)	(0.042)	(0.044)			
	$p_{75} = 0.21$	0.192[a]	0.138[a]	0.063			
		(0.040)	(0.041)	(0.044)			

Notes: Elasticity values calculating using estimates in Table 4. Delta-method standard errors are in parentheses. For each depicted two-way combination of trade orientation measures, the non-depicted measure is fixed at its sample-median value. a: $p < 0.01$, b: $p < 0.05$.

between emission intensity and REER. This relationship is attenuated, and eventually reversed, as the extent of the industry's reliance on foreign value-added content increases as measured by the intensity of the industry's intermediate imports and exports. Finally, the lower left panel depicts how IEO and FEO interact to determine θ_{ikt}. Industries for which intermediate exports are high relative to final exports see negative values of θ_{ikt}, while industries with high relative levels of final exports and low levels of intermediate exports demonstrate a positive relationship between REER and emission intensity.

Figure 1 provides a graphical counterpart to Table 5, showing the range of the θ_{ikt} point estimates implied by our regression estimates for particular combinations of the trade orientation measures, as well as the range over which these estimates are significantly different from zero at the 95% level (again fixing the non-depicted orientation measure at its median value). Along with the distribution of elasticities implied by the results in Table 4, we plot the observed values of the highlighted trade orientation measures for each industry-year observation in the sample to give a sense of the empirical distribution of θ_{ikt}.

Figure 1: Plot of REER Elasticity of CO_2 Emission Intensity as a Function of IIO, IEO, and FEO



Notes: The contours in each figure reflect the ranges of the statistically significant (at the 95% level) REER elasticity point estimates implied by our regression estimates based on different combinations of IIO, IEO, and FEO. The white band in each figure indicates the range of values for which the elasticity estimate is statistically insignificant at the 95% level. Individual points reflect the observed data on the trade orientation measures for each observation in the sample.

The graphical results offer several insights on top of the tabular representation of θ_{ikt}. Specifically, as seen in panel (a), the sharp complementarity between IIO and IEO in lowering the impact of REER appreciation on emission intensities becomes even more apparent. For those industries with middling levels of IIO and IEO, the uncolored band reflects the null relationship between emission intensity and REER. And while many industry-level observations lie in the insignificant range of estimates, a substantial share of the observed data lies in the range for which the relationship between REER and emission intensity is positive (points in the extreme southwest corner of panel (a)), while a comparatively large portion of the observations fall in the range that yields a negative relationship between REER and emission intensity (points to the northeast of the white band in panel (a)).

Panels (b) and (c) are similarly illustrative and largely portray the same findings as one another: the foreign content effects embedded in IIO and IEO work to offset the export competitiveness effects reflected by FEO, with industries that exhibit comparatively higher levels of one or the other trade orientation measure demonstrating significantly negative or positive values of θ_{ikt}. Industries for which the intensity of final exports and intermediate imports/exports are roughly the same again exhibit a null relationship between emission intensity and REER, supporting our hypothesis on the mutually-offsetting aspect of the foreign content and export competitiveness effects.

Table 5 and Figure 1 together confirm the key claims of the conceptual framework: industries which rely intensively on foreign intermediates tend to exhibit a negative relationship between REER and emission intensity (Claim 2), a reflection of the foreign content effect. Conversely, industries which rely intensively on final export sales are likelier to exhibit a positive relationship between REER and emission intensity, a reflection of the export competitiveness effect (Claim 3). For industries in the insignificant (null) range, changes in REER have no significant impact on emission intensity, a finding that accords with the hypothesis that the two effects tend to offset one another (Claim 4) for industries that are exposed to both effects in roughly equal measure.

4.3 Exchange Rates, Trade Orientation, and Total Sales

Our results on the relationship between emission intensities, REER, and trade orientation are consistent with the predictions of our theoretical framework. However, the predictions of the model rest on the validity of its underlying assumptions – most importantly, the assumption that changes

Table 6: Impacts of REER and Trade Orientation on Industry-Level Gross Output

REER	–0.385[a]
	(0.099)
IIO	–5.120[a]
	(1.636)
REER × IIO	1.195[a]
	(0.360)
IEO	–11.494[a]
	(0.909)
REER × IEO	2.655[a]
	(0.197)
FEO	7.923[a]
	(1.814)
REER × FEO	–1.937[a]
	(0.407)
Other controls	Yes
Observations	4,558
R^2	0.994

Notes: Dependent variable is (log) gross output by industry. Each specification includes country-industry and year fixed effects as well as country-specific time trends. "Other controls" includes capital-labor ratio, GDP per capita, policy stringency, environmental patents, and FDI inflows. Robust standard errors clustered by country-year are reported in parentheses.
a: $p < 0.01$, b: $p < 0.05$.

in REER affect industries' sales and output (and thus their emissions intensities), which in turn affects industries' emission intensities via technique effects and other ancillary efforts that improve industries' environmental accounts. To assess the validity of this conjecture, we provide supporting evidence that the hypothesized link between REER and output levels, particularly as mediated by industries' trade orientation, is indeed driving the findings presented above.

