Gutenberg School of Management and Economics

& Research Unit “Interdisciplinary Public Policy”

Discussion Paper Series

The Effect of Offshoring on Firm Emissions

Yen Nhi Nguyen

October 2, 2023

Discussion paper number 2315

Johannes Gutenberg University Mainz
Gutenberg School of Management and Economics
Jakob-Welder-Weg 9
55128 Mainz
Germany
https://wiwi.uni-mainz.de/

Contact details

Yen Nhi Nguyen
Chair of International Finance
Johannes-Gutenberg-Universität
Johannes-von-Müller-Weg 2
55128 Mainz
Germany
ngyennhi@uni-mainz.de

The Effect of Offshoring on Firm Emissions*

Yen Nhi Nguyen†
Johannes Gutenberg University Mainz

October 2, 2023

Click for the latest version

Abstract

This paper analyses the effect of unilateral environmental policies on global emissions under trade in intermediate inputs. I develop a model of heterogeneous firms with two countries (North-South) in which North firms can invest in abatement activities but also offshore the pollution-intensive part of the production in South. The model suggests that a unilateral increase in North emission tax promotes more abatement activities of the least productive firms while the most productive firms stop investing in abatement and offshore polluting production steps. Marginal increases in North emission tax decrease global emissions when the relative emission tax is low but increase global emissions when it is high. Tests using German firm-level data support the central prediction of the model: offshoring activities reduce firms' domestic emission intensity, particularly when firms offshore in countries with lax environmental regulations.

Keywords: Environmental Regulation, Carbon Leakage, Unilateral Policy, Heterogeneous Firms, Global Sourcing, Multinational Firms.
JEL Classification: F10, F14, F18, F23, Q52, Q54, Q56

*I would like to thank my supervisor, Prof. Philip Sauré, for his guidance, advice and support. I also thank Philipp Herkenhoff, Leandro Navarro and all seminar/conference participants at the Johannes Gutenberg University Mainz, European Public Choice Society and European Trade Study Group for their valuable feedback and discussion.

†Email: ngyennhi@uni-mainz.de.

1 Introduction

Climate change is one of the greatest threats to humanity today.[1] Despite growing awareness of its consequences, countries differ significantly in designing and implementing their environmental policies (Ben-David et al. 2021). These variations can lead to the phenomenon of emission leakage: countries with strict environmental policies reduce domestically produced emissions but increase the import of pollution-intensive goods from countries with lax environmental policies. Consequently, the total emissions embodied in their consumed goods do not necessarily decrease. The emission leakage can lower the effect of environmental policies in reducing global emissions.[2]

In this paper, I examine the mechanism of emission leakage under offshoring both theoretically and empirically. In the theoretical part, I develop a heterogeneous firm model with two countries in which a higher emission tax in one country (North) can lead to emission leakage through offshoring an intermediate input - a pollution-intensive part of the production. I adopt Antràs & Helpman (2004) but introduce emission tax instead of wage differential as an incentive for firms to offshore. Firms in North can reduce their domestically produced emissions by investing in abatement but also by offshoring the intermediate input in South. To offshore in a foreign country, however, firms have to pay an additional fixed cost. In equilibrium, the most productive firms offshore while the least productive firms produce the intermediate input domestically and invest in abatement. Increasing emission tax in North generates three groups of firms in the market, including abatement firms, new offshoring firms and firms that have already offshored. The effects of the tax change on these groups are different. The higher emission tax in North creates more incentive for abatement firms to invest in abatement activities. Their emission intensities decline, along with their outputs, leading to unambiguous reductions in their emissions. The second group contains firms that switch from investing in abatement to offshoring as the cost of abatement becomes more expensive. The new offshoring firms increase their emission intensities as they face a lower emission cost in South, along with their output increases. Consequently, their global emissions grow. The policy in North has no effect on the emission intensity of firms that have already offshored before because they are no longer subjected to North emission tax. Their total emissions, however, increase due to increased outputs. Overall, the global emission reduces only if the reduction in abatement firms' emissions dominates emission increases from the other two groups. My model suggests a

[1]IPCC (2022, p.55) reports that "Without urgent and ambitious emissions reductions, more terrestrial, marine and freshwater species and ecosystems will face conditions that approach or exceed the limits of their historical experience... Warming pathways that imply a temporary temperature increase over "well below 2°C above pre-industrial" for multi-decadal time spans imply severe risks and irreversible impacts in many natural and human systems ... even if the temperature goals are reached later."

[2]For example, Kyoto has faced criticisms for setting different responsibilities across countries on reducing emissions (See, e.g., Barrett 1998, Nordhaus 2015). The focus of the Kyoto Protocol is on industrialized economies, arguing that these countries should take more responsibility for the current climate change (Gupta 2016). Therefore, the protocol only sets binding emission reductions for developed countries, while developing countries are only encouraged to take action but are not required to make any commitment (UNFCCC 1998). Aichele & Felbermayr (2012, 2015) provide empirical evidence of carbon leakage that happens because of the exclusion of developing countries from committing to emission reduction targets.

U-shaped relationship between the global emission and North emission tax (relative to South emission tax), indicating that a marginal increase in North emission tax decreases the global emission at low relative tax levels but increases the global emission at high relative tax levels.

Empirically, I utilize German firm-level data in 2013 provided by the German Federal Statistical Office and the Statistical Offices of the Länder to test the central prediction of the model: firms engaging in offshoring activities should have lower domestic emission intensities as they shift the pollution-intensive part of the production to foreign countries.[3] The firm trade data provides disaggregated information at the country level, which allows for the consideration of heterogeneity across firms' trading countries with respect to their environmental policies. The empirical evidence supports the model's prediction: controlling for firms' sizes, firms that offshore more have lower levels of domestic emission intensity. More importantly, the negative effect of offshoring on firms' domestic emission intensity becomes more pronounced when firms trade with countries that have lax environmental policies.

My paper also suggests that theoretical models that do not consider the offshoring possibility might lead to an incorrect assessment of the trade-induced technique effect even when the effect is measured at the firm level.[4] The reductions in firms' emission intensities may not result from firms' investments in energy efficiency and abatement but because of their decision to offshore the pollution-intensive part of the production. Although both strategies could reduce firms' emission intensities, their effects on the global environment are different. While energy-efficiency and abatement investments could decrease global emissions by making firms cleaner, offshoring does not reduce firm emissions but rather shifts the pollution incident to foreign countries. My model shows that moving from autarky to trade in intermediate input reduces the domestic emission intensities of the most productive firms. However, these reductions do not result from investing more in abatement activities but from offshoring the pollution-intensive step of the production in South. Their global emission intensities increase because of lower emission tax in South. While the offshoring firms' emissions generated in North reduce, their global emissions grow, leading to an increase in the total global emission.

The phenomenon of leakage has received attention from numerous researchers, with the main focus being carbon leakage.[5] This phenomenon occurs mainly through three channels (Copeland et al. 2021).[6] The scope of this paper is limited to the competitiveness channel that

[3] The results for a longer period of the data will be updated later.

[4] Introduced by Grossman & Krueger (1993) and Copeland & Taylor (1994), changes in aggregate emissions are decomposed into three components at the industry level, namely scale, composition and technique effect. The scale effect captures the change in aggregate emissions due to the change in a country's level of production, holding the country's composition of industry and the production technique constant. The composition effect represents the change in emissions resulting from changing the share of goods from dirty industries in the national output. The last term - the technique effect captures the change in aggregate emissions due to the change in the emission generated per unit of output (emission intensity). Cherniwchan et al. (2017) point out that besides the pure changes in the firm-level technique effect, changes in the industry-level technique effect might result from firms' decision to entry and exit (selection effect) and the reallocation of the market share across firms. When firms are identical, the technique effect measured at the industry level and firm level are the same. However, when considering firm heterogeneity, the other effects may differ from zero, potentially resulting in an overstated technique effect at the industry level.

[5] Therefore, from now on, I only focus on carbon leakage.

[6] The first channel is the competitiveness channel: a stricter environmental policy raises the cost of producing

is closely linked to two hypotheses, including the pollution haven hypothesis (PHH) and the pollution offshoring hypothesis (POH). The first hypothesis (PHH) states that international trade or unilateral environmental policies can lead to a shift of pollution-intensive industries from countries with more stringent environmental regulations to those with lax regulations. However, PHH has received little empirical support.[7] The second hypothesis (POH) moves the focus on the fragmentation of production. Instead of closing down production entirely and reallocating the whole industry to foreign countries as suggested by PHH, firms can move only the pollution-intensive part of the production abroad. Compared to PHH, the literature on POH is very limited in both theory and empirics.

Most relevant to my work is the branch of the literature on POH. Although POH has received growing attention, research on this topic remains limited. Bolz et al. (2023) is the theoretical paper that is closest to my model. While my paper's framework is in line with Antràs & Helpman (2004), Bolz et al. (2023) follow Egger et al. (2015) to develop a general equilibrium model of offshoring. Aligning with my model results, they find that a unilateral increase in the home country's emission tax decreases the emission generated domestically but increases the foreign emission due to firms' offshoring activities, leading to ambiguous changes in global emissions. Compared to Bolz et al. (2023), my paper emphasizes more on the heterogeneous responses of firms to a new environmental policy. Besides, my paper provides empirical evidence from German firm data supporting the central predictions of the model that firms engaging in offshoring have lower domestic emission intensities. Cole et al. (2014) introduce the heterogeneous-firm model that examines a firm's decision between investing in abatement and offshoring. Their findings suggest that the more productive firms are more likely to offshore to avoid paying the abatement cost. Additionally, shocks including more stringent environmental regulations, wage increases at Home and reductions in transport costs increase the possibility of firms choosing offshore. Their model, however, is simple as it focuses solely

pollution-intensive goods in the home country, leading to a reallocation of these industries or part of the production to foreign countries with lower pollution costs. The second and third channels are related to the fossil fuel market. An increase in carbon price can reduce the demand for fossil fuels in countries that implement strict policies and, therefore, could lower the world market price. This, hence, will increase the consumption of fossil fuels in other countries that have weak environmental policies (the second channel). The third channel relates to the effect of policies that restrict the fossil fuel supply. These policies potentially push up the fossil fuel price, leading to an increase in extraction in other countries.

[7] One approach to examining the existence of PHH is measuring the three effects introduced by Grossman & Krueger (1993) and Copeland & Taylor (1994). According to PHH, the composition effect should have a significant role in aggregate emission changes. However, many papers following the industry-level decomposition find that the composition effect is much smaller compared to the technique effect. For example, Antweiler et al. (2001) use the data covering forty developed and developing countries to estimate the three effects and find that international trade has a small effect on sulfur dioxide (SO_2) concentrations via changing the output composition. Cole & Elliott (2003) examine Antweiler et al. (2001)'s finding for four common pollutants including SO_2, nitrogen oxides (NO_x), carbon dioxide (CO_2) and biochemical oxygen demand (BOD) and find similar evidence. Using a different approach to estimate these effects, Levinson (2009) shows that the substantial reduction in the air pollution generated by US manufacturing from 1987 to 2001 is largely attributed to the technique effect while the composition effect accounts for a much smaller share of the reduction. Following Levinson (2009), Brunel (2017) examines the case of the EU and finds a quite similar conclusion that the technique effect is the main reason for the EU cleanup. Surprisingly, EU production moved toward pollution-intensive goods and the imports from the countries with lax environmental regulations became cleaner during the examined period.

on analyzing the offshoring decision of firms and ignores the impacts of trade liberalization such as the selection effect and the reallocation effect. There are a few other theoretical papers that focus on the interaction between global sourcing and the environment; nevertheless, these models are very different from mine.[8] Similar to the theoretical literature, empirical research on POH is still relatively scarce.[9] Michel (2013) shows that a change in emission intensity is the main reason for the emission reduction from domestic intermediates in Belgium during 1995-2007. The author further decomposes this effect into four components, including technique effect, efficiency effect, industry composition effect and offshoring effect. By estimating the role of these effects, the paper finds that importing foreign intermediates to replace domestic ones accounts for approximately 20 % of the fall in emission intensity. Using Japanese firm-level data from 2009 to 2013, Cole et al. (2017*b*) show that firms engaging in outsourcing activities experience lower growth in CO_2 emission intensities compared to the non-outsourcer group. Further, the paper distinguishes between domestic outsourcing and foreign outsourcing and finds that the effect on the emission intensity growth only appears for firms that outsource to foreign producers. Ben-David et al. (2021) examine whether firms with headquarters located in countries having stricter environmental policies will allocate polluting activities abroad. Using the data on multinational firms for the period 2008-2015, they obtain supportive evidence that stricter policies at home result in a reduction in domestic emissions and an increase in total foreign emissions. Exploring further the data on destination countries where firms pollute, they find that the larger the difference in the environmental policy stringencies between Home and Foreign, the more firms export their emission to this foreign country. My paper complements the literature by providing empirical evidence of POH from German firm data. The results suggest that offshoring activities reduce the domestic emission intensity of firms, especially when firms offshoring in countries with weak environmental regulations.

