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WHY ARE FIRMS THAT EXPORT CLEANER? INTERNATIONAL TRADE, ABATEMENT AND ENVIRONMENTAL EMISSIONS

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ABSTRACT

Why are firms that export cleaner? International trade, CO2 emissions and heterogeneous firms*

This paper develops a theoretical model of trade and environmental emissions with heterogeneous firms, where firms make abatement investments and thereby affect their level of emissions. We show that investments in abatement are positively related to firm productivity and firm exports, while emission intensity is negatively related to firms' productivity and exports. The basic reason for these results is that a larger production scale supports more investments in abatement and, in turn, reduces emissions per output. We find that trade liberalization weeds out the least productive and dirtiest firms thereby shifting production away from relatively dirty low productive local firms to more productive and cleaner exporters. The overall effect of trade is therefore to reduce emissions. We test the empirical implications of the model on emission intensity, abatement and exporting using firm-level data from Sweden. The empirical results support our model.

JEL Classification: D21, F12, F15 and Q56
Keywords: heterogeneous firms, environmental emissions, abatement, and international trade

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1 Introduction

There is no consensus on the effect of international trade on the environment, in particular on the effect of trade on global emissions. Neither the theoretical nor the empirical literature provides a clean cut answer to the link between trade and environmental emissions. Hence, we do not know if international trade increases or decreases the emissions of greenhouse gases and contributes to global warming. However, this paper sets out to explain why we may expect exporter to emit less, and why trade liberalization may thus lead to cleaner industrial production. We do so by focusing on inter-firm productivity differentials and interdependence among productivity, exporting, abatement and environmental emissions.

In theoretical neoclassical models, international trade has opposing effects. On the one hand, trade increases income, which will tend to increase the demand for a clean environment and therefore increase investments in clean technology and abatement. On the other hand, trade liberalization may also imply an overall expansion of dirty production, because trade allows countries with low emission standards to become pollution havens. Copeland and Taylor (1995) show how trade liberalization may increase global emissions if the income differences between the liberalizing countries are large, as dirty industries are likely to expand strongly in the poor country with low environmental standards.

The empirical literature that analyses the link between trade in goods and emissions based on sector level data and Heckscher Ohlin type models is also inconclusive.[1] Antweiler et al. (2001) and Frankel and Rose (2005) find that trade decreases emissions. Using sector level data for the U.S., Ederington et al. (2004) do not find any evidence that pollution intensive industries have been disproportionately affected by tariff changes. On the other hand, also using sector-level trade data, Levinson and Taylor (2008) find evidence that higher environmental standards in the US have increased the imports from Mexico in dirty industries.

Our point of departure for the analysis of trade and the environment is a model with heterogeneous firms and intra-industry trade, where trade gives rise to intra-industry reallocations across firms where we build on Melitz (2003). The choice of theoretical framework is motivated by descriptive evidence on the environmental emissions of Swedish manufacturing firms. We find firms' emissions differ significantly across firms, even within rather narrowly defined industries, and that the majority of variation in emissions can be ascribed to intra- rather than inter-industry variation. Moreover, comparing non-exporters and ex-

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[1] Early surveys are made by Copeland and Taylor (2004) and Brunnermeier and Levinson (2004).

porters in Swedish manufacturing, we find that in most manufacturing industries exporters do on average have a lower emission intensity. Motivated by these basic facts we build a model with international trade and environmental emissions where firms are heterogeneous with respect to productivity, abatement investments and emission intensity. We propose and develop a mechanism for why exporters may have a lower emission intensity when emissions are subject to an environmental tax. This mechanism runs through firms' investments in abatement. Firms' abatement investments depend on their production volumes as a larger scale allow them to spread the fixed costs of abatement investment across more units. Production volumes are moreover determined by firms' productivity and export status. More productive firms access international markets, have higher volumes and make higher abatement investments. As a consequence, firms' emission intensity is negatively related to firms' productivity and export status.

Our theoretical model moreover allows for predictions on the impact of trade liberalization on total environmental emissions. We find that total emissions from the manufacturing sector decreases as a result of trade and trade liberalization. Trade affects the exporting and non-exporting sector in different ways. Exporters are for any level of trade costs always cleaner than non-exporters, and we show that trade liberalization may make exporters even cleaner by inducing them to invest more in abatement. But trade liberalization also implies higher production volumes for exporters, which ceteris paribus entails higher emissions. Total emissions therefore increases from the exporting sector. However, trade moreover increases local competition, which implies that the least productive, and therefore dirtiest, firms are forced to close down, while the remaining non-exporters are forced to scale down their production volume. Together these different effects of trade liberalization serve as to decrease total emissions from the non-exporting sector. Adding up the effects on exporters and non-exporters we find that trade liberalization will always lead to lower total emissions. Thus, as trade weeds out some of the least productive and dirtiest firms, thereby shifting production away from relatively dirty low productive local firms to more productive and cleaner exporters, the overall effect of trade liberalization is to reduce emissions.

The theoretical model allows us to derive a set of empirical predictions on emissions and exporting as well as abatement investment and exporting. Access to the detailed firm level data set for Swedish manufacturing firms allow us to test these predictions. Our data set contains firm-level emissions and firm-level abatement investments as well as firm exports. According to our model, productivity drives the firm level emission intensity as well as the export status of a firm. However, while productivity has a continuous effect on the emission intensity, the model predicts a discontinuous jump down in the emission intensity as firms become exporters. The same kind of relationship is predicted for abatement and exporting.

We exploit these features of the model as we take the model to the data. The empirical results are strongly supportive of the results derived in the theoretical model; exporters are found to invest more in abatement and to have lower emission intensity.

Our theory is related to the idea presented in Levinson (2009) that trade may contribute to reduced pollution as trade liberalization may encourage technological upgrading. From a more methodological point of view, our work is also related to the literature on heterogeneous firms and trade induced technological upgrading, see e.g. Bas (2012) and Bustos (2012). The majority of studies on international trade and environmental emissions are, unlike this paper, based on industry level analysis. There is, however, a rising literature focusing on firms rather than industries, which are thus closer in the spirit to our analysis. Holladay (2011) analyses firm-level data for the US, and find that exporters pollute less per output. Unlike Holladay we develop a rigorous theoretical model with heterogeneous firms and environmental emissions, where we introduce a mechanism - economies of scale in abatement - motivating why exporter invest more in abatement than non-exporters. Moreover, based on our theory we do not not only make predictions on exporting and emissions but also on exporting and abatement, and are able to test both of these empirically. Cui et al (2012) analyse the relationship between exporting and emissions, but on the basis of a theoretical model distinctly different from ours. In our model exporters' relatively lower emission intensity is due to their endogenous choice of abatement investment, while in their model it is due to exporters discrete choice of technology of production. Their empirical analysis focuses on emissions and exporting, while we also analyse the relationship between abatement and exporting.Batrakova and Davies (2012) examine the link between exporting and energy use employing Irish manufacturing data. Their theoretical model predicts a positive correlation between exporting and energy expenditures for low energy intensity firms and a smaller or even a negative correlation for high energy intensity firms. This asymmetry is due to the fact that trade as such requires extra energy, but on the other hand may also encourage a shift towards more energy efficient technologies if a firm is highly energy intensive. Their theoretical results are confirmed empirically. Girma et al (2008) studies the reported environmental effects of UK firms innovations and the role of exporting, and find that exporters are more likely to denote their innovations as having high environmental effects. Tang et al (2014) examine the impact of environmental policy within a framework of heterogeneous firms in a closed economy. They find that environmental policy reduces both consumption and pollution emission, but that output could be maintained using subsidies directed towards the more productive firms. Finally, Rodrigue and Soumonni (2014) employ Indonesian firm level data to investigate the impact of environmental investment on productivity dynamics and exports. While productivity dynamics do not appear to be affected, growth in exports does show a positive effect. However, our paper is to our knowledge the first to provide both a thoroughly theoretical analysis of emissions, abatement and trade that can be solved analytically and an empirical set of results that matches the theoretical findings on emissions as well as abatement.