To do this, we estimate an otherwise identical version of Equation (4) taking gross output as the dependent variable, the results for which are shown in Table 6. The results effectively mirror the results on emission intensities from earlier (Table 4): as the interaction effects move in opposite directions in comparison to the original results on emission intensities, this confirms that the relationship between output and the trade orientation measures behaves as hypothesized. As seen in the baseline results in column 2, the higher is an industry's intermediate import orientation, the larger is the positive impact of a currency appreciation on output, which we again attribute to the industry's improved efficiency in sourcing foreign inputs. The results on the export measures are also consistent with the mechanisms described earlier. Industries with a relatively high reliance on intermediate export sales see a stronger positive link between REER and output, which we attribute to the embodied foreign content effect, while the opposite relationship holds for final export orientation; each finding is consistent (reversed in sign) with the results from the baseline results on emission intensities. Therefore, while we do not explicitly quantify the emissions-reducing efforts or technique effects that accompany these observed changes in output, such factors are consistent with our findings as well as the broader literature in this area.

5 Conclusion

We study the role of exchange rates as a determinant of industrial emission intensity, specifically focusing on how this relationship interacts with industries' GVC linkages and trade orientation, i.e., the extent to which they rely on foreign-sourced production inputs and export sales, delineated between sales of intermediate versus final goods. To this end, we first develop a conceptual framework that characterizes the link between exchange rates, firms' sourcing of foreign inputs, their reliance on export sales in both intermediate and final goods, and industry-level environmental accounts. The model formalizes the intuition that exchanges rates largely affect industrial emissions via firms' foreign input sourcing decisions, which gives rise to what we denote as the foreign content effect, and changes in foreign demand for their output from changes in effective prices, which we denote as the export competitiveness effect. The exact relationship between exchange rates and emissions is ambiguous because the impacts of these two factors counteract one another, and as we show, depends on the extent of an industry's trade orientation in the import and export dimensions.

Despite the ambiguity of a number of its predictions, the model offers several clear hypotheses: first, that the appreciation of a domestic currency causes emission intensities to fall because of the foreign content effect as firms are able to more efficiently source intermediate inputs. In line with the literature in this area, we assert that the efficiency with which firms are able to obtains foreign inputs is directly associated with emissions-reducing efforts which strengthen the scope for technique-effect-driven reductions in emission intensities (though it is worth noting that these relationships rely on the particular shape of the emission generation function). Second, an appreciation causes emission intensities to rise through the export competitiveness effect, which causes the price competitiveness of the industry's exports to deteriorate. We thus characterize the role of the foreign content effect (a measure of backward linkage in GVCs) as a mitigating factor that offsets the harmful impacts of the appreciation arising through the export competitiveness channel.

We test these claims from the model in an empirical setting using a panel of data on industrial emissions, exchange rates, and trade orientation measures. Accounting for other relevant factors, including unobserved features specific to each country-industry, we show that exchange rates matter as a determinant of emission intensities vis-à-vis the intermediate import and export (intermediate versus final) orientations of an industry. The predictions of the model are borne out by the econometric results, and demonstrate (1) the decreasing relationship between emission intensities and exchange rates as a function of intermediate imports and export orientations, (2) the increasing relationship between emission intensities and exchange rates as a function of final export orientation, and (3) that these elements on average offset each other. However, industries which are disproportionately reliant on foreign content tend to see increases in exchange rates improve their emission intensities, while conversely, industries that disproportionately rely on final export sales relative to their foreign input sourcing and intermediate export sales evince a positive relationship between exchange rate movements and emission intensities.