My paper connects to recent research on trade and environment based on Melitz (2003) model framework. Depart from the traditional literature following the industry-level decomposition, Kreickemeier & Richter (2014) derive the fourth channel through which trade could affect the environment, namely the reallocation effect. As in Melitz (2003), this paper shows that trade liberalization forces the least productive firms out of the market and reallocates resources towards the most productive ones. With the assumption that the more productive firm has lower emission intensity, even though there is no change in the emission intensity of individual firms, trade would reduce the sectoral emission intensity through an increase in aggregate productivity. Shapiro & Walker (2018) develop the multi-sector model following Melitz

[8] For example,Cherniwchan et al. (2017) present a simple theoretical model which assumes that intermediate inputs can be arranged in order of increasing pollution intensity. The model shows that there is a cut-off intermediate input such that all intermediates above this threshold are offshored in countries with lax environmental policies. Trade liberalization that decreases the cost of offshoring would increase the range of intermediates that are offshored. Schenker et al. (2018) develop a model of two production stages and two regions that differ in their environmental policy strictness. The equilibrium is characterized by two thresholds for two stages, with the upstream or downstream industries above the threshold will be moved to the unregulated region. The difference in the cut-off levels of downstream and upstream industries implies the presence of both pollution haven and pollution offshoring effects.

[9] See Cole et al. (2017*a*) and Copeland et al. (2021) for the review of some other research on POH that are not mentioned in this paper.

(2003) framework to identify the main drivers of the emission decline from US manufacturing during 1990-2008. In the spirit of Copeland & Taylor (2003), they assume that the production of goods generates pollution and firms can divert the production resource to abatement. They find that the more productive firms invest more in abatement, and therefore have lower emission intensity. The shocks such as pollution taxes, productivity improvements and liberalization lead to changes in firm entry, exit, production, abatement and export decisions, which affect the pollution intensity of sectors. Departing from the standard abatement technology that only considers variable abatement cost, Forslid et al. (2018) allow for the fixed cost element of abatement technologies. Examining the effects of trade on firm and global emissions, Forslid et al. (2018) find that trade liberalization has different effects on abatement decisions and emission levels of non-exporters and exporters. In the case of symmetric countries, the changes in emissions of two groups cancel out each other, leaving aggregate emissions unaffected by trade liberalization. In this paper, I focus on trade in intermediate input rather than trade in final goods. I incorporate the offshoring model with the abatement technology introduced by Copeland & Taylor (2003). My findings suggest different effects of emission tax changes on firms' choices and performances due to firm productivity heterogeneity. Overall, the effect of new policies on global emissions depends on the state of the (relative) emission tax before implementing the new changes.

My study also relates to the branch of literature on global sourcing with the closest setting being Antràs & Helpman (2004). In Antràs & Helpman (2004), firm heterogeneity in productivity leads to differences in their choice of ownership structures and supplier locations of intermediate inputs. To focus on the environmental aspect, my model only considers the location dimension for simplicity. Depart from Antràs & Helpman (2004), I introduces the role of the emission tax differential between two countries in determining the offshoring decision of firms. The paper provides an important implication of using environmental policies that widen the differences in environmental policy strictness across countries in reducing global emissions.

The remainder of this paper is structured as follows. In section 2, I develop the model of global sourcing to assess the effect of a unilateral environmental policy in reducing global emissions. Section 3 describes my empirical strategy and dataset. The main results are presented in section 4 and section 5 concludes.

2 Theoretical Framework

In this section, I develop a simple model of two countries (North and South) and one factor of production (labor). Emissions are generated through the production of the intermediate input that firms can choose to produce either domestically or offshore in South. The two countries impose different environmental policies and, therefore, differ in their cost of polluting. Firms can exploit the lower marginal cost of producing the intermediate input in South; however, they have to pay an additional fixed cost for offshoring. Keeping South emission tax unchanged, an increase in North emission tax will affect the decision of firms in the location of the intermediate input's production.

2.1 Setup of the model

2.1.1 Demand

The representative consumer in North has the Cobb-Douglas utility function as follows:

$$U = x_0^{1-\gamma} X^{\gamma}$$

where x_0 and X denote the consumption of homogeneous good and differentiated good, respectively. Assuming that the homogeneous good is costlessly tradable in the international market and the demand for this good is large enough so that it is produced in both countries. The consumer has C.E.S utility function over a continuum of varieties indexed by i within the differentiated good:

$$X = \left[\int_{i \in \Omega} x(i)^{\alpha} d_i \right]^{1/\alpha}$$

with $\alpha \in (0, 1)$ and Ω being the mass of varieties available. The elasticity of substitution between any two varieties in the differentiated sector is $\sigma = 1/(1 - \alpha)$. The price index of differentiated good is given by:

$$P = \left[\int_{i \in \Omega} p(i)^{1-\sigma} d_i \right]^{\frac{1}{1-\sigma}} \tag{1}$$

Solving the utility maximization problem of the representative consumer gives the optimal consumption for variety i as follows:

$$x(i) = \frac{p(i)^{-\sigma}}{P^{1-\sigma}} \gamma C$$

where C denotes aggregate expenditure.

2.1.2 Production

The homogeneous good is produced with a constant return to scale technology and under a perfect competition market. Assuming that to produce one unit of the homogeneous good, producers in North and South need one unit of labor, implying that wages are equal across countries.

The variety i is produced using two inputs that are the headquarter service h_i and the intermediate input m_i with the following technology:

$$x_i = \varphi_i \left(h_i\right)^{\lambda} \left(m_i\right)^{1-\lambda}$$

where φ_i is firm-specific productivity and $\lambda \in (0, 1)$ is a technology parameter that reflects headquarter intensity of production. Following Antràs & Helpman (2004), I assume that the headquarter service h_i can be performed only in North while the intermediate input m_i can be produced in both countries. Both inputs are produced by one unit of labor per unit of output. Firms must pay a fixed cost of entry f_E in units of northern labour to draw a productivity φ from a cumulative distribution $G(\varphi)$. After discovering the productivity, firms will decide immediately whether to exit the industry or start producing. If they stay in the market, they need to decide the location of the intermediate input's production. In every period, the active firms face a constant probability δ of an exogenous bad shock that would force firms out of the market.

Considering that producing the intermediate input generates emissions, then the production of the intermediate input produces two outputs: intermediate input (m_i) and emission (z_i tons). Emissions are subjected to emission tax t_d (per ton) where $d = \{N, S\}$. Following Shapiro & Walker (2018), revenues from emission tax are considered to be lost for rent-seeking. In line with Copeland & Taylor (2003), I assume that firms can divert an endogenous fraction a_i of labour used to produce the intermediate input to abate pollution. a_i can be interpreted as the firm's effort on abatement activity. The output of the intermediate input is therefore equal:

$$m_i = (1 - a_i)\, l_{m_i} \tag{2}$$

Assuming that emission is produced with the following technology:

$$z_i = f(a_i) l_{m_i} = (1 - a_i)^{1/\beta} l_{m_i} \tag{3}$$

with $0 \leq a \leq 1$, $0 < \beta < 1$, $f(1) = 0$ and $f(0) = 1$. $f(a_i)$ represents the abatement function that is characterized by diminishing marginal return of abatement. By plugging a_i from (3) into (2), the production function of the intermediate input can be described as the Cobb-Douglas with two inputs including emissions and labors: $m_i = z_i^{\beta} l_{mi}^{1-\beta}$. The production of variety i then is given as:

$$x_i = \varphi_i \; l_{hi}^{\lambda} l_{mi}^{1-\lambda-\eta} z_i^{\eta}$$

with $0 < \eta = \beta(1 - \lambda) < 1$. A higher η indicates a higher cost share for emissions, implying a dirtier industry. Firms can decide to produce all the stages of production at Home or offshore the pollution-intensive part in South where emission tax is lower: $t_S < t_N$. With the assumption that wages are equal in two countries, it can be considered that firms only offshore emissions when they choose to produce the intermediate input abroad. If firms offshore the intermediate input in South, they must pay a higher fixed cost of production: $f_S > f_N$. Firms face the optimization problem

$$\max_{l_h, l_m, z} \pi(\varphi) = p(\varphi)x(\varphi) - w\left(l_h(\varphi) + l_m(\varphi)\right) - t_d z(\varphi) - w f_d \tag{4}$$

Solving the producer's problem gives the optimal inputs that are:

$$l^*_{h,d}(\varphi) = \frac{\alpha\lambda}{w} r^*_d(\varphi), \quad l^*_{m,d}(\varphi) = \frac{\alpha(1 - \lambda - \eta)}{w} r^*_d(\varphi), \quad z^*_d(\varphi) = \frac{\alpha\eta}{t_d} r^*_d(\varphi) \tag{5}$$

where

$$r^*_d(\varphi) = \alpha^{\sigma-1}(\gamma C)^{\sigma} X^{1-\sigma}(c_d)^{1-\sigma}\varphi^{\sigma-1} \tag{6}$$

and

$$c_d = \frac{(t_d)^{\eta} w^{(1-\eta)}}{\eta^{\eta}(1-\lambda-\eta)^{(1-\lambda-\eta)}\lambda^{\lambda}}$$

The optimal output is therefore equal:

$$x^*_d(\varphi) = \alpha \ (c_d)^{-1} \ \varphi \ r^*_d(\varphi) \tag{7}$$

Consequently, the optimal price for a variety i which is produced by a firm with productivity φ is as follows:

$$p^*(\varphi) = \alpha^{-1} \ c_d \ \varphi^{-1} \tag{8}$$

Plugging $l^*_{h,d}(\varphi)$, $l^*_{m,d}(\varphi)$ and $z^*_d(\varphi)$ into equation (4) gets the optimal profit for a firm that produces variety i :

$$\pi^*_d(\varphi) = \frac{r^*_d(\varphi)}{\sigma} - w f_d \tag{9}$$

2.2 Non-tradable intermediate inputs

Equilibrium: Denote M is the number of active firms in equilibrium.[10] The aggregate price P defined in (1) can be written as:

$$P = M^{\frac{1}{1-\sigma}} p(\tilde{\varphi}_{non}) \tag{10}$$

where

$$\tilde{\varphi}_{non} = \left[\int_0^{\infty} \varphi^{\sigma-1}\mu(\varphi)d\varphi\right]^{\frac{1}{\sigma-1}} \tag{11}$$

is the weighted average of firm productivity levels. Assuming that the probability distribution is Pareto, that is

$$G(\varphi) = 1 - \left(\frac{b}{\varphi}\right)^k$$

where k is the shape parameter of the distribution. The scale parameter is normalized to unity, i.e., $b = 1$. The distribution of productivity levels in the market, therefore, is:

$$\mu(\varphi) = \begin{cases} \dfrac{g(\varphi)}{1-G(\varphi^*)} = k\dfrac{(\varphi^*)^k}{\varphi^{k+1}} & \text{if } \varphi \geq \varphi^* \qquad (12) \\ 0 & \text{otherwise,} \qquad (13) \end{cases}$$

with φ^* is the market entry productivity cutoff and $p_{in} \equiv 1 - G(\varphi^*)$ is the ex-ante probability of successful entry. Following Shapiro & Walker (2018), I assuming that $k > \sigma - 1$ so that the

[10] Assume that we are in an open economy for the intermediate inputs but a closed economy for final goods. So the number of active firms equals the number of varieties

firm's expected profit is finite. Denote the market entry productivity cutoff as φ^*_{non}, then:[11]

$$\tilde{\varphi}_{non} = \left[\frac{k}{k-(\sigma-1)}\right]^{\frac{1}{\sigma-1}} \varphi^*_{non}$$

Zero cutoff profit (ZCP) and free entry (FE) conditions give:

$$wf_N \frac{\sigma-1}{k-(\sigma-1)} = \delta w f_E \left(\varphi^*_{non}\right)^k$$

Therefore, the cutoff productivity is given by:

$$\varphi^*_{non} = \left[\frac{1}{\delta}\frac{f_N}{f_E}\frac{\sigma-1}{k-(\sigma-1)}\right]^{1/k}$$

The number of active firms equals:

$$M^*_{non} = \frac{\gamma C}{r(\tilde{\varphi}_{non})} = \frac{\gamma C}{\sigma w f_N}\frac{k-(\sigma-1)}{k}$$

Firm's Emission Intensity: From equations (3) and (5), I have:

$$a = 1 - \left(\frac{w}{t_N}\frac{\beta}{1-\beta}\right)^{\beta}$$

that increases in t_N, implying that an increase in North emission tax will increase the effort of firms on abatement in autarky. From equations (5), (6) and (7), the firm's emission intensity equals:

$$e^*_{non}(\varphi) = \frac{z^*_{non}(\varphi)}{x^*_{non}(\varphi)} = \varphi^{-1}\left(\frac{w}{t_N}\frac{\eta}{\Theta}\right)^{(1-\eta)}$$

where $\Theta = \left[(1-\lambda-\eta)^{(1-\lambda-\eta)}\lambda^{\lambda}\right]^{\frac{1}{1-\eta}}$. In autarky, the more productive firms have lower emission intensities because they are more efficient in using their inputs. An increase in North emission tax reduces firms' emission intensities as it increases the effort of firms on abatement to reduce production-generated emissions.