The structure of the paper is as follows. In the next section we present a set of basic facts on the variation in environmental emission intensity across industries and firms, and examine the differences in emission intensity and abatement among non-exporters and exporters relying on data for Swedish manufacturing firms. Motivated by the descriptive evidence on emissions and firms, in Section 3 we develop a theoretical model on international trade, environmental emissions and heterogeneous firms. Based on this model we are able to derive a set of propositions and empirical implications regarding emissions, abatement and trade. In Section 4 we take the theory to the data, and test the empirical predictions on the relationship between environmental emissions, export and productivity, and on the relationship between abatement, export and productivity. Finally, Section 5 concludes.

2 Data and background

2.1 Data

In order to analyze the relationship between trade, emissions and abatement, we use manufacturing census data for Sweden. The census data contains information at the firm level for a large number of variables such as export, employment (number of employees), capital stock , value of purchase of intermediates and value of output. Reported values are in thousand Swedish kroner (tSEK). Our firm level data covers the period 2000-2011 and include all firms with at least one employee. This leaves us with an unbalanced panel of around 23000 firms per year.

We moreover have data for three types of environmental emissions, SO2, NOx and CO2. Information on emissions is, however, not available for the whole panel of manufacturing firms. As for SO2 and NOx emissions, we rely on calculations made by Statistics Sweden. Statistics Sweden calculate SO2 and NOx emissions on an annual basis for all manufacturing firms that uses at least 325 tons of oil equivalents the respective year.

As for CO2 emissions, we rely on own calculations exploiting data on energy usage and emissions coefficients. Statistics Sweden collect information on the usage of energy from all manufacturing plants with 10 or more employees, and we have data for the time period 2005-2011. The energy statistics include all types of fuel use, from which CO2 emissions can be calculated by using fuel specific CO2 emissions coefficients provided by Statistics Sweden.

CO2 emissions are accurately calculated from fuel inputs since a technology for capturing CO2 at the pipe is not yet operational.[2] The calculated plant level emissions are aggregated to the firm level. We match the firm level emission data with the census data.[3] Note that the data at hand allows us to estimate emission intensity as tonnes of emissions relative to value added - rather than relative to sales or the value of output. Hence, unlike other studies we implicitly take into account differences across firms with respect to outsourcing when measuring emission intensity.

We also have access to firm level data on abatement over the period 2000-2011. The abatement data is collected based on an annual survey where firms are asked about abatement investments (tSEK) as well as variable abatement costs (tSEK). The firms are asked to report not only investments in machines and equipment specifically aimed at reducing emissions, but in addition to report extra expenses related to investment in relative more environment friendly machines and technology. Hence, investments which allow for fuel-switching or increased energy efficiency are also counted. Firms are asked to report abatement related to air, water and waste. The abatement data is based on a semi-random sample of manufacturing firms, and include all manufacturing firms with more than 250 employees, 50 percent of the firms with 100-249 employees, and 20 percent of the firms with 50-99 employees. In total, around 1500 manufacturing firms are surveyed over the time period 2000-2011.

Swedish firms face uniform SO2 and a NOx taxes which were introduced in 1990 and 1992 respectively. Swedish manufacturing firms also face a CO2 tax. Sweden enacted a tax on carbon emissions in 1991 which has applied throughout our period of observation. The tax is a general one, and applies to all sectors, but manufacturing industries have from the introduction of the tax been granted a tax credit. The tax credit is unified and identical across industries and firms. Moreover, in 2005 the European Union Emissions Trading System (EU-ETS) was set up, of which Sweden is a member. The EU-ETS mainly applies to firms in the energy intensive industries,[4] but also to some energy intensive firms outside these industries. The firms included in the EU-ETS face the quota regime but are on the other hand exempted from the national CO2 tax. Our dataset identifies all firms with an EU-ETS quota.

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[2] A few large power plants are experimenting with capturing CO2 under ground, but as we are focusing on manufacturing, these are not included in our data.

[3] We are left with a firm level panel with CO2 emission information of around 3700 manufacturing firms per year for the period 2005-2011, and a firm level panel with SO2 and NOx emission information of around 550 firms for the period 2000-2011.

[4] The energy intensive industries are paper and pulp (17), coke and refined petroleum products (19), chemicals (20), non-metallic mineral products (23), and basic metals (24).

2.2 Basic Facts on Swedish Firms' Environmental Emissions and Trade

The manufacturing sector was in 2010 responsible for 28 percent of the CO2 emissions, 24 percent of the SO2 emissions and 11 percent of the NOx emissions in Sweden. But needless to say there are huge differences in environmental intensities across individual industries within the manufacturing sector. The energy intensive industries have much higher emissions as well as emission intensities than the other industries. So far these inter-industry variations have got the most attention from academics and policy makers. Hence, also analyses of environmental emissions and international trade have until recently mainly focused on differences in emissions across sectors and industries as surveyed by Copeland and Taylor (2004) and Brunnermeier and Levinson (2004). However, we conduct a simple decomposition of the variation in environmental emission intensity (measured as tonnes of emissions relative to value added) of Swedish manufacturing firms, splitting the variation in emission intensity into (i) variation across firms within sectors and (ii) variation between sectors. Table 1 shows that the majority of the variation in emission intensity can be ascribed to firm heterogeneity within rather narrowly sectors.[5]

Table 1: Decomposition of Environmental Emissions

	Within sectors (5 digit)	Between sectors
CO2 emission intensity	85%	15%
SO2 emission intensity	64%	36%
NOx emission intensity	94%	6%

Note: Environmental emission intensity is measured as tonnes of emissions relative to value added.[6]

Our hypothesis is that the inter-firm differences in emission intensities may be linked to other heterogeneous characteristics of the firms and in particular to their internationalization. Analyses of various countries (see e.g. Bernard et al., 2007) have shown that exporters are bigger, more productive and more capital intensive. As shown in Table 10 in the Appendix, our data for Swedish manufacturing firms confirms these stylized facts. Swedish exporters employ more people, have relatively higher investment in capital and have higher total factor productivity.[7] Hence, we proceed by comparing the emission intensity of exporters and non-exporters. We do this for CO2, SO2 and NOx emissions. We report the ratio of average emission intensity of exporters relative to non-exporters for all sectors, for energy intensive

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[5] See the Appendix for details on the decomposition calculation.

[7] An exporter is defined as a firm with foreign sales of any amount, but we have also run our regressions with exporters defined as firms with sales above ten or hundred thousand dollars. This does not affect the results.

sectors and for non-energy intensive sectors, see Table 2.[8] The picture is not quite clear. But we note that in the non-energy intensive sectors, which account for more than 80 percent of manufacturing employment exporters' emission intensity is on average much lower than that of non-exporters. Doing a count of industries, we also find that in 13 out of 24 manufacturing industries (NACE 2 digit level) exporters' CO2 and SO2 environmental emission intensity is lower than that of non-exporters, while the number of industries where exporters have lower NOx emission intensity than non-exporters, is 14 out of 24.

Table 2: Environmental emission intensities

	All sectors Emission intensity: Exporters vs. Non-Exporters		
	All Sectors	Energy intensive	Non-Energy intensive
CO2 emission intensity	2.37	2.15	0.42
SO2 emission intensity	0.85	1.06	0.45
NOx emission intensity	1.20	2.41	0.38

Note: Environmental emission intensity is measured as environmental emissions relative to value added.

In line with the definition applied by Swedish authorities, 5 industries are categorized as energy intensive, and 19 as non-energy intensive.[9]

Motivated by the facts on environmental emissions and their variation across firms, we proceed by developing a simple theory of heterogeneous firms where firms within an industry differ in their emissions. In particular, we propose and develop a mechanism for why emissions may differ across firms, and why export performance may have an impact on firms' emissions.

3 The Model

We develop a model with international trade and heterogeneous firms (see Melitz (2003)) whose production entails environmental emissions.. Firms that are productive enough to set up production make two distinct decisions, whether to enter the export market and how much to invest in abatement to reduce emissions. Firms make these decision subject to trade costs and emission taxes.

We consider the case of two countries, *Home* and *Foreign* (denoted by ”*”). Each economy is active in the production in two industries: a monopolistic competitive industry (M) where firms produce differentiated goods under increasing returns and subject to environmental emissions, and a background industry (A) characterized by perfect competition and which produces homogenous goods subject to constant returns to scale. To make things simple, we shall assume that there is just one factor of production. This may be a composite

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[8] The energy intensive sectors are paper and pulp (17), coke and refined petroleum products (19), chemicals (20), non-metallic mineral products (23), and basic metals (24).

factor, but for the sake of simplicity we shall refer to it as labour. We present the equations describing *Home′s* consumers and firms, and note that corresponding equations apply to *Foreign*.