Our results speak to several important aspects of the nexus of globalization and the environment. We show that exchange rates matter for environmental outcomes, particularly with regard to the extent of an industry's backward linkage in GVCs and its export orientation. While we abstract from questions of how exchange rates alter these trade orientation measures themselves, we show that the intensity of an industry's orientation in either dimension is a key determinant of whether an exchange rate movement causes an industry's emission intensity to improve or deteriorate. We characterize this finding as arising from gains in economic efficiency that accrue to firms whose purchasing power for foreign inputs improves from a currency appreciation, or conversely, losses in efficiency that manifest because of diminished export competitiveness. While exploring the fundamental causes of our findings – for instance, increased abatement efforts by firms, expanded technology adoption, or broader composition and technique effects – is beyond our scope, our results are nonetheless consistent with each of these factors that reflect firms' reactions to such dynamics as a function of their exposure to trade.

Our findings at once characterize the impacts of exchange rate movements on industrial emission intensities, a relationship that has heretofore received scant attention in the literature, and also highlight a novel role for trade and GVC participation in influencing environmental outcomes. While we find no significant evidence that backward GVC participation nor export orientation per se contribute to lower or higher emission intensities, we find strong and consistent support for the proposition that these effects matter significantly when considered in tandem with exchange rates. Our findings thus depict a new channel through which trade, production fragmentation and macroeconomic shocks affect environmental outcomes. The extent to which our findings on foreign input sourcing reflect improvements in environmental quality arising from pure efficiency gains versus emission outsourcing/offshoring, as well as the extent to which trade policy plays a role in shaping our findings, remain open but critical questions, which we leave for future work.

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Appendix

List of Countries in the Empirical Analysis

Table A1: Countries in the Empirical Analysis

Australia	France	Portugal
Austria	Germany	Slovakia
Belgium	Greece	South Korea
Brazil	Hungary	Spain
Canada	Ireland	Sweden
China	Italy	Turkey
Czech Republic	Japan	United Kingdom
Denmark	Netherlands	United States
Finland	Poland	

Summary Statistics for Other Control Variables

Table A2: Country-Level Summary Statistics for Other Controls

	K/L		**GDP per capita**		**Policy stringency**		**Env. patents**		**FDI inflows**	
Country	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.	Mean	s.d.
Australia	0.8	0.9	30.8	10.1	1.6	0.6	1.8	0.4	3.0	2.6
Austria	0.7	0.6	36.0	9.4	2.5	0.4	1.0	0.4	5.8	7.8
Belgium	0.6	0.4	34.3	9.0	1.7	0.7	0.7	0.3	22.5	13.5
Brazil	1.1	1.0	5.0	2.2	0.5	0.1	0.3	0.2	3.0	1.2
Canada	1.0	1.0	32.8	8.7	1.9	1.1	2.2	0.5	3.9	2.7
China	1.7	0.7	1.9	1.0	0.7	0.2	1.9	1.6	3.7	0.6
Czech Republic	0.8	0.7	12.5	5.6	1.8	0.8	0.2	0.1	6.6	2.9
Denmark	2.1	7.1	45.1	11.6	2.8	0.5	1.2	0.5	4.3	6.4
Finland	0.7	0.8	36.2	9.9	2.4	0.7	0.9	0.3	4.7	3.6
France	0.6	0.4	32.5	8.0	2.3	0.8	4.9	2.3	2.8	0.9
Germany	0.4	0.4	33.1	7.5	2.6	0.4	15.6	4.4	3.0	3.3
Greece	0.6	0.7	20.7	7.0	1.8	0.2	0.1	0.1	0.6	0.6
Hungary	0.8	0.9	9.5	3.7	2.0	0.7	0.2	0.1	15.6	17.1
Ireland	1.3	2.0	43.6	12.9	1.5	0.5	0.2	0.1	15.4	9.0
Italy	0.6	0.6	29.5	7.1	1.9	0.6	1.9	0.9	1.4	0.9
Japan	1.9	4.7	35.2	2.3	1.7	0.1	18.0	9.5	0.2	0.2
Netherlands	1.9	4.9	39.0	10.6	2.3	0.7	1.8	0.7	24.3	23.6
Poland	0.6	0.4	7.7	3.1	1.7	0.7	0.1	0.1	4.0	1.4
Portugal	0.6	0.5	17.4	4.7	2.0	0.5	0.1	0.1	3.2	2.2
Slovakia	1.9	1.3	10.8	4.6	1.4	0.5	0.0	0.0	5.6	3.1
South Korea	0.7	0.7	16.2	4.2	2.2	1.0	3.1	2.3	1.3	0.5
Spain	0.8	1.0	24.1	7.3	2.5	0.4	1.1	0.7	3.7	1.7
Sweden	0.7	0.8	40.0	9.6	2.5	0.5	1.7	0.5	7.5	5.5
Turkey	1.6	1.0	6.2	2.4	1.0	0.4	0.1	0.1	1.5	1.2
United Kingdom	0.7	1.5	35.5	7.7	1.7	0.6	3.9	1.1	5.9	3.1
United States	1.0	1.4	42.0	4.8	1.7	0.6	26.3	8.1	1.9	0.8
All Countries	*1.0*	*2.2*	*26.0*	*15.2*	*1.9*	*0.8*	*3.4*	*6.9*	*5.9*	*9.4*