Firm's Emission Levels: From equation (5), firm emission is given by:

$$z^*_{non}(\varphi) = \frac{\alpha\eta}{t_N} r^*_{non}(\varphi)$$

The revenue of a firm that has productivity φ in autarky is

[11] see Appendix for the derivation of the model in more detail

$$r^*_{non}(\varphi) = \left(\frac{\varphi}{\varphi^*_{non}}\right)^{\sigma-1} r^*_{non}(\varphi^*_{non}) = \sigma w f_N \left\{ \frac{\varphi}{\left[\frac{1}{\delta}\frac{f_N}{f_E}\frac{\sigma-1}{k-(\sigma-1)}\right]^{1/k}} \right\}^{\sigma-1}$$

so

$$z^*_{non}(\varphi) = \alpha\eta\sigma f_N \frac{w}{t_N} \left\{ \frac{\varphi}{\left[\frac{1}{\delta}\frac{f_N}{f_E}\frac{\sigma-1}{k-(\sigma-1)}\right]^{1/k}} \right\}^{\sigma-1}$$

In autarky, although the more productive firms have lower emission intensities, they have higher emission levels due to their larger production scales. An increase in North emission tax will reduce firm emission levels since polluting becomes more expensive.

Aggregate Emission: The global emission will equal the total emission generated by active firms in North market:

$$E^*_{non} = \int_{i\in\Omega} z(i)^*_{non} di = \frac{\alpha\eta}{t_N}\gamma C$$

In autarky, an increase in North emission tax will reduce the aggregate emission as the emission levels of active firms in the market reduce.

2.3 Tradable intermediate inputs

Equilibrium: Denote $r^*_N(\varphi)$ ($r^*_S(\varphi)$) and $\pi^*_N(\varphi)$ ($\pi^*_S(\varphi)$) are revenue and profit of abatement (offshoring) firm, respectively. I define the offshoring premium in revenues as the difference between the revenue of the offshoring firm and the abatement firm that have the same productivity level:

$$r^{prem}(\varphi) \equiv r^*_S(\varphi) - r^*_N(\varphi) = r^*_N(\varphi)\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]$$

Equivalently, the offshoring premium in profits is given by:

$$\pi^{prem}(\varphi) \equiv \pi^*_S(\varphi) - \pi^*_N(\varphi) = \frac{r^*_N(\varphi)}{\sigma}\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right] - w(f_S - f_N)$$

Firms will choose to offshore the intermediate input in South if the offshoring premium in profits is positive. Denote φ^*_{NO} is the offshoring productivity cutoff and $\tilde{\varphi}_{NO}$ is the average productivity of firms doing offshoring:

$$\tilde{\varphi}_{NO} = \left(\frac{1}{1-G\left(\varphi^*_{NO}\right)}\int_{\varphi^*_{NO}}^{\infty}\varphi^{\sigma-1}g(\varphi)d\varphi\right)^{\frac{1}{\sigma-1}}$$

The share of offshoring firms is given by:

$$s = \frac{1 - G(\varphi^*_{NO})}{1 - G(\varphi^*_N)} = \left(\frac{\varphi^*_N}{\varphi^*_{NO}}\right)^k \tag{14}$$

In equilibrium, the market entry productivity cutoff is:

$$\varphi^*_N = \left[\frac{f_N + s(f_S - f_N)}{\delta f_E} \frac{\sigma - 1}{k - (\sigma - 1)}\right]^{1/k}$$

and the offshoring productivity cutoff equals[12]

$$\varphi^*_{NO} = \left[\frac{s^{-1} f_N + (f_S - f_N)}{\delta f_E} \frac{\sigma - 1}{k - (\sigma - 1)}\right]^{1/k}$$

It can be proved that an increase in North emission tax leads to a higher market entry productivity cutoff and a lower offshoring productivity cutoff, implying a higher share of offshoring firms.

The ratio of the cutoff productivity in autarky and in trade scenario equals:

$$\frac{\varphi^*_{non}}{\varphi^*_N} = \left(\frac{f_N}{f_N + s(f_S - f_N)}\right)^{1/k}$$

With the assumption $f_S > f_N$ and $s > 0$, then $\varphi^*_N > \varphi^*_{non}$. Trade in intermediate input forces the least productive firms out of the market. The number of active firm is given by:

$$M^* = \frac{\gamma C}{\sigma w \left[f_N + s\ (f_S - f_N)\right]} \frac{k - (\sigma - 1)}{k}$$

The number of active firms in the case of tradable inputs is smaller than that in the case of nontradable inputs as the possibility of offshoring intensifies competition in the final good markets. Under trade scenario, an increase in North emission tax reduces the number of firms surviving in the market.

2.4 Effect of trade in intermediate input

Firm's Emission Intensity: For abatement firms, the emission intensity remains unchanged and equal:

$$e^*_N(\varphi) = \frac{z^*_N(\varphi)}{x^*_N(\varphi)} = \varphi^{-1} \left(\frac{w}{t_N} \frac{\eta}{\Theta}\right)^{(1-\eta)} \tag{15}$$

When firms offshore the pollution-intensive part of the production, their emission intensity becomes zero as they no longer produce the intermediate input that generates emission. How-

[12] In this paper, I only consider the case where $\varphi^*_{NO} > \varphi^*_N$, meaning that not all firms in the market choose to offshore. The condition for this case is that $\frac{t_N}{t_S} < \left(\frac{f_S}{f_N}\right)^{\frac{1}{\eta(\sigma-1)}}$

ever, when considering the emission generated through the firm's import of the intermediate input as the firm's responsibility, the emission intensity of the offshoring firm will be:

$$e_S^*(\varphi) = \frac{z_S^*(\varphi)}{x_S^*(\varphi)} = \varphi^{-1}\left(\frac{w}{t_S}\frac{\eta}{\Theta}\right)^{(1-\eta)} \tag{16}$$

Since $t_S < t_N$, the emission intensity of firms that choose to offshore the intermediate input increases. The offshoring firms face a lower cost of polluting in South; therefore, they increase the emission generated to produce one unit of output.

Firm's Emission Level: The emission level of abatement firms equal

$$z_N^*(\varphi) = \frac{\alpha\eta}{t_N} r_N^*(\varphi) = \frac{\alpha\eta}{t_N}\sigma w f_N \left\{ \frac{\varphi}{\left[\frac{f_N + s(f_S - f_N)}{\delta f_E}\frac{\sigma-1}{k-(\sigma-1)}\right]^{1/k}} \right\}^{\sigma-1}$$

For offshoring firms:

$$z_S^*(\varphi) = \frac{\alpha\eta}{t_S} r_S^*(\varphi) = \frac{\alpha\eta}{t_S}\left(\frac{\varphi}{\varphi_{NO}^*}\right)^{\sigma-1}\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} \sigma w f_N s^{\frac{1-\sigma}{k}}$$

It can be proved that for abatement firms $r_N^*(\varphi) < r_{non}^*(\varphi)$ while for offshoring firms $r_S^*(\varphi) > r_{non}^*(\varphi)$ (see Appendix for proof). Moving from autarky to trade in intermediate input, therefore, decreases the emission levels of abatement firms but increases offshoring firms' emissions. The abatement firms reduce their emissions only because they contract their production scales. For the offshoring firms, they increase both their emission intensities and outputs; therefore, increasing their emission levels.

Aggregate Emission: The total emission in North is equal the total emission generated by abatement firms, so:

$$E_N^* = M^* \int_{\varphi_N^*}^{\varphi_{N0}^*} z_N^*(\varphi)\mu(\varphi)d\varphi = \frac{\alpha\eta}{t_N}\gamma C \frac{1 - s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}} \tag{17}$$

Trade in intermediate input leads to a change in North's total emission that equals:

$$\Delta E_N = E_N^* - E_{non}^* = \frac{\alpha\eta}{t_N}\gamma C \frac{-\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}$$

As $k > \sigma - 1$ and $0 < s < 1$, then $\Delta E_N < 0$

PROPOSITION 1: The total emission generated in North reduces when the country opens to trade in intermediate inputs.

The reduction in the North emission is driven by two reasons. First, openness to trade leads to a stronger competition in the final good market, forcing the least productive firms out of the market and reducing the number of active firms. Additionally, some of the active firms have moved their pollution-intensive part of the production abroad. Consequently, the number of polluters in North decreases. Second, trade reduces the output of abatement firms (see Appendix for the proof). As a result, the emission generated by each polluter in North declines.

The total emission in South that is generated because of North firms' import equals:

$$E_S^* = M^* \int_{\varphi_{N0}^*}^{\infty} z_S^*(\varphi)\mu(\varphi)d\varphi = \frac{\alpha\eta}{t_S}\gamma C \frac{\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}$$

The global emission is given by:

$$E_G^* = E_N^* + E_S^* = \frac{\alpha\eta}{t_N}\gamma C \frac{1 - s^{\frac{k-(\sigma-1)}{k}} + \frac{t_N}{t_S}\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}$$

The change in the global emission is, therefore, equal:

$$\Delta E_G = E_G^* - E_{non}^* = \frac{\alpha\eta}{t_N}\gamma C \frac{\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}} \left(\frac{t_N}{t_S} - 1\right)}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}$$

With an assumption that $t_N > t_S$ and $0 < s < 1$, $\Delta E_G > 0$.

PROPOSITION 2: Moving from autarky to trade in intermediate inputs increases the global emission. The emission reduction in North is not sufficient to offset the emission increase in South that results from offshoring activities of North firms.

2.5 Effect of an increase in North emission tax

I now investigate how a unilateral increase in North emission tax affects firms' and global emissions. As discussed in section 2.3, raising emission tax in North forces the least productive firms out of the market while encouraging the most productive firms in the abatement group to switch to offshore. Figure 1 illustrates the movement of the productivity cutoffs. Firms active in the market are categorized into three groups, including abatement firms, firms that switch from investing in abatement to offshoring and firms that have already offshored. It can be shown later that the effects of the new environmental policy in North on firm performances differ across three groups.

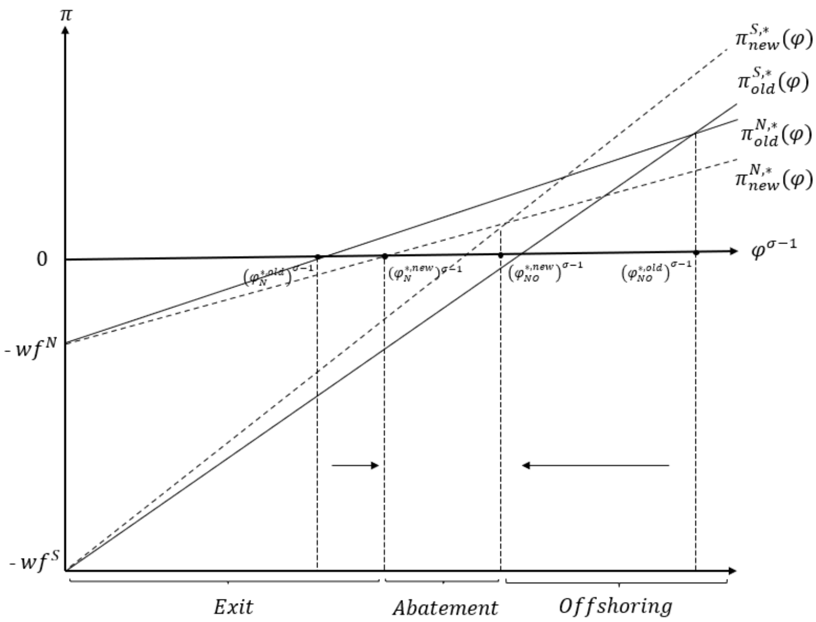

Figure 1: Equilibrium

Firm emission: From equation (15), the emission intensity of firms that choose to produce all stages at home and invest in abatement equals:

$$e^*_N(\varphi) = \varphi^{-1}\left(\frac{w}{t_N}\frac{\eta}{\Theta}\right)^{1-\eta}$$

Recall that

$$a = 1 - \left(\frac{w}{t_N}\frac{\beta}{1-\beta}\right)^{\beta}$$

An increase in North emission tax increases the effort of abatement firms on abatement activities as a polluting cost becomes more expensive, which leads to reductions in their emission intensities. Besides, abatement firms experience decreases in their outputs.[13] Since both emission intensities and outputs decrease, the emission levels of abatement firms also reduce.

Firms that have already offshored are no longer subject to North emission tax. As a result, the implementation of stricter environmental policies in North has no effect on their emission intensity. However, these firms experience increases in their emission levels due to the growth in their outputs. For firms that switch from abatement to offshoring, the ratio of the emission intensity is given by:

$$\frac{e^*_{new}(\varphi)}{e^*_{old}(\varphi)} = \left(\frac{t^N}{t^S}\right)^{1-\eta} > 1$$

implying increases in the emission intensities of switching firms. As firms face a lower cost of emissions in South, they use more emissions to produce each unit of output. Since outputs of switching firms also increase, their emission levels unambiguously increase.