The theoretical model allows us to derive analytical expressions for equilibrium emission intensity and equilibrium abatement investments, and to analyze the relationship between emission intensity, abatement investment and trade. Our analysis delivers predictions on export performance, emission and abatement. In Section 4 we proceed by testing empirically these theoretical predictions using the Swedish manufacturing firm level data.

3.1 Demand

Consumers preferences are given by a two-tier utility function with the upper tier (Cobb-Douglas) determining the representative consumer's division of expenditure between goods produced in sectors A and M, and the second tier (CES), giving the consumer's preferences over the continuum of differentiated varieties produced within the manufacturing sector. Hence, all individuals in *Home* have the utility function

$$U = C_M^{\mu} C_A^{1-\mu}, \tag{1}$$

where $\mu \in (0, 1)$ and C_A is consumption of the homogenous good. Goods produced in the A sector can be costlessly traded internationally and are produced under constant returns to scale and perfect competition. The A-good is chosen as the numeraire, so that the world market price of the agricultural good, p_A, is equal to unity. By choice of scale, the labour requirement in the A-sector is one, which gives

$$p_A = w = 1 \tag{2}$$

and thus, wages are normalized to one across both countries and sectors. We assume that demand for A goods is sufficiently large to guarantee that the A sector is active in both countries. The consumption of goods from the M sector is defined as an aggregate C_M,

$$C_M = \left[\int_{i \in I} c(i)^{(\sigma-1)/\sigma} \, di \right]^{\sigma/(\sigma-1)}, \tag{3}$$

where $c(i)$ represents consumption of each variety with elasticity of substitution between any pair of differentiated goods being $\sigma > 1$. The measure of the set I represents the mass of varieties consumed in the *Home* country. Each consumer spends a share μ of his income on goods from industry M, and the demand for each single variety produced locally and in the foreign country is therefore given by respectively

$$\begin{aligned} x_d &= \frac{p^{-\sigma}}{P^{1-\sigma}}\mu L \\ x_e &= \frac{\tau^{1-\sigma}(p^*)^{-\sigma}}{P^{1-\sigma}}\mu L, \end{aligned} \tag{4}$$

where p is the consumer price, is income, and $P \equiv \left(\int\limits_{i \in I} p\,(i)^{1-\sigma}\, di \right)^{\frac{1}{1-\sigma}}$ the price index of M goods consumed in the *Home* country. Products from Foreign sold in Home incur an iceberg trade cost τ, i.e. for each unit of a good from *Foreign* to arrive in *Home*, $\tau > 1$ units must be shipped. It is assumed that trade costs are equal in both directions.

3.2 Entry, Exit and Production Costs in the M Sector

To enter the M sector in country j, a firm bears the fixed costs of entry f_E measured in labour units. After having sunk f_E, an entrant draws a labour-per-unit-output coefficient a from a cumulative distribution function$G(a)$. We follow Helpman et al. (2004) in assuming the probability distribution to be a Pareto distribution,[10] i.e. $G(a) = \left(\frac{a}{a_0}\right)^k$, where k is the shape parameter, and we normalize the scale parameter to unity, $a_0 \equiv 1$. Since a is unit labour requirement, $1/a$ depicts labour productivity. Upon observing this draw, a firm may decide to exit and not produce. If it chooses to stay, it bears the additional fixed overhead costs, f_D. If the firm does not only want to serve the domestic market but also wants to export, it has to bear the additional fixed costs, f_X. Hence, firm technology is represented by a cost function that exhibits a variable cost and a fixed overhead cost. In the absence of emissions and abatement investment, labour is used as a linear function of output according to

$$l = f + ax \tag{5}$$

with $f = f_D$ for firms only serving the domestic market and $f = f_D + f_X$ for exporters. We make the simplifying assumption that not just variable costs but also all types of fixed costs are incurred in labour. However, since we do not focus on issues related to factor markets or comparative advantage, this only serves as means to simplify the analysis, without having any impact on the results.

Industrial activity in sector M entails pollution in terms of environmental emissions. We follow Copeland and Taylor (2003) and assume that each firm produces two outputs: an

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[10] This assumption is consistent with the empirical findings by e.g. Axtell (2001).

industrial good (x) and emissions (e). In order to reduce emissions, a firm can divert a fraction θ of the primary factor, labour, away from the production of x. We may think of θ as a variable abatement expenditure that is chosen optimally by each firm. The joint production of industrial goods and emissions is given by

$$x = (1-\theta)\frac{l}{a} \tag{6}$$

$$e = \varphi(\theta)\frac{l}{a} \tag{7}$$

with $0 \leq \theta < 1$. Emissions are determined by the abatement function

$$\varphi(\theta) = \frac{(1-\theta)^{1/\alpha}}{h(f_A)} \tag{8}$$

which is characterized by $\varphi(0) = 1$, $\varphi(1) = 0$, $\varphi'(.) < 0$ and $0 < \alpha < 1$. The abatement function reflects that firms may reduce their emission intensity through two types of abatement activities that incur variable and fixed costs respectively. As already noted, θ determines the variable abatement costs, while f_A represent investments in abatement, e.g. machines and equipment that allow for reduced emissions.[11] A given reduction of emissions may be reached either through increased θ or through increased f_A, since we assume $h'(f_A) > 0$.

We proceed by using (8) to substitute for in (7), which can then be solved for $(1-\theta)$, and in turn used to substitute for $(1-\theta)$ in (6). This gives us an integrated expression for the joint production of goods and emission, and exploits the fact that although pollution is an output, it can equivalently also be treated as an input:[12]

$$x = (h(f_A)\,e)^{\alpha}\left(\frac{l}{a}\right)^{1-\alpha}. \tag{9}$$

Hence, with such an interpretation, production implies the use of labour as well as emission. Note that while firms are heterogeneous with respect to labour productivity and abatement, they are identical with respects to the structure of their basic production technology and face the same tax rate on emissions. Firms minimize costs subject to the production function (9), taking wages ($w = 1$) and emission taxes ($t > 0$) as given. Disregarding the sunk entry

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[11] We depart from the standard formulation of the abatement function in the literature on trade and emissions by assuming that firms can have an impact on emission intensity through fixed abatement investments (f_A).

[12] See Copeland and Taylor (2003) for a discussion of this feature of the model.

cost we can derive firms' total cost function using (5) and (9).

$$C = f + f_A + \kappa \left(\frac{t}{h\left(f_A\right)} \right)^{\alpha} a^{(1-\alpha)} x \tag{10}$$

with $\kappa \equiv \alpha^{-\alpha} \left(1 - \alpha\right)^{\alpha - 1}$ and where $f = f_D$ for firms only serving the domestic market, and $f = f_D + f_X$ for exporters, i.e. firms serving both the domestic and the foreign market. The cost function reflects that emissions are not for free, rather they incur a tax $t > 0$. But through increasing their investments in abatement, firms can reduce their emissions as well as their tax bill. Hence, in contrast to the other fixed costs, investment in abatement is an endogenous variable.

Our analysis focuses on steady-state equilibria and intertemporal discounting is ignored. The present value of firms is kept finite by assuming that firms face a constant Poisson hazard rate δ of "death" independently of productivity. An entering firm with productivity a will immediately exit if its profit level $\pi\left(a\right)$ is negative, or will produce and earn $\pi\left(a\right) \geq 0$ in every period until it is hit by a bad shock and forced to exit.

3.3 Profit Maximization

Having drawn their productivity, firms follow a two-step decision process. We solve their problem using backwards induction: Firms first calculate their optimal pricing rule given abatement investments, second they make their decision on abatement investment given the optimal pricing rule. Implicitly they then also decide on emission intensity and on share of input factor to divert away from production and towards abatement, i.e. the variable costs of abatement. From equations (6), (7) and (8) follow that there is an inverse relationship between variable abatement costs and abatement investments.