Notes: Capital-labor ratio is defined as the value of compensation to capital over the value of compensation to labor, calculated at the industry-level; all other variables are defined at the country-level. GDP per capita is in thousands of dollars.

Estimates Based on Fixed Import and Export Orientation

Table A3 presents estimates of Equation (1) in which we fix the values of IIO, IEO, and FEO at their start-of-sample (1999) values in order to address potential simultaneity between REER and trade orientation; results are shown in columns 2, 4, and 6. That is, because the level of trade depends on exchange rates, we seek to isolate the effects of REER from any potential impacts of changes in REER on the trade orientation measures. For comparison, we reproduce the results for our baseline specification from columns 2, 4, and 6 of Table 4. Because of our inclusion of country-industry fixed effects, the main effects of IIO, IEO, and FEO cannot be estimated and are thus omitted in this version. The results on the interaction effects are largely preserved, which we take as evidence that simultaneity in the REER and trade orientation measures does not significantly affect our estimates of the impacts of REER.

Table A3: Impacts of REER and Trade Orientation on Industry-Level Emission Intensities, Fixed Orientation Measures

	CO_2		SO_x		NO_x	
	(1)	(2)	(3)	(4)	(5)	(6)
	Baseline	Fixed IIO/EO	Baseline	Fixed IIO/EO	Baseline	Fixed IIO/EO
REER	0.089[b]	0.068	0.094	0.069	–0.078	–0.097
	(0.044)	(0.045)	(0.127)	(0.115)	(0.115)	(0.107)
IIO	6.189[a]		13.665[a]		6.819[a]	
	(0.677)		(2.097)		(1.344)	
REER × IIO	–1.380[a]	–1.760[a]	–3.121[a]	–4.222[a]	–1.553[a]	–2.195[a]
	(0.152)	(0.205)	(0.468)	(0.555)	(0.299)	(0.381)
IEO	2.947[a]		4.897[a]		3.807[a]	
	(0.417)		(1.260)		(0.854)	
REER × IEO	–0.677[a]	–0.554[a]	–1.192[a]	–0.838[a]	–0.929[a]	–0.682[a]
	(0.091)	(0.101)	(0.279)	(0.319)	(0.187)	(0.214)
FEO	–8.195[a]		–18.004[a]		–13.287[a]	
	(0.611)		(1.284)		(0.895)	
REER × FEO	1.828[a]	2.047[a]	4.054[a]		2.998[a]	3.361[a]
	(0.136)	(0.148)	(0.282)		(0.199)	(0.223)
Other controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	4,558	4,558	4,558	4,558	4,558	4,558
R^2	0.948	0.947	0.887	0.886	0.937	0.936

Notes: Dependent variables are the (log) industry-level emission intensities for the indicated pollutants. Each specification includes country-industry and year fixed effects as well as country-specific time trends. "Other controls" includes capital-labor ratio, GDP per capita, policy stringency, environmental patents, and FDI inflows. Robust standard errors clustered by country-year are reported in parentheses. a: $p < 0.01$, b: $p < 0.05$.

Effects of Other Controls on Emission Intensity

Table A4 presents the results on the "other controls" in Table 4 (the results for the REER and trade orientation variables are suppressed here for brevity). The results on these variables are largely insignificant, with some exceptions. The capital/labor ratio reflects that emission intensity is decreasing in an industry's capital intensiveness, which accords with findings from the literature on the relationship between capital intensity and an industry's cleanliness. Higher levels of innovation in environmental technology creation (as measured by environment-related patent applications) are associated with lower NO_x emission intensities, suggesting that the development of new environmental technologies reduces emissions of this particular pollutant. FDI inflows are estimated to be positively correlated with NO_x intensities, which conceivably reflects pollution offshoring effects.