[13]see Appendix for the detailed derivation of changes in firm output.

Aggregate Emission: From equation (17), the total emission in North equals:

$$E_N^* = M^* \int_{\varphi_N^*}^{\varphi_{N0}^*} z_N^*(\varphi)\mu(\varphi)d\varphi = \frac{\alpha\eta}{t_N}\gamma C \; \frac{1 - s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}$$

It can be proved that E_N^* decreases in t^N (see Appendix for proof), implying that an increase in North emission tax will lead to a decrease in the total emission generated within the border of the country. The North aggregate emission reduces because of the decrease in the mass of polluters in North as well as the emission levels of these firms.

PROPOSITION 3: A unilateral increase in North emission tax reduces the total emission generated within North border.

The global emission is given by:

$$\begin{aligned} E_G^* &= \int_{\varphi_N^*}^{\varphi_{N0}^*} e_N^*(\varphi)\ x_N^*(\varphi)\ \mu(\varphi)d\varphi + \int_{\varphi_{NO}^*}^{\infty} e_S^*(\varphi)\ x_S^*(\varphi)\ \mu(\varphi)d\varphi \\ &= \frac{\alpha\eta}{t_S}\gamma C \; \left(\frac{t_S}{t_N} \frac{1 - s^{\frac{k-(\sigma-1)}{k}} + \frac{t_N}{t_S}\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}} \right) \end{aligned}$$

How E_G^* changes in t_N depend on how the term in the bracket changes in $\frac{t_N}{t_S}$. I do not solve the model but use the numerical simulation to examine the movement of aggregate emission. Figure 2 shows the co-movement of the term inside the bracket and the relative emission tax under various parameter settings. As shown in the figure, there is a U-shape relationship between the global emission and North emission tax, implying that the aggregate emission at first falls with North emission tax but then increases once the relative tax level surpasses a certain threshold. The negative relationship in the left part of the U-curve is due to the dominant effect of abatement firms' emission reduction over the increase in emissions from the other two groups. However, when the relative emission tax is higher, more and more firms switch to offshore the intermediate input and therefore the effect from the abatement group becomes smaller. Once the threshold is reached, the positive effects from the groups of firms that switch to offshoring and firms that have already offshored dominate the negative effect from the abatement group, leading to an increase in global emissions.

PROPOSITION 4: A unilateral increase in North emission tax could increase the global emission when trade in intermediate inputs is feasible for firms.

Decomposition: Following Anouliès (2017), a change in the aggregate emission can be de-

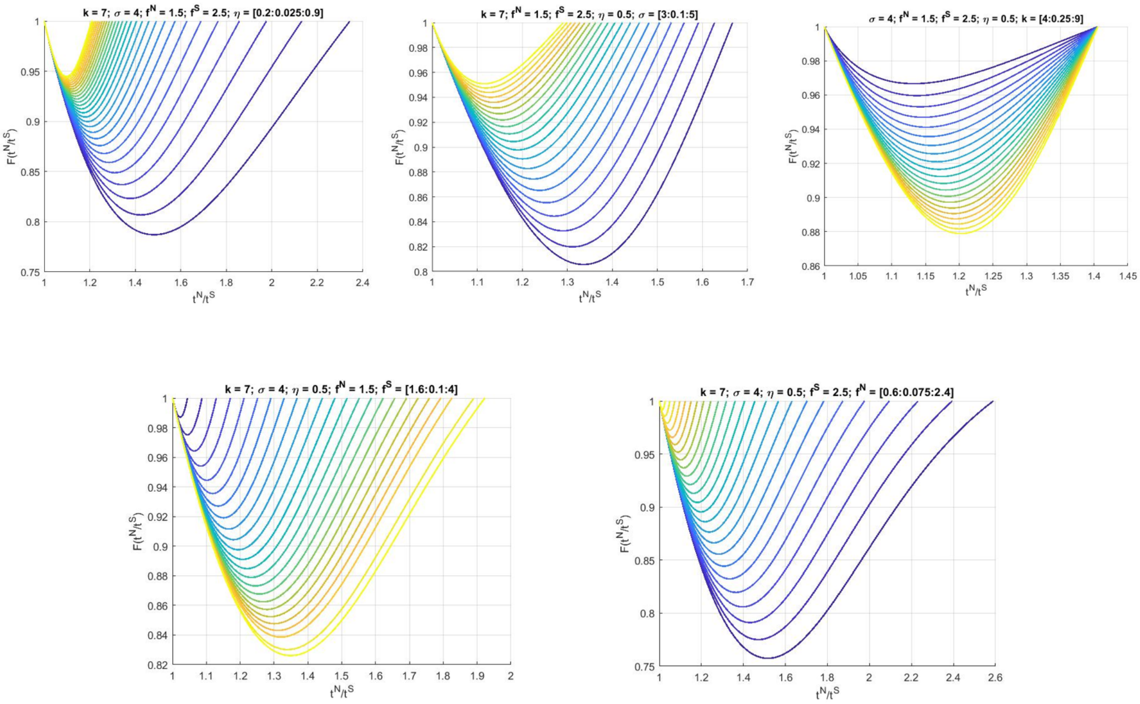

Figure 2: The relative emission tax and aggregate emissions

composed as follows:

$$
\begin{aligned}
\frac{dE^G}{dt^N} = \frac{dM^*}{dt^N} & \left(\int_{\varphi^*_N}^{\varphi^*_{N0}} e^{N,*}(\varphi)\ x^{N,*}(\varphi)\ \mu(\varphi) d\varphi + \int_{\varphi^*_{NO}}^{\infty} e^{S,*}(\varphi)\ x^{S,*}(\varphi)\ \mu(\varphi) d\varphi \right) \\
& - M^* e^{N,*}(\varphi^*_N)\ x^{N,*}(\varphi^*_N)\ \mu(\varphi^*_N) \frac{d\varphi^*_N}{dt^N} \\
& + M^* \left(\int_{\varphi^*_N}^{\varphi^*_{NO}} \frac{de^{N,*}(\varphi)}{dt^N}\ x^{N,*}(\varphi)\ \mu(\varphi) d\varphi + \int_{\varphi^*_{NO}}^{\infty} \frac{de^{S,*}(\varphi)}{dt^N}\ x^{S,*}(\varphi)\ \mu(\varphi) d\varphi \right) \\
& + M^* \left(\int_{\varphi^*_N}^{\varphi^*_{N0}} e^{N,*}(\varphi) \frac{dx^{N,*}(\varphi)}{dt^N}\ \mu(\varphi) d\varphi + \int_{\varphi^*_{NO}}^{\infty} e^{S,*}(\varphi) \frac{dx^{S,*}(\varphi)}{dt^N}\ \mu(\varphi) d\varphi \right) \\
& + M^* \left(\int_{\varphi^*_N}^{\varphi^*_{N0}} e^{N,*}(\varphi)\ x^{N,*}(\varphi)\ \frac{d\mu(\varphi)}{dt^N} d\varphi + \int_{\varphi^*_{NO}}^{\infty} e^{S,*}(\varphi)\ x^{S,*}(\varphi)\ \frac{d\mu(\varphi)}{dt^N} d\varphi \right) \\
& + M^* \left(e^{N,*}(\varphi^*_{NO})\ x^{N,*}(\varphi^*_{NO})\ \mu(\varphi^*_{NO}) - e^{S,*}(\varphi^*_{NO})\ x^{S,*}(\varphi^*_{NO})\ \mu(\varphi^*_{NO}) \right) \frac{d\varphi^*_{NO}}{dt^N}
\end{aligned}
$$

The first term in the equation reflects changes in the global emission resulting from changes in the mass of active firms, namely the scale effect at the extensive margin. The second term captures changes in emissions associated with the selection effect in the Melitz (2003) framework. As discussed in section 2.3, an increase in North emission tax reduces the number of active firms in the market and increases the entry productivity cutoff; therefore, these effects are negative, implying a reduction in the aggregate emission. The third term accounts for changes in the total emission due to changes in the emission intensity of firms (the technique effect). Since implementing a new environmental policy in North has no impact on the emission intensity of offshoring firms, the second component of the technique effect equals zero. The emission intensity of abatement firms decreases in North emission tax, making the first component of the technique effect negative and so implying a lower aggregate emission. The fourth term measures changes in the total emission resulting from changes in firm outputs (the scale effect at the intensive margin). As increasing North emission tax reduces the output of abatement firms but increases the output of offshoring firms (see Appendix for proof), the sign of the scale effect at the intensive margin is ambiguous. The fifth term corresponds to changes in aggregate emissions associated with a reallocation of resources among firms. Implementing a stricter environmental policy in North reallocates the resources in favor of the most productive firms (i.e. $d\mu(\varphi)/dt^N > 0$. See Appendix for proof), causing an increase in global emission.[14] The last term reflects changes in the total emission due to the offshoring selection effect. An increase in North emission tax encourages more firms to offshore to avoid the high cost of abatement at home, leading to an increase in the global emission as firms' demand for emission is higher when they offshore the intermediate input.

3 Empirical Strategy and Data

3.1 Empirical Strategy

The theoretical model suggests that at a given productivity level, firms engaging in offshoring activities should have lower domestic emission intensities as they shift the pollution-intensive part of the production to foreign countries. Besides, conditional on the offshoring status, the more productive firms should have lower emission intensities as they are more efficient in using production inputs. To test the predictions, I estimate the following regression equation:

$$ln\ e_{is} = \alpha_0 + \alpha_1\ ln\ mi_i + \alpha_2\ ln\ EPS\_\ m_i + \alpha_3\ ln\ \omega_i + \delta_s + \varepsilon_{is} \tag{18}$$

where e_{is} is either energy intensity or CO_2 emission intensity of firm i in sector s that is measured as the ratio of the energy consumption or CO_2 emission to firm's sales, respectively. mi_i denotes the firm's import intensity. To take into account the heterogeneity in the environmental policy stringency of firms' trading countries, I combine the disaggregated trade data from the "Micro Data Linking-Panel" (MDL) and the environmental policy stringency from the World Economic Forum (WEF) to compute variable $EPS\_\ m_i$ as:

$$EPS\_\ m_i = \sum_o mi_{io} * EPS_o$$

with EPS_o reflects the strictness of the environmental policies in country o where firm i import inputs. ω_i represents firm productivity. In this paper, I use firm size, measured as firm sales, as a proxy for productivity. A set of sector fixed effects are included to control for unobservable

[14]Note that although the more productive firms have lower emission intensities, they still pollute more due to their higher outputs.

characteristics at the sector. The sign of α_1 is predicted to be negative, implying that the offshoring firm has lower domestic emission intensity than the abatement firm that has the same productivity. The offshoring effect is expected to become larger when firms import inputs from countries with lax environmental regulations, resulting in the expected positive signs of α_2. Since larger firms are predicted to be more efficient in using inputs, α_3 should be negative.

3.2 Data and descriptive statistics

This paper employs the AFiD[15] data in 2013 provided by the German Federal Statistical Office and the Statistical Offices of the Länder. The data offers reliable and detailed information on plant-level energy consumption across different fuel types as well as various plant- and/or firm-level characteristics such as sales, production costs, and trade statistics. The project draws on four AFiD datasets including the "Unternehmensregister (URS)" (Firm Register), the "AFiD-Modul Energieverwendung" (AFiD Module Energy Use), the "AFiD-Panel Industrieunternehmen" (AFiD Panel Manufacturing Firms) and MDL. The URS data contains fundamental information about firms such as sales, sector and the location of the firm headquarters, along with information on the plants owned by firms.[16] The AFiD Energy-Use Module provides detailed data on the annual consumption of electricity and 9 different fuels[17] (measured in kWh) of plants with at least 20 employees in the manufacturing industry. To merge with other AFiD datasets, the plant-level energy usages are aggregated to firm-level.[18] I measure firms' energy intensity by dividing firms' total energy consumption by sales. Following Petrick et al. (2011), I combine data from AFiD Energy-Use Module with the fuel-specific emission factors to estimate the amount of CO_2 generated by firms' energy consumption.[19] I use this information to define firms' emission intensity as the ratio of firms' total emission to sales. The third data set, AFiD Panel Manufacturing Firms, provide another variable that measures firms' energy expenditure (in €) for all German manufacturing firms that have at least 20 employees. This information is utilized as an alternative approach for calculating firms' energy intensity.[20] The final AFiD dataset used in the paper is MDL data that offers unique information on the

[15]AFiD stands for Amtliche Firmendaten für Deutschland

[16]German firms in almost all economics sectors are included in URS. The following sectors are excluded from this data set: "Agriculture, forestry and fishing" (Section A), "Public administration and defence, compulsory social security" (Section O), "Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use" (Section T) and "Extraterritorial organisations and bodies" (Section U) of the WZ 2008.

[17]Nine different fuels include natural gas, light fuel oil, district heat, liquid gas, coal products, mineral oil products, other gases, renewable energy and waste and other fuels.