Each producer operates under increasing returns to scale at the plant level and in line with Dixit and Stiglitz (1977), we assume there to be large group monopolistic competition between the producers in the M sector. Thus, the perceived elasticity of demand equals the elasticity of substitution between any pair of differentiated goods and is equal to σ. Regardless of its productivity, each firm then chooses the same profit maximizing markup over marginal costs (MC) equal to $\sigma/(\sigma - 1)$. This yields a pricing rule

$$p = \frac{\sigma}{\sigma - 1} MC \tag{11}$$

for each producer. Using (4) and (10) we can formulate the expression for firms' profits. We let super- and subscript D and X denote non-exporters and exporters respectively. Firms only serving the domestic market earn profits

$$\pi_D = \left(a^{1-\alpha} \left(\frac{t}{h(f_A)} \right)^{\alpha} \right)^{1-\sigma} B - f_D - f_A, \tag{12}$$

while the exporting firms, serving both the local and the foreign market, earn profits

$$\pi_X = \left(a^{1-\alpha} \left(\frac{t}{h(f_A)} \right)^{\alpha} \right)^{1-\sigma} (B + \phi B^*) - f_D - f_X - f_A, \tag{13}$$

where $B \equiv \frac{\kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}\mu L}{P^{1-\sigma}}$ in an index of the market potential of the home country, and $B^* \equiv \frac{\kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}\mu L^*}{(P^*)^{1-\sigma}}$ depicts the market potential of the foreign country, and $\phi \equiv \tau^{1-\sigma} \in \langle 0, 1]$ depicts the freeness of trade.

3.4 Fixed Cost Investments in Abatement

Having solved the second stage of firms' decision problem, we proceed to the first stage. In order to be able to derive explicit analytical expression for abatement investments we employ the specific functional form $h(f_A) = f_A^{\rho}$, with $\rho > 0$. Since firms' profits depend on whether they are exporters or non-exporters, abatement investments will differ between the two groups of firms. Maximizing non-exporting firms' profits with respect to abatement investments f_A using (12) gives:

$$f_A^D = (1-\beta)^{\frac{1}{\beta}} B^{\frac{1}{\beta}} t^{-\frac{\alpha(\sigma-1)}{\beta}} a^{-\frac{(1-\alpha)(\sigma-1)}{\beta}}, \tag{14}$$

with $\beta \equiv 1 - \alpha\rho(\sigma - 1)$. Profit maximization requires that $\beta > 0$. Hence, we assume that this is always true, see Section A.3 in the Appendix. The optimal investment in abatement for exporters is found using (13):

$$f_A^X = (1-\beta)^{\frac{1}{\beta}} (B + \phi B^*)^{\frac{1}{\beta}} t^{-\frac{\alpha(\sigma-1)}{\beta}} a^{-\frac{(1-\alpha)(\sigma-1)}{\beta}}. \tag{15}$$

From (14) and (15) follow that firms' abatement investments depend on their exogenously given marginal productivity, taxes, and the market potential.[13] Having examined (14) and (15) we can formulate the following propositions on the relationship between abatement investments and firm characteristics.

Proposition 1. *More productive firms invest more in abatement.*

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[13] Note that the effects of trade liberalisation (a higher ϕ) cannot be seen from this equation since B and B^* are functions of ϕ.

Proof. The statement follows directly from (14) and (15). The logic behind this result is that more productive firms have higher sales. Hence, the exploiting of scale economies makes it profitable for them to make a higher investment in order to reduce marginal costs. ☐

Proposition 2. *For any given level of productivity, exporters invest more in abatement than non-exporters.*

Proof. Since $\left(\frac{B+\phi B^*}{B}\right)^{\frac{1}{\beta}} > 1$ it follows from (14) and (15) that $f_A^X > f_A^D$ for any given productivity level $(1/a)$.

Note, that for any given level of productivity, exporters invest more in abatement since abatement investment are correlated with firms' market potential. As regards abatement intensity, i.e. abatement investment relative to value of output, it can be shown that exporters and non-exporters have the same abatement intensity. ☐

3.5 Cut off Conditions and Free Entry

Finally, based on equilibrium abatement investments, we can now determine the cut off conditions for the two types of active firms. The cut off productivity level for firms only serving the domestic market $(1/a_D)$ identifies the lowest productivity level of producing firms. From (12) and (13), we see that profits are increasing in firms' productivity. The least productive firms expect negative profits and therefore exit the industry. This applies to all firms with a unit labour input coefficient above a_D, the point at which profits from domestic sales equal zero, and is determined by

$$\left(a_D^{1-\alpha}\left(\frac{t}{h(f_A^D)}\right)^{\alpha}\right)^{1-\sigma} B = f_D + f_A^D. \tag{16}$$

With $\sigma > 1$ it follows that $a^{(1-\alpha)(1-\sigma)}$ increases along with productivity and can thus be used as a productivity index. Exporters' abatement investments affect the production and profits earned both in the home market and the foreign market. The cut-off productivity level for exporters (a_X) identifies the lowest productivity level of exporting firms, and is given by the productivity level where the export profits plus the net extra profit in the home market from the higher abatement investments equals the extra fixed costs incurred by exporting and the incremental investment in abatement:

$$\left(a_X^{1-\alpha}\left(\frac{t}{h(f_A^X)}\right)^{\alpha}\right)^{1-\sigma} \phi B^* + \left(a_X^{1-\alpha}\left(\frac{t}{h(f_A^X)}\right)^{\alpha}\right)^{1-\sigma} B - \left(a_X^{1-\alpha}\left(\frac{t}{h(f_A^D)}\right)^{\alpha}\right)^{1-\sigma} B = f_X + f_A^X - f_A^D, \tag{17}$$

We note that since abatement investments have an impact on firms' marginal costs, it also affects the profitability of being a domestic versus an exporting firm.[14]

The model is closed by the free-entry condition

$$f_E = \int_0^{a_X} \pi_X dG(a) + \int_{a_X}^{a_D} \pi_D dG(a). \tag{18}$$

3.6 Environmental Emissions

Taking abatement investment as given, firms decide on their use of labour as well as on emissions. As we are primarily interested in emissions, we shall focus on these. Firms' participation in trade affects their investment in abatement and therefore the emission intensity (emissions relative to output) of firms.

The general expression for emission intensity is found by using Shepard's lemma on the cost function (10) as we exploit that due to the special features of the model, emissions appear not only as an output of production, but also as an input to production:

$$\frac{e}{x} = \alpha\kappa t^{\alpha-1} f_A^{-\rho\alpha} a^{1-\alpha} \tag{19}$$

We see that there is a simple relationship between abatement investment and emission intensity. The more a firm invest in abatement, the lower its emission intensity. Using (14) and (15), to substitute in (19) gives the emission intensity of non-exporters and exporters respectively:

$$\frac{e^D}{x} = \alpha\kappa t^{\frac{\alpha-\beta}{\beta}} B^{-\frac{\rho\alpha}{\beta}} \left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} a^{\frac{1-\alpha}{\beta}}, \tag{20}$$

$$\frac{e^X}{x} = \alpha\kappa t^{\frac{\alpha-\beta}{\beta}} (B+\phi B^*)^{-\frac{\rho\alpha}{\beta}} \left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} a^{\frac{1-\alpha}{\beta}} \tag{21}$$

A set of results on the relationship between emissions, firm characteristics, taxes and trade emerge directly from equations (20) and (21):

Proposition 3. *More productive firms have a lower emission intensity.*

Proof. The statement follows directly from equations (20) and (21). □

Proposition 4. *For any given level of productivity, an exporter would have a lower emission intensity than a non-exporter.*

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[14] The paper is in this sense related to the literature on trade induced technological upgrading. See e.g. Bas (2008) and Bustos (2011).

Proof. The statement follows from (20), (21), and the fact that $(B+\phi B^*)^{-\frac{\rho\alpha}{\beta}} < B^{-\frac{\rho\alpha}{\beta}}$. $\square$

Note that the latter proposition is based on a thought experiment, since according to the model, depending on productivity level a firm is either an exporter *or* a non-exporter. There is no such productivity level at which some firms are exporters and some are non-exporters. Note also that Proposition 3 holds for $\rho = 0$ as seen from (19). Thus, more productive producers would have a lower emission intensity even without the fixed abatement cost. However, without the fixed abatement cost, which introduces scale economies in abatement, there would be no intrinsic difference in emissions between exporters and non-exporters implying that Proposition 4 would not hold.