Table A4: Impacts of REER and Trade Orientation on Industry-Level Emission Intensities

	CO_2		**SO_x**		**NO_x**	
	(1)	(2)	(3)	(4)	(5)	(6)
	Direct Effects	Baseline	Direct Effects	Baseline	Direct Effects	Baseline
K/L	–0.139[a]	–0.152[a]	–0.112[b]	–0.142[a]	–0.256[a]	–0.265[a]
	(0.029)	(0.029)	(0.049)	(0.052)	(0.068)	(0.067)
GDP per capita	–0.076[b]	–0.099[a]	–0.166	–0.215[b]	–0.197[b]	–0.227[b]
	(0.035)	(0.034)	(0.097)	(0.100)	(0.088)	(0.089)
Policy stringency	0.002	0.005	0.003	0.007	0.014[b]	0.015[b]
	(0.003)	(0.003)	(0.008)	(0.009)	(0.007)	(0.007)
Env. patents	–0.003	–0.003	0.001	0.002	–0.017[b]	–0.018[b]
	(0.003)	(0.003)	(0.011)	(0.012)	(0.008)	(0.009)
FDI inflows	–0.001	–0.001	0.036	0.037	0.062[a]	0.062[a]
	(0.007)	(0.007)	(0.024)	(0.027)	(0.020)	(0.021)
Observations	4,558	4,558	4,558	4,558	4,558	4,558
R^2	0.940	0.948	0.879	0.887	0.931	0.937

Notes: Dependent variables are the (log) industry-level emission intensities for the indicated pollutants. GDP per capita and Env. patents are expressed in logs. Each specification includes country-industry and year fixed effects as well as country-specific time trends. Robust standard errors clustered by country-year are reported in parentheses. a: $p < 0.01$, b: $p < 0.05$.

REER-in-Tasks and Emission Intensity

As described in the main text, the baseline measure of REER does not explicitly account for the prices associated with trade in intermediate inputs, which are a fundamental element of GVCs. To address this limitation, we additionally consider the alternative real exchange rate measures proposed by Bayoumi et al. (2013), who define a "REER-in-tasks" that measures REER in terms of the intermediate inputs and services (tasks) that a country transacts with foreign partners, taking input-output linkages between countries and sectors into explicit account. While for most countries and currencies, values of this and the standard REER-in-goods measure used earlier are typically very close to one another, differences do arise, particularly for emerging economies in which the relative price of tasks is sensitive to changes in domestic factor prices (for labor in particular) which account for a comparatively large share of the costs of performing intermediate tasks.

Table A5: Results for REER in Tasks

	(1) CO_2	(2) SO_x	(3) NO_x
REER-in-tasks	–0.051	–0.130	–0.238^b
	(0.050)	(0.128)	(0.113)
IIO	3.642^a	4.534^b	2.183
	(0.878)	(1.854)	(1.208)
REER-in-tasks × IIO	–0.805^a	–1.083^a	–0.523^b
	(0.192)	(0.400)	(0.259)
IEO	2.027^a	6.173^a	4.468^a
	(0.404)	(1.218)	(0.713)
REER-in-tasks × IEO	–0.469^a	–1.460^a	–1.065^a
	(0.088)	(0.269)	(0.155)
FEO	–6.984^a	–14.304^a	–10.817^a
	(0.569)	(1.239)	(0.987)
REER-in-tasks × FEO	1.529^a	3.177^a	2.401^a
	(0.123)	(0.265)	(0.214)
Other controls	Yes	Yes	Yes
Observations	4,382	4,382	4,382
R^2	0.946	0.882	0.933

Notes: Dependent variables are the (log) industry-level emission intensities for the indicated pollutants. REER-in-tasks is the real effective exchange rate in tasks from Bayoumi et al. (2013). Each specification includes country-industry and year fixed effects as well as country-specific time trends. "Other controls" includes capital-labor ratio, GDP per capita, policy stringency, environmental patents, and FDI inflows. Robust standard errors clustered by country-year reported in parentheses. a: $p < 0.01$, b: $p < 0.05$.

Table A5 presents the results using the alternative REER-in-tasks measure. The results are qualitatively similar to the results from the baseline results columns in columns 2, 5, and 8 from Table 4, with only slight differences in estimated magnitudes.[18]

[18] The number of observations differs between Tables 4 and A5 because the alternative REER measures of Bayoumi et al. are not calculated for the Czech Republic.