[18]It should be noted that some firms do not report all their plants in the AFiD Module Energy Use. Using the URS data to examine the "complete" status of the firms, I find that approximately 84% of firms in my main sample have all their plants covered in the AFiD Energy-Use Module. In the robustness check, I will limit the sample to only these complete firms.

[19]Most of the emission factors are obtained and calculated using the data from German Environmental Agency (German Environmental Agency 2022*a*,*b*). The emission factor of "District Heat" comes from von Graevenitz & Rottner (2020).

[20]In this paper, I measure energy intensity in two different ways. The first approach is dividing the physical quantities of energy uses by the total sales of firms. The second method calculates the energy intensity variable as the ratio of firms' energy expenditure to sales.

annual import and export of German firms for the period from 2009 to 2013. This data is exploited to calculate firms' import intensity and export intensity as the ratio of total import and total export to sales, respectively. In addition, the trade data is disaggregated by partner countries from 2011 to 2013. The disaggregated data enables the paper to take into account the heterogeneity in the environmental policy stringency of firms' trading partners.

For a measure of country-level environmental policy stringency, I use the dataset coming from the WEF. The WEF provides the environmental policy measure that is conducted based on the Executive Opinion Survey. The business leaders are asked to assess the stringency of environmental policies in their countries on the scale from 1 to 7 with a higher number indicating a stricter environmental policies.[21] Since the WEF stringency index is a survey-based indicator, it is determined solely by the perceptions of the respondents. However, Botta & Koźluk (2014) show high correlations between the WEF index and other policy-based measures such as OECD EPSI. The advantage of using the WEF data is its broad coverage of countries, with 140 countries in 2013.

After removing observations with missing main variables and dropping the ones with the total emission below 0.1 (ton) to delete obvious outliers, the dataset contains 15,337 firms. Table 1 presents an overview of the firm characteristics for the entire sample, as well as separately for offshoring and non-offshoring firms. Around 90% of firms in the main sample involve in offshoring activities. As illustrated in the table, offshoring firms are considerably larger in terms of sales and more engage in exporting activities compared to non-offshoring firms. Offshoring firms have, on average, the same emission intensity and even a higher energy intensity than non-offshoring firms, which contradicts the initial prediction. It should be noted, however, that the data sets are highly positively skewed and leptokurtic, especially in the case of the offshoring firm sample. To address this issue, a log transformation has been applied.[22]

4 Results

In Table 2, Columns (1) and (4) present the results of estimating equation (18). Since the estimated coefficients for the case of energy intensity and emission intensity are very similar, the focus in this section will be on the latter. The model predicts that a larger firm should have a lower emission intensity due to a higher production efficiency, which is supported by the negative and significant coefficient of $ln\ \omega_i$. After controlling for firm size, the coefficient of $ln\ mi_i$ is negative and highly significant, implying that a firm with a higher level of engagement in offshoring activities has a lower domestic emission intensity. Moreover, this effect is larger when firms import inputs from countries with lax environmental policies, as indicated by the positive estimate of α_2. The intuition behind this is the following. Firms can reduce their domestic emissions by moving the production of intermediate inputs that generate emissions

[21] In this paper, the variable was rescaled to a range of 0 to 1.

[22] To handle the existence of zero values when transforming into a logarithmic format, a very small value was added to the original value. I also use inverse hyperbolic sine transformation as an alternative way of log transformation in the robustness check.

Variable	(1) Mean	(2) Std. Dev.	(3) p1*	(4) p99*	(5) Skewness	(6) Kurtosis	(7) N
A. Full sample							
CO2 emission intensity (t/ €1000)	0.27	5.58	0.00	16.48	77.21	7142.33	15,337
Enegry intensity (kWh/ €1000)	848.85	19581.83	3.43	53770.30	77.23	6900.89	15,337
Sales (€1000)	103464.95	1.24e+06	706.08	5306015.00	43.05	2133.99	15,337
Export share of sales	0.27	1.33	0	4.16	62.53	4542.05	15,337
Import share of sales	0.12	1.67	0	4.06	76.33	6682.89	15,337
B. Offshoring firms							
CO2 emission intensity (t/ €1000)	0.27	5.80	0.00	16.40	76.03	6790.68	13,819
Enegry intensity (kWh/ €1000)	857.48	20402.37	4.30	54226.61	75.49	6494.81	13,819
Sales (€1000)	110255.54	1.29e+06	927.58	5565031.00	42.05	2018.93	13,819
Export share of sales	0.29	1.40	0	4.50	59.68	4122.40	13,819
Import share of sales	0.14	1.76	0.00	4.43	72.50	6026.32	13,819
C. Non-Offshoring firms							
CO2 emission intensity (t/ €1000)	0.27	2.91	0.00	16.22	22.47	549.68	1,518
Enegry intensity (kWh/ €1000)	770.25	9211.30	1.00	46843.64	29.10	954.84	1,518
Sales (€1000)	41647.34	639468.29	178.50	2670063.00	36.38	1380.53	1,518
Export share of sales	0.03	0.11	0	0.81	6.34	59.74	1,518

Note : p1 and p99 cannot be obtained due to data privacy concerns. The reported numbers represent the mean of all observations with values below the 1% (for p1) or above the 99% (for p99) percentile in any of the variables

Source: Research Data Centres of the Federal Statistical Office and the Statistical Offices of the Länder, 2013; own calculations

Table 1: Descriptive statistics.

to other countries, which potentially lowers their domestic emission intensities. The weaker the environmental policies of the trading partner country, the lower the cost of offshoring pollution-intensive inputs and therefore the higher degree of emissions shifted to these countries.

In Columns (2) and (5), I include control variables for firms' exporting activities, specifically export intensity x_i and variable EPS_x_i that accounts for the heterogeneity in environmental policy stringency across destination countries.[23] The results in these two columns demonstrate that adding the export variables does not alter the sign or significance levels of the three main variables of interest. The positive coefficients of $ln\ x_i$ suggest that exporting firms tend to have higher emission intensities than non-exporting firms. This finding contradicts the existing research that supports the idea of emission productivity enhancement resulting from exporting activities (e.g., Richter & Schiersch 2017, Forslid et al. 2018). One potential explanation for this result is that, even though I control for sector fixed effects at the three-digit level, exporting firms within the same sector may produce more pollution-intensive products compared to non-exporting firms. Additionally, the estimated coefficients of the export intensity variable are not highly significant in the case of emission intensity or even insignificant in the case of energy intensity. The estimated coefficients of $ln\ EPSI\_x_i$ are negative, implying that the positive effect of exporting on emission intensity weakens when firms export to countries with stricter environmental policies. Potentially, stricter environmental policies could reflect greater consumer awareness and concern about environmental issues in destination countries, which motivates exporting firms to adopt environmentally friendly technology, and therefore, reduce their emission intensities. In columns (3) and (6), a new variable that measures the environmental policy stringency of the countries where firms' headquarters are located, $EPSI\_HQ$, is

[23] Variable EPS_x_i is defined as follows: $EPS\_x_i = \sum_d xi_{id} * EPS_d$, while d denotes the destination country where firm i export to and EPS_d reflects the stringency of the environmental regulations in country d.

	Energy Intensity			*Emission Intensity*		
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
$ln\ mi_i$	-0.3994***	-0.4251***	-0.4349***	-0.4219***	-0.4524***	-0.4611***
	(0.0457)	(0.0485)	(0.0687)	(0.0434)	(0.0461)	(0.0654)
$ln\ EPS\_m_i$	0.3995***	0.4254***	0.4366***	0.4219***	0.4527***	0.4624***
	(0.0454)	(0.0483)	(0.0682)	(0.0431)	(0.0459)	(0.0649)
$ln\ \omega_i$	-0.0736***	-0.0723***	-0.0994***	-0.0719***	-0.0702***	-0.0982***
	(0.0067)	(0.0068)	(0.0086)	(0.0064)	(0.0064)	(0.0082)
$ln\ xi_i$		0.0843	0.1617**		0.0902*	0.1473**
		(0.0551)	(0.0783)		(0.0524)	(0.0745)
$ln\ EPS\_x_i$		-0.0833	-0.1619**		-0.0895*	-0.1480**
		(0.0542)	(0.0769)		(0.0515)	(0.0732)
EPS_HQ			-1.3984***			-1.2999***
			(0.1452)			(0.1382)
R2	0.0096	0.0098	0.0239	0.0107	0.0110	0.0250
Observations	15,337	15,337	9,495	15,337	15,337	9,495

Sector FEs are included in all regressions. Robust standard errors in parentheses.
***,**,*: statistical significance at the 1%, 5% and 10% level, respectively

Table 2: Main results.

introduced. Due to data availability, approximately 40% of observations are dropped from the analysis. Similar to the main regression, the estimates of α_1 and α_3 remain negative while the estimate of α_2 is positive, providing support for the model's prediction. All three coefficients are highly significant at the 1 % level. Although the inclusion of $EPSI\_HQ$ does not affect the signs of the export variables, the significance levels of these variables are improved. The coefficients of $EPSI\_HQ$ are negative and highly significant, indicating that firms whose headquarters are located in countries with more stringent environmental policies tend to have lower emission intensities.

So far, I have ignored the fact that not all firms in the main sample report energy consumption data for all their plants in the AFiD Module Energy Use. To address this issue, I conducted a robustness check by only including firms that completely reported their energy consumption. The results when emission intensity is the dependent variable are presented in the first three columns of Table 3. For the case of energy intensity, the estimated coefficients are very similar and shown in Appendix. Compared to the main results, the magnitude, sign, and significant level of the estimated coefficients of all variables are almost unchanged when the sample is limited. Additionally, I conducted the estimation of equation (18) using the sample with the restriction that energy expenditure share is smaller than 1, aiming to further eliminate potential outliers. The estimated results are shown in the last three columns of Table 3. Dropping observations with energy expenditure share greater than 1 does not affect the sign and the significance of the main three variables as well as $EPSI\_HQ$'s coefficients as indicated

	Emission Intensity					
	Complete firms			*Expenditure share < 1*		
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
$ln\ mi_i$	-0.3988***	-0.4294***	-0.4481***	-0.3491***	-0.3646***	-0.3454***
	(0.0459)	(0.0484)	(0.0694)	(0.0420)	(0.0446)	(0.0626)
$ln\ EPSI\_m_i$	0.3994***	0.4305***	0.4509***	0.3488***	0.3643***	0.3461***
	(0.0456)	(0.0482)	(0.0689)	(0.0417)	(0.0443)	(0.0622)
$ln\ \omega_i$	-0.0669***	-0.0647***	-0.0918***	-0.0400***	-0.0392***	-0.0496***
	(0.0075)	(0.0076)	(0.0099)	(0.0062)	(0.0063)	(0.0080)
$ln\ xi_i$		0.0851	0.1453*		0.0520	0.0757
		(0.0548)	(0.0795)		(0.0505)	(0.0713)
$ln\ EPSI\_x_i$		-0.0848	-0.1469*		-0.0514	-0.0761
		(0.0539)	(0.0781)		(0.0497)	(0.0701)
$EPSI\_HQ$			-1.2756***			-0.9576***
			(0.1529)			(0.1325)
R2	0.0091	0.0094	0.0224	0.0056	0.0057	0.0109
Observations	12,957	12,957	7,756	15,248	15,248	9,427

Sector FEs are included in all regressions. Robust standard errors in parentheses.
***,**,*: statistical significance at the 1%, 5% and 10% level, respectively

Table 3: Robustness check.

in the table. The estimates for the export variables, however, are now insignificant in columns (5) and (6). All the estimated effects are smaller in terms of absolute value in comparison to the main results.

5 Conclusion

Over the last decades, emission leakage has raised doubt about the effect of unilateral environmental policies in addressing global environmental issues. Many researchers have so far focused on industry-level analysis and ignored the important role of firm heterogeneity. In this paper, I develop the firm heterogeneity model to examine how unilateral environmental policies affect firm and global emissions in the context of offshoring. My model suggests that a unilateral increase in North emission tax only increases the effort on abatement and thus reduces the emission intensity of the least productive firms. The policy encourages the most productive firms in the old abatement group to stop investing in abatement and offshore the intermediate input, leading to an increase in their global emission intensity. Changes in North emission tax have no effect on the emission intensity of firms that have already offshored. Combined with the changes in firm outputs, only abatement firms reduce their emission levels while the other two groups experience increases in their emissions. Overall, I find a U-shaped relationship between the global emission and North emission tax (relative to South emission tax), indicating that a marginal increase in North emission tax decreases the global emission only when the initial relative emission tax is at low level.

My theory also suggests that theoretical models that do not consider the offshoring possibility could measure trade-induced technique effect incorrectly even at the firm level. The reduction in the firms' emission intensity may not only be attributed to firms' efforts on abatement but also to their offshoring activities. My model finds that moving from autarky to trade in intermediate inputs makes the most productive firms stop investing in abatement and start offshoring the intermediate input abroad to avoid the domestic emission tax. In terms of domestic variables, offshoring firms are considered to be cleaner as they no longer produce intermediate inputs that generate emissions. However, their global emission intensity and emission level increase, implying that these firms become dirtier.