3.7 Trade Liberalization, Abatement and Emissions

Eventually we want to investigate the relationship between trade liberalization, abatement and emissions. In order to analyze the effects of trade liberalization we need to fully solve the model. This requires that we make additional assumptions with respect to market size. We proceed by assuming that the two economies are identical regarding tax regime and market size. Hence, we solve the model for $t = t^*$ and $B = B^*$. Due to symmetry it suffices to solve for equilibrium in the home country. Equations (14), (15), (16), (17), and (18) determine the endogenous variables $\overline{f}^D_A, \overline{f}^X_A, \overline{a}_D, \overline{a}_X$, and $\overline{B}$, where we use upper bar to denote equilibrium values derived based on the symmetry assumption. This gives us the following two expressions for the cut-off productivities:[15]

$$\overline{a}^k_D = \frac{f_E}{\left(\frac{\gamma}{k\beta-\gamma}\right) f_D \left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}} f_D^{\frac{k\beta}{\gamma}-1} f_X^{1-\frac{k\beta}{\gamma}}+1\right)}, \tag{22}$$

$$\overline{a}^k_X = \frac{f_E}{\left(\frac{\gamma}{k\beta-\gamma}\right) f_X \left(1+\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{-\frac{k\beta}{\gamma}} f_X^{\frac{k\beta}{\gamma}-1} f_D^{1-\frac{k\beta}{\gamma}}\right)}, \tag{23}$$

with $\beta \equiv 1-\alpha\rho(\sigma-1)$, $\beta \in (0.1)$, and $\gamma \equiv (1-\alpha)(\sigma-1) > 0$. Note that the equilibrium expressions reduce to the standard Melitz (2003) cut-off conditions for $\alpha = 0$, in which case production does not entail any emissions. Exporters are more productive than non-exporters, i.e. $a_X < a_D$,as long as $\frac{f_X}{f_D\left((1+\phi)^{\frac{1}{\beta}}-1\right)} > 1$, and we assume this to hold.[16] We also assume

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[15] See the Appendix Section A.8 for details on calculation.

[16] The corresponding condition in the standard Melitz model is $\frac{f_X}{f_D\phi} > 1$.

that $k\beta > \gamma$, which guaranties that the cut off productivities are positive.[17] From (22) and (23) follow that trade liberalization will make the domestic cut-off tougher, i.e. a_X increases, which is in line with the results in the standard Melitz model.

3.7.1 Trade liberalization and Abatement Investments

Using (16) and substituting for the cut off productivity employing (22) we can calculate B. Substituting this into (14) and (15) we derive the abatement investments for non-exporters (f_A^D) and exporters (f_A^X) for the symmetric equilibrium case:

$$\overline{f}_A^D = \left(\frac{1-\beta}{\beta}\right) f_D \left(\frac{a}{\overline{a}_D}\right)^{-\frac{\gamma}{\beta}}, \tag{24}$$

$$\overline{f}_A^X = \left(\frac{1-\beta}{\beta}\right) (1+\phi)^{\beta} f_D \left(\frac{a}{\overline{a}_D}\right)^{-\frac{\gamma}{\beta}}. \tag{25}$$

We can now formulate the following proposition on the effect of trade liberalization on abatement investments:

Proposition 5. *Trade liberalization (higher ϕ) will decrease non-exporting firms' abatement investments. Trade liberalization will always increase exporters' abatement investments for sufficiently high trade costs.*

Proof. See the Appendix, Section A.4.

Trade liberalization increases competition, which leads to lower sales for the non-exporters. This implies that the least productive firms close down and the remaining firms lower their abatement investments. Exporters also face increased competition in the domestic market, but on the other hand, they also experience higher sales in the foreign market as trade is liberalized. For higher level of trade costs, the latter effects dominate and leads to increased investment in abatement. However, as trade costs reach a low level, the former effect gets stronger, and as a consequence, investments in abatement may be reduced. ☐

3.7.2 Trade liberalization and Emission Intensity

Next, we turn to the effect of trade liberalization on emission intensity. Again we use (16) and (22) to calculate $\bar{B}$, and substitute this into (20) and (21) in order to derive emission

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[17] The condition may be written: $\frac{k}{\sigma-1} > 1 - \alpha + \alpha k \rho$, which reduces to the standard condition that $\frac{k}{\sigma-1} > 1$ for $\alpha = 0$.

intensities for domestic firms and exporters for the symmetric case:

$$\frac{\bar{e}^D}{\bar{x}} = \alpha\kappa t^{\alpha-1} \bar{f}_D^{-\rho\alpha} \bar{a}_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left(\frac{\beta}{1-\beta}\right)^{\rho\alpha} a^{\frac{1-\alpha}{\beta}}, \tag{26}$$

$$\frac{e^{\bar{X}}}{\bar{x}} = \alpha\kappa t^{\alpha-1} \bar{f}_D^{-\rho\alpha} (1+\phi)^{-\frac{\rho\alpha}{\beta}} \bar{a}_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left(\frac{\beta}{1-\beta}\right)^{\rho\alpha} a^{\frac{1-\alpha}{\beta}}. \tag{27}$$

Making use of (22), gives us the following propositions:

Proposition 6. *Trade liberalization (a higher ϕ) leads to a higher emission intensity among non-exporters. Trade liberalization leads to a lower emission intensity among exporters if $k > (\phi + 1)^{\frac{1}{\beta}}$.*

Proof. See Section A.5 in the Appendix. □

We observe that the higher the initial level of trade costs prior to liberalization, the more likely is it that trade liberalization will have a benign impact on emissions.

3.7.3 Trade liberalization and Total Emissions

Trade liberalization affects emissions by weeding out some of the least productive firms with low abatement investments and accordingly high emission intensities. For relatively high levels of initial trade costs trade liberalization moreover induces exporters to invest more in abatement, which in turn lowers their emission intensity. However, trade liberalization also implies lower abatement investments by non-exporters and larger production volumes as such for the exporters, both of which contribute to higher total emissions. The overall effect of trade liberalization depends on the net effect of this set of effects. We proceed by analyzing total emissions by the non-exporters and the exporters separately. Total emissions are finally given by the sum of these. Total emissions by non-exporters and exporters are given by the integrals

$$\overline{E}_D = \overline{n} \int_{a_{\bar{X}}}^{\bar{a}_D} \overline{e}\, dG(a \mid \overline{a}_D), \tag{28}$$

and

$$\overline{E}_X = \overline{n} \int_0^{\bar{a}_X} \overline{e}\, dG(a \mid \overline{a}_D). \tag{29}$$

Solving these integrals conditional on firm entry gives the expressions for emissions of non-exporters and exporters respectively. The derivation of these expressions is found in the Appendix Section A.8. Total emissions of non-exporters are given by

$$\overline{E}_D = \frac{\alpha\left(\sigma-1\right)\left(1-\left(\left(\left(\phi+1\right)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{\gamma}-1}\right)}{\sigma\left(1+\phi\left(1+\phi\right)^{\frac{1-\beta}{\beta}}\left(\left(\left(\phi+1\right)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{\gamma}-1}\right)} t^{-1}\mu L. \tag{30}$$

The expression leads to the following proposition:

Proposition 7. *Trade liberalization decreases total emissions of non-exporting firms.*

Proof. The proposition follows directly from (30), given our assumption that $k\beta > \gamma$. □

The weeding out of the least productive and dirtiest firms together with lower production volumes for those remaining lead to falling emissions by non-exporters. Trade liberalization also leads to a lower mass of firms, which also contributes lower emissions. These benign effects on emissions overshadow the fact that all non-exporters decrease their abatement emissions (see Proposition 5).