Empirically, I exploit the German firm data to examine a central prediction of the model: firms engaging in offshoring activities should have lower domestic emission intensities as they move the pollution-intensive part of the production to foreign countries. I found the supportive evidence for the prediction and the results remain robust after conducting sensitivity analyses. There are some limitations in my empirical findings. First, the results from data spanning a longer period would be appreciated. These results will be updated soon in future work. Second, because of the data availability, my results are silent on the movement of firms' foreign emissions. The data containing information about the firm emissions abroad would improve the empirical tests for the predictions of the model.

References

Aichele, R. & Felbermayr, G. (2012), 'Kyoto and the carbon footprint of nations', *Journal of Environmental Economics and Management* **63**(3), 336–354.

Aichele, R. & Felbermayr, G. (2015), 'Kyoto and carbon leakage: An empirical analysis of the carbon content of bilateral trade', *The Review of Economics and Statistics* **97**(1), 104–115.

Anouliès, L. (2017), 'Heterogeneous firms and the environment: a cap-and-trade program', *Journal of Environmental Economics and Management* **84**, 84–101.

Antràs, P. & Helpman, E. (2004), 'Global sourcing', *Journal of Political Economy* **112**(3), 552–580.

Antweiler, W., Copeland, B. R. & Taylor, M. S. (2001), 'Is free trade good for the environment?', *American Economic Review* **91**(4), 877–908.

Barrett, S. (1998), 'Political economy of the kyoto protocol', *Oxford review of economic policy* **14**(4), 20–39.

Ben-David, I., Jang, Y., Kleimeier, S. & Viehs, M. (2021), 'Exporting pollution: where do multinational firms emit co2?', *Economic Policy* **36**(107), 377–437.

Bolz, S. J., Naumann, F. & Richter, P. M. (2023), 'Offshoring and environmental policy: Firm selection and distributional effects'.

Botta, E. & Koźluk, T. (2014), 'Measuring environmental policy stringency in oecd countries: A composite index approach', *OECD Economics Department Working Paperss, No.1177* .

Brunel, C. (2017), 'Pollution offshoring and emission reductions in eu and us manufacturing', *Environmental and Resource Economics* **68**(3), 621–641.

Cherniwchan, J., Copeland, B. R. & Taylor, M. S. (2017), 'Trade and the environment: New methods, measurements, and results', *Annual Review of Economics* **9**, 59–85.

Cole, M. A. & Elliott, R. J. (2003), 'Determining the trade–environment composition effect: the role of capital, labor and environmental regulations', *Journal of Environmental Economics and Management* **46**(3), 363–383.

Cole, M. A., Elliott, R. J. & Okubo, T. (2014), 'International environmental outsourcing', *Review of World Economics* **150**(4), 639–664.

Cole, M. A., Elliott, R. J. & Zhang, L. (2017*a*), 'Foreign direct investment and the environment', *Annual Review of Environment and Resources* **42**, 465–487.

Cole, M. A., Elliott, R. R. & ZHANG, O. T. L. (2017*b*), 'The pollution outsourcing hypothesis: an empirical test for japan', *RIETI: Research Institute of Economy Trade and Industry Discussion Paper No. 17096* .

Copeland, B. R., Shapiro, J. S. & Taylor, M. S. (2021), 'Globalization and the environment', *NBER Working Paper 28797* .

Copeland, B. R. & Taylor, M. S. (1994), 'North-south trade and the environment', *The Quarterly Journal of Economics* **109**(3), 755–787.

Copeland, B. & Taylor, M. S. (2003), *Trade and Environment: Theory and Evidence*, Princeton University Press.

Egger, H., Kreickemeier, U. & Wrona, J. (2015), 'Offshoring domestic jobs', *Journal of International Economics* **97**(1), 112–125.

Forslid, R., Okubo, T. & Ulltveit-Moe, K. H. (2018), 'Why are firms that export cleaner? international trade, abatement and environmental emissions', *Journal of Environmental Economics and Management* **91**, 166–183.

German Environmental Agency (2022*a*), 'Carbon dioxide emissions for the german atmospheric emission reporting'.
URL: *https://www.umweltbundesamt.de/themen/klima-energie/treibhausgas-emissionen*

German Environmental Agency (2022*b*), 'Entwicklung der spezifischen treibhausgas-emissionen des deutschen strommix in den jahren 1990 - 2021'.
URL: *https://www.umweltbundesamt.de/publikationen/entwicklung-der-spezifischen-kohlendioxid-8*

Grossman, G. M. & Krueger, A. B. (1993), Environmental impacts of a north american free trade agreement, *in* P. M. Garber, ed., 'The U.S.-Mexico free trade agreement', MIT Press, pp. 13–56.

Gupta, A. (2016), Chapter 1 - climate change and kyoto protocol: An overview, *in* V. Ramiah & G. N. Gregoriou, eds, 'Handbook of Environmental and Sustainable Finance', Academic Press, San Diego, pp. 3–23.

IPCC (2022), Climate change 2022: Impacts, adaptation and vulnerability. contribution of working group ii to the sixth assessment report of the intergovernmental panel on climate change, [Pörtner, H.-O. and Roberts, D. C. and Tignor, M. and Poloczanska, E. S. and Mintenbeck, K. and Alegría, A. and Craig, M. and Langsdorf, S. and Löschke, S. and Möller, V. and Okem, A. and Rama, B (eds.)], Cambridge University Press, Cambridge, UK and New York, NY, USA.

Kreickemeier, U. & Richter, P. M. (2014), 'Trade and the environment: The role of firm heterogeneity', *Review of International Economics* **22**(2), 209–225.

Levinson, A. (2009), 'Technology, international trade, and pollution from us manufacturing', *American Economic Review* **99**(5), 2177–92.

Melitz, M. J. (2003), 'The impact of trade on intra-industry reallocations and aggregate industry productivity', *Econometrica* **71**(6), 1695–1725.

Michel, B. (2013), 'Does offshoring contribute to reducing domestic air emissions? evidence from belgian manufacturing', *Ecological Economics* **95**, 73–82.

Nordhaus, W. (2015), 'Climate clubs: Overcoming free-riding in international climate policy', *American Economic Review* **105**(4), 1339–70.

Petrick, S., Rehdanz, K. & Wagner, U. J. (2011), 'Energy use patterns in german industry: Evidence from plant-level data', *Jahrbücher für Nationalökonomie und Statistik* **231**(3), 379–414.

Richter, P. M. & Schiersch, A. (2017), 'Co2 emission intensity and exporting: Evidence from firm-level data', *European Economic Review* **98**, 373–391.

Schenker, O., Koesler, S. & Löschel, A. (2018), 'On the effects of unilateral environmental policy on offshoring in multi-stage production processes', *Canadian Journal of Economics/Revue canadienne d'économique* **51**(4), 1221–1256.

Shapiro, J. S. & Walker, R. (2018), 'Why is pollution from u.s. manufacturing declining? the roles of environmental regulation, productivity, and trade', *American Economic Review* **108**(12), 3814–54.

UNFCCC (1998), Kyoto protocol to the united nations framework kyoto protocol to the united nations framework., Technical report, United Nations.

von Graevenitz, K. & Rottner, E. (2020), Energy use patterns in german manufacturing since 2003, Discussion Paper 20-008, ZEW-Centre for European Economic Research.

Appendix A

1 Non-tradable intermediate inputs

With the assumption that $k > \sigma - 1$, the weighted average of firm productivity levels can be written as:

$$\tilde{\varphi}_{non} = \left[\int_0^\infty \varphi^{\sigma-1}\mu(\varphi)d\varphi\right]^{\frac{1}{\sigma-1}} = \left(\frac{1}{1-G\left(\varphi^*_{non}\right)}\int_{\varphi^*_{non}}^\infty \varphi^{\sigma-1}g(\varphi)d\varphi\right)^{\frac{1}{\sigma-1}} = \left[\frac{k}{k-(\sigma-1)}\right]^{\frac{1}{\sigma-1}}\varphi^*_{non}$$

ZCP Condition: From equation (6), the revenue of the average firm can be written as the function of the market entry productivity cutoff as follows:

$$r(\tilde{\varphi}_{non}) = \left(\frac{\tilde{\varphi}_{non}}{\varphi^*_{non}}\right)^{\sigma-1} r(\varphi^*_{non})$$

ZCP condition implies that

$$\pi(\varphi^*_{non}) = 0 \Rightarrow \frac{r(\varphi^*_{non})}{\sigma} - wf_N = 0 \Rightarrow r(\varphi^*_{non}) = \sigma w f_N$$

so

$$r(\tilde{\varphi}_{non}) = \frac{k}{k-(\sigma-1)}\sigma w f_N$$

The profit of the average firm equals:

$$\pi(\tilde{\varphi}_{non}) = \frac{r(\tilde{\varphi}_{non})}{\sigma} - wf_N = wf_N\frac{\sigma-1}{k-(\sigma-1)}$$

FE Condition: Except for the cutoff firm, all active firms in the market earn positive profits. The average profit is, therefore, greater than zero. Firms consider paying a sunk cost of entry f_E only because of the expectation of positive profits. In equilibrium, a fixed cost of entry must equal the firm's expected profit:

$$p_{in}\sum_{t=0}^{\infty}(1-\delta)^t\pi(\tilde{\varphi}_{non}) = wf_E \;\Rightarrow\; \pi(\tilde{\varphi}_{non}) = \delta w f_E \left(\varphi^*_{non}\right)^k$$

Equilibrium: From FE and ZCP conditions we have

$$wf^N\frac{\sigma-1}{k-(\sigma-1)} = \delta w f_E \left(\varphi^*_{non}\right)^k$$

Therefore, the cutoff productivity is given by:

$$\varphi_{non}^{*}=\left[\frac{1}{\delta}\frac{f^{N}}{f_{E}}\frac{\sigma-1}{k-(\sigma-1)}\right]^{1/k}$$

The number of active firms is:

$$M_{non}^{*}=\frac{\gamma C}{r(\tilde{\varphi}_{non})}=\frac{\gamma C}{\sigma w f_{N}}\frac{k-(\sigma-1)}{k}$$

2 Tradable intermediate inputs

The ratio of the abatement and offshoring firm's revenue that have the same productivity level are:

$$\frac{r_{S}^{*}(\varphi)}{r_{N}^{*}(\varphi)}=\left(\frac{t_{N}}{t_{S}}\right)^{\eta(\sigma-1)}$$

Define the offshoring premium in revenues is the difference between the revenue of the offshoring firm and the abatement firm that have the same productivity level:

$$r^{prem}(\varphi)\equiv r_{S}^{*}(\varphi)-r_{N}^{*}(\varphi)=r_{N}^{*}(\varphi)\left[\left(\frac{t_{N}}{t_{S}}\right)^{\eta(\sigma-1)}-1\right]$$

Equivalently, the offshoring premium in profits is given by:

$$\pi^{prem}(\varphi)\equiv\pi_{S}^{*}(\varphi)-\pi_{N}^{*}(\varphi)\Leftrightarrow\pi^{prem}(\varphi)=\frac{r_{N}^{*}(\varphi)}{\sigma}\left[\left(\frac{t_{N}}{t_{S}}\right)^{\eta(\sigma-1)}-1\right]-w(f_{S}-f_{N})$$

Denote φ_{NO}^{*} is the offshoring productivity cutoff and $\tilde{\varphi}_{NO}$ is the average productivity of the firms doing offshoring. $\tilde{\varphi}_{NO}$ is then defined by:

$$\tilde{\varphi}_{NO}=\left(\frac{1}{1-G\left(\varphi_{NO}^{*}\right)}\int_{\varphi_{NO}^{*}}^{\infty}\varphi^{\sigma-1}g(\varphi)d\varphi\right)^{\frac{1}{\sigma-1}}=\left[\frac{k}{k-(\sigma-1)}\right]^{\frac{1}{\sigma-1}}\varphi_{NO}^{*}$$

I still denote φ_{N}^{*} as the market entry productivity cutoff and define $\tilde{\varphi}_{N}$ as

$$\tilde{\varphi}_{N}=\left(\frac{1}{1-G\left(\varphi_{N}^{*}\right)}\int_{\varphi_{N}^{*}}^{\infty}\varphi^{\sigma-1}g(\varphi)d\varphi\right)^{\frac{1}{\sigma-1}}=\left[\frac{k}{k-(\sigma-1)}\right]^{\frac{1}{\sigma-1}}\varphi_{N}^{*}$$

The probability of successful entry is expressed as:

$$p_{in}=1-G(\varphi_{N}^{*})=(\varphi_{N}^{*})^{-k}$$

and the share of offshoring firms is given by:

$$s = \frac{1 - G(\varphi_{NO}^*)}{1 - G(\varphi_N^*)} = \left(\frac{\varphi_N^*}{\varphi_{NO}^*}\right)^k$$

ZCP condition implies that

$$\pi_N^*(\varphi_N^*) = 0 \Rightarrow \frac{r_N^*(\varphi_N^*)}{\sigma} - wf_N = 0 \Rightarrow r_N^*(\varphi_N^*) = \sigma w f_N$$