Total emissions by exporters are given by

$$\overline{E}_X = \frac{\alpha\left(\sigma-1\right)}{\sigma\left(\left(\frac{f_X}{f_D}\right)^{\frac{k\beta}{\gamma}-1}\left(1+\phi\right)^{-\frac{1}{\beta}}\left(\left(1+\phi\right)^{\frac{1}{\beta}}-1\right)^{1-\frac{k\beta}{\gamma}}+\frac{\phi}{(1+\phi)}\right)} t^{-1}\mu L. \tag{31}$$

Even if the condition in Proposition 6 holds, so that the emission intensity of exporters decrease, this group of firms always increases its emissions because of increased total production volume:

Proposition 8. *Trade liberalization increases total emissions from exporters.*

Proof. See section A.6 in the Appendix. □

The question now is what the overall effect of on emissions is. Adding emissions by exporters and non-exporters give

$$\overline{E} = \frac{\alpha\left(\sigma-1\right)}{\sigma}\left(\frac{1-\left(\frac{f_X}{f_D}\right)^{1-\frac{k\beta}{\gamma}}\left(1+\phi\right)^{\frac{1}{\beta}}\left(\left(1+\phi\right)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}}}{\left(1+\left(\frac{f_X}{f_D}\right)^{1-\frac{k\beta}{\gamma}}\phi\left(1+\phi\right)^{\frac{1}{\beta}-1}\left(\left(1+\phi\right)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}-1}\right)}\right) t^{-1}\mu L, \tag{32}$$

which leads to the following proposition:

Proposition 9. *Trade liberalization, i.e. higher ϕ, decreases total emissions.*

Proof. The proposition follows directly from (32). $\square$

Hence, we find that in the case with symmetric countries, the overall effect of trade liberalization is to decrease emissions. Trade increases production volumes but the combined effect of the weeding out of low productive and dirty firms, the higher abatement investments by exporters, and the shift of production from dirty non-exporters to relatively clean exporters, leads to lower overall emissions. Note that emissions implied by transportation are accounted for in the analysis due to how they are modeled. Iceberg transportation costs imply that transportation costs are in incurred terms of the good transported, and emissions related to the production of the quantity that is absorbed by transportation are thus accounted for in equation (32).

4 Empirical Design and Results

4.1 Environmental Emission Intensity and Exports

Based on our theoretical model we expect there to be a relationship between emission intensity and export status. More specifically, we expect exporters to have relatively lower emission intensity than non-exporters. This is ultimately driven by exporters facing a higher market potential, therefore find it profitable to invest relatively more in abatement and as a consequence, emit relatively less.

We proceed by taking the model's predictions on the relationship on firms' exporting and emission intensity to the data. We examine three types of environmental emissions, CO2 , SO2 and NOx emissions. We calculate emission intensity at the firm level as total emissions relative to value added. In the model emission intensity is given by total emissions relative to the value of output. But taking the model to the data, we need to account for purchases of intermediates, see Section 2.1. Value added defined by the value of output minus value of intermediates provides a more correct measure of the firms' activity in Sweden. The theoretical model suggests a log linear specification between emission intensity on the one hand, and productivity ($1/a$), market potential (MP) and taxes (t) on the other hand (see equations (20) and (21)):

$$ln(\frac{e^D}{x}) = ln\left(\frac{\alpha\kappa}{1-\beta}\right) + \frac{\alpha-\beta}{\beta}ln(t) - \frac{\rho\alpha}{\beta}ln(MP) + \frac{1-\alpha}{\beta}ln(a), \tag{33}$$

where firms differ in their market potential depending on whether they serve the just the domestic market ($MP = B$) or both the domestic as well as the export market ($MP = B + \phi B^*$).

In order to handle concerns about endogeneity of the right hand side variables we utilise the fact that there is a discontinuous jump in the market potential when comparing an exporter and a non-exporter. According to our theory, productivity is the forcing variable. It drives the export status of a firm as well as the firm level emission intensity. From (20) and (21) follow that for any given level of productivity, an exporter will have lower emission intensity than a non-exporter. However, while productivity has a continuous effect on the emission intensity, the model predicts a discontinuous jump down in the emission intensity when we compare an exporter to a non-exporter. We exploit this discontinuity by proxying for market potential by using a dummy for export status which takes the value one if the firm has positive export income, and the value zero otherwise. Moreover, we control for firm productivity in a very flexible manner using a continuous polynomial up to the fourth order. Firms' productivity is measured by total factor productivity (TFP), and is calculated from estimates of productivity functions using the method by Levinsohn and Petrin (2003).[18] Emission taxes (t) for all three kinds of emissions are uniform across firms apart from those exposed to EU-ETS, and have only changed slightly over time. Hence, we account for these as well as other time trends by including year fixed effects. Most firms in the energy intensive industries, and a few firms in the non-energy intensive industries, have since the start of our period of observation (year 2005) been included in the EU Emission Trading System (EU-ETS). These firms are exempted from the national CO2 tax. Hence, we add firm- year fixed effects to control for whether or not a firm face EU-ETS .

We consequently estimate the emission intensity of firm i in industry j in year t as

$$\ln \text{Emission intensity}_{ijt} = \alpha_0 + f(\log \text{productivity}_{ijt}) + \alpha_2 \text{Exporter}_{ijt} + \Lambda_t + EUETS_{it} + \Gamma_j + \varepsilon_i \tag{34}$$

where f is a polynomial function of firm $i's$ productivity in year t, and Exporter$_{ijt}$ equals one if the firm exports in year t, and zero otherwise, Λ_t depicts year fixed effects, EUETS$_{it}$ is a firm-year specific dummy taking the value one if the firm is exposed to EU-ETS , and zero otherwise, while variation in emissions across industries is picked up by Γ_j, which is an industry dummies based on NACE 5-digit industries.

We estimate equation (34) for CO2, SO2 and NOx emission intensity. Results are reported in Tables 3-5 respectively. We report regression results where errors are clustered at the firm level, while noting that clustering at the sector level gives very similar results. In Tables 35 we report the OLS results for estimations based on the entire samples. We

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[18] Production functions are estimated at the two-digit sector level, where we use value added as measure of firm output. Explanatory variables are labour (measured by the wage bill) and capital. Finally we use raw materials as proxy for contemporaneous productivity shocks. All variables are in logs.

report results for five different specifications with respect to the modeling of the productivity variable. In line with what our theory with fixed abatement investments would predict, we find that the coefficients for the exporter dummy are negative and significant at the one percent level in all specifications. This is true for all three types of environmental emissions. Exporters emit around 12 percent less CO2 per unit of output than non-exporters active in the same industry. They also have 31 percent less SO2 and 21 percent NOx emissions relative to their value added than their peers in the same industry.[19] There are obviously huge variations in emission intensity across industries. Hence, including industry dummies increases the R-square substantially. We have also explored the impact of using industry dummies based on a more aggregate industry classification (2 digit level). Not surprisingly, the results are roughly the same as with the finer classification, but the fit of the model as suggested by the R- square is reduced.

Table 3: CO2 emission intensity, productivity and exporting (OLS), I

Dependent variable: ln CO2 emission intensity	(1)	(2)	(3)	(4)	(5)
Exporter	-.317^a	-.109^a	-.112^a	-.114^a	-.114^a
	(.038)	(.038)	(.038)	(.038)	(.038)
ln TFP	none	linear	2nd order polynom.	3rd order polynom.	4th order polynom.
Industry FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
EUETS firm-Year FE	Yes	Yes	Yes	Yes	Yes
R-squared	.32	.35	.35	.35	.35
No. of obs.	26928	26468	26468	26468	26468

Note: OLS estimates are based on the panel 2005-2011. Errors are clustered at the firm level. ^{a}significant at 1% level, ^{b}significant at 5% level, ^{c}significant at 10% level.

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[19] This is based on the calculation: $100 * (exp(\alpha_2) - 1)$

Table 4: SO2 emission intensity, productivity and exporting (OLS), I

Dependent variable: ln SO2 emission intensity					
	(1)	(2)	(3)	(4)	(5)
Exporter	-.667^a	-.267^a	-.278^a	-.267^a	-.267^a
	(.073)	(.065)	(.065)	(.064)	(.064)
ln TFP	none	linear	2nd order polynom.	3rd order polynom.	4th order polynom.
Industry FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
R-squared	.31	.37	.37	.37	.37
No. of obs.	8392	8256	8256	8256	8256

Note: OLS estimates are based on the panel 2000-2011. Errors are clustered at the firm level. ^{a}significant at 1% level, ^{b}significant at 5% level, ^{c}significant at 10% level.

Table 5: NOx emission intensity, productivity and exporting (OLS), I

Dependent variable: ln NOx emission intensity					
	(1)	(2)	(3)	(4)	(5)
Exporter	-.538^a	-.171^a	-.184^a	-.187^a	-.187^a
	(.057)	(.054)	(.054)	(.054)	(.054)
ln TFP	none	linear	2nd order polynom.	3rd order polynom.	4th order polynom.
Industry FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
R-squared	.38	.43	.43	.43	.43
No. of obs.	10253	10090	10090	10090	10090

Note: OLS estimates are based on the panel 2000-2011. Errors are clustered at the firm level. ^{a}significant at 1% level, ^{b}significant at 5% level, ^{c}significant at 10% level.