Since φ_{NO}^* is the offshoring productivity cutoff, I have

$$\pi_S^*(\varphi_{NO}^*) = \pi_N^*(\varphi_{NO}^*) \Rightarrow r_N^*(\varphi_{NO}^*) = \sigma w(f_S - f_N)\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1} \tag{19}$$

so

$$\frac{r_N^*(\varphi_{NO}^*)}{r_N^*(\varphi_N^*)} = \frac{f_S - f_N}{f_N}\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1} \tag{20}$$

Also,

$$\frac{r_N^*(\varphi_{NO}^*)}{r_N^*(\varphi_N^*)} = \left(\frac{\varphi_{NO}^*}{\varphi_N^*}\right)^{\sigma-1}$$

Therefore,

$$\frac{\varphi_{NO}^*}{\varphi_N^*} = \left\{\frac{f_S - f_N}{f_N}\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1}\right\}^{\frac{1}{\sigma-1}} \tag{21}$$

Denote $\chi = \left\{\frac{f_S - f_N}{f_N}\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1}\right\}^{\frac{1}{\sigma-1}}$, then:

$$\chi = \frac{\varphi_{NO}^*}{\varphi_N^*} = s^{-\frac{1}{k}}$$

The condition for at least some firms in the market producing the intermediate input domestically, i.e. $\varphi_{NO}^* > \varphi_N^*$, is that $\frac{t_N}{t_S} < \left(\frac{f_S}{f_N}\right)^{\frac{1}{\eta(\sigma-1)}}$. The average offshoring revenue premium is defined by:

$$r^{S,prem}(\tilde{\varphi}_{NO}) \equiv r_S^*(\tilde{\varphi}_{NO}) - r_N^*(\tilde{\varphi}_{NO}) \Rightarrow r^{S,prem}(\tilde{\varphi}_{NO}) = r_N^*(\tilde{\varphi}_{NO})\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]$$

The average offshoring profit premium is defined by:

$$\begin{aligned} &\pi^{prem}(\tilde{\varphi}_{NO}) \equiv \pi_S^*(\tilde{\varphi}_{NO}) - \pi_N^*(\tilde{\varphi}_{NO}) \\ &\Rightarrow \pi^{prem}(\tilde{\varphi}_{NO}) = \frac{r_N^*(\tilde{\varphi}_{NO})}{\sigma}\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right] - w(f_S - f_N) \end{aligned} \tag{22}$$

The average profit and revenue can be written as:

$$\bar{\pi} = \pi_N^*(\tilde{\varphi}_N) + s\ \pi^{prem}(\tilde{\varphi}_{NO}) \tag{23}$$
$$\bar{r} = r_N^*(\tilde{\varphi}_N) + s\ r^{prem}(\tilde{\varphi}_{NO}) \tag{24}$$

ZCP Condition: The ZCP condition implies that

$$\pi_N^*(\varphi_N^*) = 0 \Rightarrow \frac{r_N^*(\varphi_N^*)}{\sigma} - wf_N = 0 \Rightarrow r_N^*(\varphi_N^*) = \sigma w f_N$$

Therefore,

$$\pi_N^*(\tilde{\varphi}_N) = \frac{1}{\sigma}\frac{k}{[k-(\sigma-1)]} r_N^*(\varphi_N^*) - wf_N = wf_N \frac{\sigma-1}{k-(\sigma-1)}$$

On the other hand:

$$\frac{r_N^*(\tilde{\varphi}_{NO})}{r_N^*(\varphi_{NO}^*)} = \left(\frac{\tilde{\varphi}_{NO}}{\varphi_{NO}^*}\right)^{\sigma-1} \Rightarrow r_N^*(\tilde{\varphi}_{NO}) = \left(\frac{\tilde{\varphi}_{NO}}{\varphi_{NO}^*}\right)^{\sigma-1} r_N^*(\varphi_{NO}^*) = \frac{k}{k-(\sigma-1)} r_N^*(\varphi_{NO}^*)$$

Combining with equation (19) gives

$$r_N^*(\tilde{\varphi}_{NO}) = \frac{k}{k-(\sigma-1)} \frac{f_S - f_N}{f_N} \left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1} \sigma w f_N$$

Plug $r_N^*(\tilde{\varphi}_{NO})$ into (22), then:

$$\pi^{prem}(\tilde{\varphi}_{NO}) = w(f_S - f_N)\frac{\sigma-1}{k-(\sigma-1)}$$

Equation (23) becomes:

$$\bar{\pi} = wf_N \frac{\sigma-1}{k-(\sigma-1)} + s\ w(f_S-f_N)\frac{\sigma-1}{k-(\sigma-1)} = w\frac{\sigma-1}{k-(\sigma-1)}\left[f_N + s(f_S - f_N)\right]$$

FE Condition: As before, in equilibrium, a fixed cost of entry must equal the firm's expected profit:

$$p_{in}\sum_{t=0}^{\infty}(1-\delta)^t \bar{\pi} = wf_E \Rightarrow \bar{\pi} = \delta w f_E \left(\varphi_N^*\right)^k$$

Equilibrium: From ZCP and FE conditions I have:

$$w\frac{\sigma-1}{k-(\sigma-1)}\left[f_N + s(f_S-f_N)\right] = \delta w f_E \left(\varphi_N^*\right)^k$$

Therefore, the market entry productivity cutoff is:

$$\varphi_N^* = \left[\frac{f_N + s(f_S - f_N)}{\delta f_E} \frac{\sigma - 1}{k - (\sigma - 1)}\right]^{1/k}$$

The offshoring productivity cutoff is:

$$\varphi_{NO}^* = s^{-\frac{1}{k}} \varphi_N^* = \left[\frac{s^{-1} f_N + (f_S - f_N)}{\delta f_E} \frac{\sigma - 1}{k - (\sigma - 1)}\right]^{1/k}$$

φ_N^* increases in s while φ_{NO}^* decreases in s. As s increases in t_N, φ_N^* increases in t_N and φ_{NO}^* decreases in t_N.

The average revenue is given by:

$$\bar{r} = r_N^*(\tilde{\varphi}_N) + s\ r^{S,prem}(\tilde{\varphi}_{NO}) = \frac{k}{k - (\sigma - 1)} \sigma w \left[f_N + s\ (f_S - f_N)\right]$$

Therefore, the number of active firm equals:

$$M^* = \frac{\gamma C}{\bar{r}} = \frac{\gamma C}{\sigma w \left[f_N + s\ (f_S - f_N)\right]} \frac{k - (\sigma - 1)}{k}$$

The number of active firms in the case of tradable inputs is smaller than that in the case of nontradable inputs as the possibility of offshoring leads to stronger competition in the final good market. M^* decreases in s while s increases in t_N, so M^* decreases in t_N.

3 Effect of trade in intermediate input

3.1 Firm Emissions

Firm's Emission Intensity: For abatement firms, the emission intensity is unchanged and equal:

$$e_N^*(\varphi) = \frac{z_N^*(\varphi)}{x_N^*(\varphi)} = \varphi^{-1} \left(\frac{w}{t_N} \frac{\eta}{\Theta}\right)^{1-\eta}$$

Firms that offshore the pollution-intensive part of the production will have the emission intensity being zero as they no longer produce the intermediate input that generates pollution. However, when considering the emission generated through firms' offshoring activities as firms' responsibility, the emission intensity of offshoring firms will be:

$$e_S^*(\varphi) = \frac{z_S^*(\varphi)}{x_S^*(\varphi)} = \varphi^{-1} \left(\frac{w}{t_S} \frac{\eta}{\Theta}\right)^{1-\eta}$$

Firm's Emission: From equation (5) a firm's emission equal:

$$z_d^*(\varphi) = \frac{\alpha\eta}{t_d} r_d^*(\varphi) \tag{25}$$

For abatement firms, I have

$$\frac{r_N^*(\varphi)}{r_N^*(\varphi_N^*)} = \left(\frac{\varphi}{\varphi_N^*}\right)^{\sigma-1} \Rightarrow r_N^*(\varphi) = \left(\frac{\varphi}{\varphi_N^*}\right)^{\sigma-1} r_N^*(\varphi_N^*) = \sigma w f_N \left\{\frac{\varphi}{\left[\frac{f_N+s(f_S-f_N)}{\delta f_E}\frac{\sigma-1}{k-(\sigma-1)}\right]^{1/k}}\right\}^{\sigma-1}$$

so

$$z_N^*(\varphi) = \frac{\alpha\eta}{t_N}\sigma w f_N \left(\frac{\varphi}{\left\{\frac{f_N+s(f_S-f_N)}{\delta f_E}\frac{\sigma-1}{k-(\sigma-1)}\right]^{1/k}}\right\}^{\sigma-1}$$

For offshoring firms:

$$\frac{r_S^*(\varphi)}{r_S^*(\varphi_{NO}^*)} = \left(\frac{\varphi}{\varphi_{NO}^*}\right)^{\sigma-1} \Rightarrow r_S^*(\varphi) = \left(\frac{\varphi}{\varphi_{NO}^*}\right)^{\sigma-1} r_S^*(\varphi_{NO}^*)$$

As $\frac{r_S^*(\varphi)}{r_N^*(\varphi)} = \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)}$ and $r_N^*(\varphi_{NO}^*) = \sigma w(f_S - f_N)\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1}$, so

$$r_S^*(\varphi_{NO}^*) = \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} \sigma w(f_S - f_N)\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1}$$

Plug into $z_S^*(\varphi)$ then:

$$\begin{aligned}
z_S^*(\varphi) &= \frac{\alpha\eta}{t_S}\left(\frac{\varphi}{\varphi_{NO}^*}\right)^{\sigma-1}\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} \sigma w(f_S - f_N)\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1} \\
&= \frac{\alpha\eta}{t_S}\left(\frac{\varphi}{\varphi_{NO}^*}\right)^{\sigma-1}\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} \sigma w f_N \; s^{\frac{1-\sigma}{k}}
\end{aligned}$$

3.2 Aggregate Emission

The total emission in North will equal the total emission generated by abatement firms, so:

$$\begin{aligned}
E_N^* &= M^*\int_{\varphi_N^*}^{\varphi_{N0}^*} z_N^*(\varphi)\mu(\varphi)d\varphi = M^*\int_{\varphi_N^*}^{\varphi_{N0}^*}\frac{\alpha\eta}{t^N}\sigma w f_N\left(\frac{\varphi}{\varphi_N^*}\right)^{\sigma-1}\mu(\varphi)d\varphi \\
&= M^*\frac{\alpha\eta}{t^N}\sigma w f_N \frac{k}{k-(\sigma-1)}\left(1 - s^{\frac{k-(\sigma-1)}{k}}\right) \\
&= \frac{\alpha\eta}{t^N}\gamma C\ \frac{1 - s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}
\end{aligned}$$

As assuming that $k > \sigma - 1$ and $0 < s < 1$, E^N decrease in t_N. (Recall: M^* decreases in t_N and s increases in t_N)

The total emission in South that is generated because of the Northern firms' import is:

$$E_S^* = M^* \int_{\varphi_{N0}^*}^{\infty} z_S^*(\varphi)\mu(\varphi)d\varphi = M^* \int_{\varphi_{N0}^*}^{\infty} \frac{\alpha\eta}{t_S} \left(\frac{\varphi}{\varphi_{NO}^*}\right)^{\sigma-1} \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} \sigma w f_N s^{\frac{1-\sigma}{k}} \mu(\varphi)d\varphi$$
$$= \frac{\alpha\eta}{t_S}\gamma C \frac{\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}$$

The global emission equals:

$$E_G^* = E_N^* + E_S^* = \gamma C\alpha\eta \frac{1}{t_N} \frac{1 - s^{\frac{k-(\sigma-1)}{k}} + \frac{t_N}{t_S}\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}{1 - s^{\frac{k-(\sigma-1)}{k}} + \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} s^{\frac{k-(\sigma-1)}{k}}}$$

3.3 Proof for changes in firm output

From (6) and (7) I have

$$\frac{x_d^*(\varphi)}{r_d^*(\varphi)} = \alpha\varphi(c_d)^{-1} \tag{26}$$

Now I write down the revenue as the function of the productivity cutoff.

Under non-tradable scenario:

$$r_{non}^*(\varphi) = \left(\frac{\varphi}{\varphi_{non}^*}\right)^{\sigma-1} r_{non}^*(\varphi_{non}^*) = \left(\frac{\varphi}{\varphi_{non}^*}\right)^{\sigma-1} \sigma w f_N \tag{27}$$

Under tradable scenario:

Firms that exit will stop producing and therefore their output and revenue will equal zero.