The descriptive statistics presented in Section 2.2 suggested that energy and non-energy intensive industries differ significantly. Hence, to allow for variation between the energy and non-energy intensive industries, we proceed by splitting the sample into energy intensive industries and non energy intensive industries. The results are reported for both groups of industries in Tables 6-8. It appears that exporting goes hand in hand with lower emission intensity in the non-energy intensive, while we do not find any significant relationship between exporting and emission intensity in the energy intensive industries. Hence, the results on a benign impact of exporting on emissions are driven by firms in the former group of industries, which is responsible for around 80 percent of the employment in the manufacturing sector in Sweden.

Table 6: CO2 emission intensity, productivity and exporting (OLS), II

Dependent variable: ln CO2 emission intensity								
	Energy intensive industries				Non-energy intensive industries			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Exporter	-.257^c	-.243^c	-.186	-.192	-.087^b	-.092^b	-.089^b	-.089^b
	(.146)	(.142)	(.145)	(.146)	(.039)	(.039)	(.039)	(.039)
ln TFP	linear	2nd order polynom.	3rd order polynom.	4th order polynom.	linear	2nd order polynom.	3rd order polynom.	4th order polynom.
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
EUETS firm-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	.44	.45	.46	.46	.31	.31	.31	.31
No. obs.	3207	3207	3207	3207	23660	23261	23261	23261

Note: OLS estimates are based on the panel 2005-2011. Errors are clustered at the firm level.

^{a}significant at 1% level, ^{b}significant at 5% level, ^{c}significant at 10% level.

Table 7: SO2 emission intensity, productivity and exporting (OLS), II

Dependent variable: ln SO2 emission intensity								
	Energy intensive industries				Non-energy intensive industries			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Exporter	-.371	-.379	-.269	-.238	-.199^a	-.221^a	-.205^a	-.201^a
	(.261)	(.262)	(.261)	(.259)	(.062)	(.061)	(.059)	(.059)
ln TFP	linear	2nd order polynom.	3rd order polynom.	4th order polynom.	linear	2nd order polynom.	3rd order polynom.	4th order polynom.
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	.40	.40	.40	.41	.36	.36	.36	.36
No. obs.	1753	1753	1753	1753	6503	6503	6503	6503

Note: OLS estimates are based on the panel 2000-2011. Errors are clustered at the firm level.

^{a}significant at 1% level, ^{b}significant at 5% level, ^{c}significant at 10% level.

Table 8: NOx emission intensity, productivity and exporting (OLS), II

Dependent variable: ln NOx emission intensity								
	Energy intensive industries				Non-energy intensive industries			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Exporter	-.031	-.035	.017	-.001	-.135[a]	-.158[a]	-.149[a]	-.146[a]
	(.191)	(.191)	(.192)	(.192)	(.053)	(.052)	(.052)	(.051)
ln TFP	linear	2nd order polynom.	3rd order polynom.	4th order polynom.	linear	2nd order polynom.	3rd order polynom.	4th order polynom.
Industry FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R-squared	.40	.40	.41	.42	.42	.42	.42	.42
No. obs.	2240	2240	2240	2240	7850	7850	7850	7850

Note: OLS estimates are based on the panel 2000-2011. Errors are clustered at the firm level.

[a]significant at 1% level, [b]significant at 5% level, [c]significant at 10% level.

4.2 Abatement and Exports

Our theory proposes a mechanism through which firms' export status affects their abatement investment and thereby their emission intensity. According to the theory, fixed investment costs must be presented in order for exporting to have a benign impact on emission intensity. The availability of abatement investment data allows us to test directly the model's predictions on exporting and abatement. Similarly as in the case with emission intensity, the theoretical model suggests a log linear specification between abatement investments on the one hand, and productivity ($1/a$), market potential (MP) and taxes (t) on the other hand (see equations (14) and (15)):

$$ln\,(f_A) = ln(1-\beta)^{\frac{1}{\beta}} + \frac{1}{\beta} ln\,(MP) - \frac{\alpha(\sigma-1)}{\beta} ln\,(t) - \frac{(1-\alpha)(\sigma-1)}{\beta} ln\,(a)\,, \qquad (35)$$

where firms differ in their market potential depending on whether they serve the just the domestic market ($MP = B$) or both the domestic as well as the export market ($MP = B + \phi B^{*}$). We follow the same empirical strategy as with emission intensity, and let export status proxy for a discrete increase in market potential while we control for firm productivity in a very flexible manner using a continuous polynomial up to the fourth order. Consequently, we estimate abatement investment of firm i in industry j in year t as

$$\ln \text{Abatement investment}_{it} = \alpha_0 + f(\log \text{productivity}_{it}) + \alpha_2 \text{Exporter}_{it} + \Lambda_t + EUETS_{it} + \Gamma_j + \varepsilon_i \qquad (36)$$

where f is a polynomial function of firm $i's$ productivity in year t, and Exporter_{ijt} equals one if the firm exports in year t, and zero otherwise, Λ_t depicts year fixed effects, EUETS_{it} is a firm-year specific dummy taking the value one if the firm is exposed to EU-ETS , and zero otherwise, while variation in emissions across industries is picked up by Γ_j, which is an industry dummies based on NACE 5-digit industries. Industry, time and EU-ETS controls are the same as employed when estimating the relationship between emission intensities and exporting. However, as the estimations based on the split samples reveal that the results on exporting and emission intensities are driven by the non-energy intensive industries firms, we limit the analysis to these industries. In Table 9 we report the results from estimating equation (36) using OLS.[20] Again, we report results for five different specifications with respect to the modeling of the productivity variable. Our results suggest that exporters make significantly higher investment in abatement than non-exporters. Controlling for industry, an exporter invests about twice as much in abatement as a non-exporter.[21]

Table 9: Abatement, productivity and exporting (OLS)

Dependent variable: ln Abatement Investments	(1)	(2)	(3)	(4)	(5)
Exporter	1.157^a	$.616^a$	$.658^a$	$.627^a$	$.728^a$
	(.218)	(.200)	(.203)	(.200)	(.196)
ln TFP	none	linear	2nd order polynom.	3rd order polynom.	4th order polynom.
Industry FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
EUETS Year FE	Yes	Yes	Yes	Yes	Yes
R-squared	.22	.28	.28	.28	.24
No. obs.	5906	5774	5774	5774	5774

Note: OLS estimates are based on the panel 2000-2011 for non-energy intensive industries. Errors are clustered at the firm level.

^{a}significant at 1% level,^{b}significant at 5% level, ^{c}significant at 10% level.

5 Conclusion

This paper analyses environmental emissions and exporters within a framework with heterogeneous firms and trade. We develop a theoretical model that proposes a mechanism for why exporters may be expected to have lower emission intensities than non-exporters: In line with the standard theory on heterogeneous firms and trade, the most productive firms

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[20] Yearly firm level abatement investments vary between 0 and more than 400 mio SEK. In order not to exclude the firms with zero abatement investments from the sample as we use logs, we let the dependent variable be $\ln(abatement\ investments + 1)$.

[21] Which is found using that $100 * (exp(0.728) - 1) = 107$.

become exporters. Exporters' larger production scale supports higher fixed investments in abatement which in turn reduces both their emission tax bills and their emission intensity. Hence, according to our model we would expect emission intensity to be negatively related to firm-level productivity and export status.

Solving the model for symmetric countries we find that trade liberalization allows for a higher production volume and make new exporters cleaner as they are induced to invest more in abatement. But trade liberalization also makes non-exporters dirtier as these firms are forced to downsize and reduce their investments in abatement. We show that the overall effect of trade liberalization is to reduce emissions. This is a result of the less productive and dirtiest firms being weeded out, and of production being shifted from relatively dirty non-exporters to more efficient and cleaner exporting firms.