For firms that produce all stages of the production domestically in both scenarios, the revenue after opening to trade equals:

$$r_N^*(\varphi) = \left(\frac{\varphi}{\varphi_N^*}\right)^{\sigma-1} \sigma w f_N \tag{28}$$

The revenue of firms that switch to offshoring is:

$$r_S^*(\varphi) = \left(\frac{\varphi}{\varphi_{NO}^*}\right)^{\sigma-1} r_S^*(\varphi_{NO}^*) = \left(\frac{\varphi}{\varphi_N^* s^{-\frac{1}{k}}}\right)^{\sigma-1} r_N^*(\varphi_{NO}^*) \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)}$$

From (20) I have:

$$r_N^*(\varphi_{NO}^*) = r_N^*(\varphi_N^*) s^{\frac{1-\sigma}{k}} = \sigma w f_N s^{\frac{1-\sigma}{k}}$$

so

$$r_S^*(\varphi) = \left(\frac{\varphi}{\varphi_N^* s^{-\frac{1}{k}}}\right)^{\sigma-1} \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} \sigma w f_N s^{\frac{1-\sigma}{k}} = \left(\frac{\varphi}{\varphi_N^*}\right)^{\sigma-1} \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} \sigma w f_N \tag{29}$$

First, I examine the effect of offshoring possibility on firms that choose to abate in both scenarios. In this case:

$$\frac{x_N^*(\varphi)}{x_{non}^*(\varphi)} = \frac{r_N^*(\varphi)}{r_{non}^*(\varphi)}$$

From (27) and (28) the effect of offshoring on revenue is:

$$\frac{r_N^*(\varphi)}{r_{non}^*(\varphi)} = \left(\frac{\varphi_{non}^*}{\varphi_N^*}\right)^{\sigma-1} < 1 \quad \text{since} \quad \varphi_{non}^* < \varphi_N^*$$

Trade in intermediate input reduces the revenue and the output of firms that choose to abate in both scenarios.

Next, I examine the effect on firms that switch to offshore the dirty parts of the production. I have:

$$\frac{x_S^*(\varphi)}{x_{non}^*(\varphi)} = \frac{r_S^*(\varphi)}{r_{non}^*(\varphi)} \frac{c^N}{c^S} = \frac{r_S^*(\varphi)}{r_{non}^*(\varphi)} \left(\frac{t_N}{t_S}\right)^{\eta}$$

From (27) and (29), the effect of offshoring on revenue is:

$$\frac{r_S^*(\varphi)}{r_{non}^*(\varphi)} = \left(\frac{\varphi_{non}^*}{\varphi_N^*}\right)^{\sigma-1} \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} = \left(\frac{f_N}{f_N + s(f_S - f_N)}\right)^{\frac{\sigma-1}{k}} \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)}$$

The offshoring possibility increases the revenue of offshoring firms if

$$\left(\frac{f_N}{f_N + s(f_S - f_N)}\right)^{\frac{\sigma-1}{k}} \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} > 1 \Leftrightarrow s\frac{f_S - f_N}{f_N} < \left(\frac{t_N}{t_S}\right)^{k\eta} - 1$$

As $s^{\frac{-1}{k}} = \left\{\frac{f_S - f_N}{f_N}\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1}\right\}^{\frac{1}{\sigma-1}}$, then:

$$\left\{\frac{f_S - f_N}{f_N}\left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{-1}\right\}^{\frac{-k}{\sigma-1}} \frac{f_S - f_N}{f_N} < \left(\frac{t_N}{t_S}\right)^{k\eta} - 1$$

$$\Leftrightarrow \left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{\frac{k}{\sigma-1}} < \left[\left(\frac{t_N}{t_S}\right)^{k\eta} - 1\right] \left(\frac{f_S - f_N}{f_N}\right)^{\frac{k-(\sigma-1)}{\sigma-1}}$$

With the assumption that $\frac{f_S - f_N}{f_N} > \left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1$ and $k > \sigma - 1$, so:

$$\left[\left(\frac{t_N}{t_S}\right)^{k\eta} - 1\right] \left(\frac{f_S - f_N}{f_N}\right)^{\frac{k-(\sigma-1)}{\sigma-1}} > \left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right] \left[\left(\frac{t_N}{t_S}\right)^{\eta(\sigma-1)} - 1\right]^{\frac{k-(\sigma-1)}{\sigma-1}}$$

$$= \left[\left(\frac{t_N}{t_S} \right)^{\eta(\sigma-1)} - 1 \right]^{\frac{k}{\sigma-1}}$$

Therefore, trade in intermediate input increases the revenue of the offshoring firms. Since:

$$\frac{x_S^*(\varphi)}{x_{non}^*(\varphi)} = \frac{r_S^*(\varphi)}{r_{non}^*(\varphi)} \left(\frac{t_N}{t_S} \right)^{\eta}$$

and $t_N > t_S$, then trade in intermediate input increases the output of offshoring firms.

4 Effect of an increase in the North emission tax

4.1 Proof for the scale effect at the intensive margin

From (26) and (28) the output of abatement firms equal:

$$x_N^*(\varphi) = \alpha\varphi(c_N)^{-1} r_N^*(\varphi) = \alpha\varphi^{\sigma}(c_N)^{-1} \left(\frac{1}{\varphi_N^*} \right)^{\sigma-1} \sigma w f_N$$

As c_N and φ_N^* increase in t_N, $x_N^*(\varphi)$ decreases in t_N. An increase in the North emission tax reduces the output of abatement firms.

From (26) and (29) the output of firms that have already offshored is given by:

$$x_S^*(\varphi) = \alpha\varphi(c_S)^{-1} r_S^*(\varphi) = \alpha\varphi^{\sigma}(c_S)^{-1} \left(\frac{1}{\varphi_N^*} \right)^{\sigma-1} \left(\frac{t_N}{t_S} \right)^{\eta(\sigma-1)} \sigma w f_N$$

How $x_S^*(\varphi)$ changes in the North emission tax depends on how $(\varphi_N^*)^{-(\sigma-1)} (t_N)^{\eta(\sigma-1)}$ changes in t_N. I have:

$$\begin{aligned} (\varphi_N^*)^{-(\sigma-1)} (t_N)^{\eta(\sigma-1)} &= \left[\frac{f_N + s(f_S - f_N)}{\delta f_E} \frac{\sigma - 1}{k - (\sigma - 1)} \right]^{-(\sigma-1)/k} (t_N)^{\eta(\sigma-1)} \\ &= \left[\frac{\sigma - 1}{k - (\sigma - 1)} \right]^{-(\sigma-1)/k} \left[\frac{f_N + s(f_S - f_N)}{\delta f_E} \right]^{-(\sigma-1)/k} (t_N)^{\eta(\sigma-1)} \end{aligned}$$

so how $(\varphi_N^*)^{-(\sigma-1)} (t_N)^{\eta(\sigma-1)}$ changes in t_N will depend on how $\left[\frac{f_N+s(f_S-f_N)}{\delta f_E} \right]^{-(\sigma-1)/k} (t_N)^{\eta(\sigma-1)}$ changes in t_N. Taking log:

$$A = \ln \left\{ \left[\frac{f_N + s(f_S - f_N)}{\delta f_E} \right]^{-(\sigma-1)/k} (t_N)^{\eta(\sigma-1)} \right\} = \eta(\sigma - 1) \ln t_N - \frac{\sigma - 1}{k} \ln \left[\frac{f_N + s(f_S - f_N)}{\delta f_E} \right]$$

Recall $s = \left\{ \frac{f_S - f_N}{f_N} \left[\left(\frac{t_N}{t_S} \right)^{\eta(\sigma-1)} - 1 \right]^{-1} \right\}^{\frac{-k}{\sigma-1}}$. Differentiating yield:

$$\frac{dA}{dt_N} = \eta(\sigma-1)\frac{1}{t_N} \left\{ 1 - [f_N + s(f_S - f_N)]^{-1} f_N s^{\frac{k-(\sigma-1)}{k}} \left(\frac{t_N}{t_S} \right)^{\eta(\sigma-1)} \right\}$$

$x^*_S(\varphi)$ increases in t_N if and only if:

$$[f_N + s(f_S - f_N)]^{-1} f_N s^{\frac{k-(\sigma-1)}{k}} \left(\frac{t_N}{t_S} \right)^{\eta(\sigma-1)} < 1 \Leftrightarrow s < 1$$

This condition is satisfied as I only consider the case that not all firms offshore.

For firms that switch to offshoring, the output before and after the change in t_N are as follows:

$$x^*_{N,before}(\varphi) = \alpha\varphi^{\sigma}(c_{N,before})^{-1} \left(\frac{1}{\varphi^*_{N,before}} \right)^{\sigma-1} \sigma w f_N$$

$$x^*_{S,after}(\varphi) = \alpha\varphi^{\sigma}(c_S)^{-1} \left(\frac{1}{\varphi^*_{N,after}} \right)^{\sigma-1} \left(\frac{t_{N,after}}{t_S} \right)^{\eta(\sigma-1)} \sigma w f_N$$

Since $t_N > t_S$, then:

$$x^*_{N,before}(\varphi) < \alpha\varphi^{\sigma}(c^S)^{-1} \left(\frac{1}{\varphi^*_{N,before}} \right)^{\sigma-1} \left(\frac{t_{N,before}}{t_S} \right)^{\eta(\sigma-1)} \sigma w f_N$$

From above I have $(\varphi^*_N)^{-(\sigma-1)} (t_N)^{\eta(\sigma-1)}$ increases in t_N, so:

$$\left(\varphi^*_{N,before}\right)^{-(\sigma-1)} (t_{N,before})^{\eta(\sigma-1)} < \left(\varphi^*_{N,after}\right)^{-(\sigma-1)} (t_{N,after})^{\eta(\sigma-1)} \Rightarrow x^*_{N,before}(\varphi) < x^*_{S,after}(\varphi)$$

4.2 Proof of the reallocation effect

From equation (12):

$$d\mu(\varphi) = \frac{k\mu(\varphi)}{\varphi^*_N} d\varphi^*_N = \frac{k(\varphi^*_N)^{k-1}}{\varphi^{k+1}} d\varphi^*_N \ > 0 \text{ and decreases in } \varphi$$

Appendix B: Empirical Results

	Energy Intensity			*Emission Intensity*		
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
$asinh\ mi_i$	-1.8220***	-1.8737***	-2.1516***	-1.8606***	-1.8964***	-2.1167***
	(0.3227)	(0.3265)	(0.3976)	(0.3063)	(0.3098)	(0.3777)
$asinh\ EPS\_m_i$	3.1008***	2.9179***	3.1369***	3.1737***	2.9660***	3.1268***
	(0.3841)	(0.3902)	(0.4679)	(0.3646)	(0.3704)	(0.4445)
$asinh\ \omega_i$	-0.0514***	-0.0598***	-0.0857***	-0.0487***	-0.0568***	-0.0837***
	(0.0060)	(0.0062)	(0.0082)	(0.0057)	(0.0059)	(0.0078)
$asinh\ xi_i$		-0.3339	-0.6208**		-0.4038**	-0.6749***
		(0.2110)	(0.2726)		(0.2003)	(0.2590)
$asinh\ EPS\_x_i$		0.8542***	1.2194***		0.9482***	1.2995***
		(0.2786)	(0.3595)		(0.2644)	(0.3415)
EPS_HQ			-1.2871***			-1.1778***
			(0.1463)			(0.1390)
R2	0.0211	0.0253	0.0410	0.0238	0.0287	0.0452
Observations	15,337	15,337	9,495	15,337	15,337	9,495

Sector FEs are included in all regressions. Robust standard errors in parentheses.
***,**,*: statistical significance at the 1%, 5% and 10% level, respectively

Table B1: Inverse Hyperbolic Sine Transformation

	Energy Intensity					
	Complete firms			*Expenditure share < 1*		
	(1)	*(2)*	*(3)*	*(4)*	*(5)*	*(6)*
$ln\ mi_i$	-0.3754***	-0.4019***	-0.4218***	-0.3263***	-0.3369***	-0.3185***
	(0.0484)	(0.0511)	(0.0731)	(0.0443)	(0.0471)	(0.0661)
$ln\ EPS\_m_i$	0.3763***	0.4032***	0.4252***	0.3261***	0.3367***	0.3196***
	(0.0481)	(0.0508)	(0.0726)	(0.0440)	(0.0468)	(0.0657)
$ln\ \omega_i$	-0.0721***	-0.0702***	-0.0955***	-0.0418***	-0.0414***	-0.0510***
	(0.0079)	(0.0080)	(0.0104)	(0.0066)	(0.0066)	(0.0085)
$\ln\ xi_i$		0.0771	0.1634*		0.0471	0.0910
		(0.0578)	(0.0837)		(0.0534)	(0.0753)
$ln\ EPS\_x_i$		-0.0766	-0.1646**		-0.0462	-0.0909
		(0.0568)	(0.0822)		(0.0525)	(0.0740)
EPS_HQ			-1.3410***			-1.0576***
			(0.1611)			(0.1400)
R2	0.0084	0.0086	0.0216	0.0047	0.0048	0.0107
Observations	12,957	12,957	7,756	15,248	15,248	9,427

Sector FEs are included in all regressions. Robust standard errors in parentheses.
***,**,*: statistical significance at the 1%, 5% and 10% level, respectively

Table B2: Robustness check: Energy Intensity