A rich firm-level data set for Swedish manufacturing firms that includes information on firm-level abatement investments and firm-level environmental emissions for CO2, SO2 and NOx allows us to test the empirical predictions of the model on the relationship between productivity, export status and emission intensity as well as on productivity, export status and abatement investments. Productivity is the forcing variable in our model. It drives the firm level emission intensity as well as the export status of a firm. While productivity has a continuous effect on the emission intensity, the model predicts a discontinuous jump down in the emission intensity as we compare exporters to non-exporters. We therefore estimate the relationships between exporting, abatement and emission intensity controlling for firm productivity in a very flexible manner using a continuous polynomial up to the fourth order. The empirical results strongly support the notion that the firm-level environmental emission intensity is negatively related to firm productivity and to being an exporter. The estimated coefficient for the entire sample implies that exporters have a 10-30 percent lower emission intensity of CO2, SO2 and NOx.

The availability of abatement investment data allows us furthermore to explicitly investigate the relationship between abatement investments and export status.The estimated coefficients are in line with what the theory predicts, and suggest that there is a positive relationship between exporting and productivity on the hand side and abatement on the other side. The empirical results suggest that exporters invest on average twice as much in abatement.

The paper provides both theoretical arguments as well as empirical evidence of one mechanism whereby which international trade can have a benign effect working against climate change, as it promotes investments abatement, leads to lower environmental emission intensity and lower total emissions. We also provide evidence on exporters having lower emission intensity. These effects of trade on environmental emissions stand in stark contrast to the predictions of e.g. the pollution haven hypothesis, which suggests that international trade will tend to increase emissions, as it decreases the effects of environmental regulations by making it easier for firms to expand polluting activities in countries with less stringent environmental standards.

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A Appendix

A.1 Decomposition of Emission intensity

The variance of the emission intensity is decomposed into a between and a within effect using the following decomposition

$$\frac{1}{N_i}\sum_i\left(\frac{e_i}{x_i}-\frac{\overline{e}}{x}\right)^2=\frac{1}{N_i}\sum_s\sum_{i\in s}\left(\frac{e_i}{x_i}-\frac{\overline{e_s}}{x_s}\right)^2+\frac{1}{N_i}\sum_s N_s\left(\frac{\overline{e_s}}{x_s}-\frac{\overline{e}}{x}\right)^2,$$

where subscript i refer to the firm, subscript s refer to sector (5 digit level), N_i and N_s are the total number of firms and sectors respectively, e denote emissions, x denote output and $\frac{\overline{e}}{x}$ and $\frac{\overline{e_s}}{x_s}$ are the overall and sector specific average emission intensities.

The between variation is found by regressing firms' emission intensity on sector dummies at the 5-digit level. The within variation is accordingly calculated as one minus the R-square from the regression analysis.

A.2 Descriptive Statistics on Exporter versus Non-Exporters

Table 10: Firm characteristics: Exporters versus Non-Exporters

	Exporters vs. Non-Exporters
Productivity (FTP)	2.63
Capital intensity (Capital/Employees)	1.35
Firm Size (No of Employees)	11.87

Note: Exporters vs. Non-Exporters gives the ratio of mean exporter relative to mean non-exporter for productivity, capital intensity and firm size respectively.
Calculations are based on the panel 2000-2011.

A.3 Optimal abatement and productivity level

The optimal level of abatement investments is given by:

$$f_A^D=\left\{\frac{1}{B}\left(a^{1-\alpha}t^{\alpha}\right)^{\sigma-1}\frac{1}{\alpha\rho(\sigma-1)}\right\}^{\frac{1}{\alpha\rho(\sigma-1)-1}}=\Omega_D a^{\frac{(1-\alpha)(\sigma-1)}{\alpha\rho(\sigma-1)-1}} \tag{37}$$

We differentiate optimal abatement level with respect to productivity level:

$$\frac{\partial f_A^D}{\partial a}=\frac{(1-\alpha)(\sigma-1)}{\alpha\rho(\sigma-1)-1}\Omega_D a^{\frac{(1-\alpha)(\sigma-1)}{\alpha\rho(\sigma-1)-1}-1}<0 \tag{38}$$

i.e. abatement investments are increasing in firms' productivity level, provided that:

$$\alpha\rho(\sigma-1)-1<0 \tag{39}$$

However, we assume this condition will always hold, as it is a necessary condition for profit maxmization:

$$\frac{\partial^2 \pi_D}{\partial \left(f_A^D\right)^2} = (\alpha\rho(\sigma-1)-1)\alpha\rho(\sigma-1)\left(a^{1-\alpha}t^{\alpha}\right)^{1-\sigma}\left(f_A^D\right)^{-\alpha\rho(1-\sigma)-2} B < 0 \;\; \nabla \;\; \alpha\rho(\sigma-1)-1<0 \tag{40}$$

and it implies that abatement has a decreasing marginal effect on firms' profit:

A.4 Proof of Proposition 5

A.4.1 Proof that $\frac{d\overline{f}_A^D}{d\phi} < 0$

The cut-off of non-exporters is given by:

$$\overline{a}_D = \left(\frac{f_E}{\left(\frac{\gamma}{k\beta-\gamma}\right) f_D \left(\left((\phi+1)^{\frac{1}{\beta}} - 1 \right)^{\frac{k\beta}{\gamma}} f_D^{\frac{k\beta}{\gamma}-1} f_X^{1-\frac{k\beta}{\gamma}} + 1 \right)} \right)^{\frac{1}{k}} \tag{41}$$

From this equation follows that:

$$\frac{d\overline{a}_D}{d\phi} < 0 \tag{42}$$

Next, the abatement investments by non-exporters are given by:

$$\overline{f}_A^D = \left(\frac{1-\beta}{\beta}\right) f_D \left(\frac{a}{\overline{a}_D}\right)^{-\frac{\gamma}{\beta}} \tag{43}$$

From this equation follows that:

$$\frac{d\overline{f}_A^D}{d\overline{a}_D} > 0 \tag{44}$$

Thus, using (42) and (44), we have that:

$$\frac{d\overline{f}_A^D}{d\phi} = \frac{d\overline{f}_A^D}{d\overline{a}_D}\frac{d\overline{a}_D}{d\phi} < 0$$

A.4.2 Proof of condition for $\frac{d\overline{f}_A^X}{d\phi} > 0$

The abatement investment by exporters is given by:

$$\overline{f}_A^X = \left(\frac{1-\beta}{\beta}\right)(1+\phi)^{\beta} f_D \left(\frac{a}{\overline{a}_D}\right)^{-\frac{\gamma}{\beta}} \tag{45}$$

Differentiating w.r.t. ϕ gives:

$$\begin{aligned}\frac{\partial \overline{f}_A^X}{\partial \phi} &= \frac{\partial \overline{f}_A^X}{\partial \phi} + \frac{\partial \overline{f}_A^X}{\partial \overline{a}_D}\frac{d\overline{a}_D}{d\phi} \\ &= \overline{f}_A^X \frac{\beta}{1+\phi} + \overline{f}_A^X \frac{\gamma}{\beta \overline{a}_D}\frac{d\overline{a}_D}{d\phi} \\ &= \overline{f}_A^X \left(\frac{\beta}{1+\phi} + \frac{\gamma}{\beta \overline{a}_D}\frac{d\overline{a}_D}{d\phi}\right)\end{aligned} \tag{46}$$

The term $\frac{d\overline{a}_D}{d\phi}$ is from (22):

$$\frac{d\overline{a}_D}{d\phi} = -\frac{\overline{a}_D\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}-1}(\phi+1)^{\frac{1}{\beta}-1}}{\gamma\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}} + f_D^{1-\frac{k\beta}{\gamma}} f_X^{\frac{k\beta}{\gamma}-1}\right)} \tag{47}$$

Substituting into (46) gives:

$$\frac{\partial \overline{f}_A^X}{\partial \phi} = \overline{f}_A^X\left(\frac{\beta}{1+\phi} - \frac{\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}-1}(\phi+1)^{\frac{1}{\beta}-1}}{k\beta\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}} + f_D^{1-\frac{k\beta}{\gamma}} f_X^{\frac{k\beta}{\gamma}-1}\right)}\right) \tag{48}$$

Hence, $\frac{\partial \overline{f}_A^X}{\partial \phi} > 0$ iff

$$\frac{\beta}{1+\phi} > \frac{\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}-1}(\phi+1)^{\frac{1}{\beta}-1}}{\beta\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}} + f_D^{1-\frac{k\beta}{\gamma}} f_X^{\frac{k\beta}{\gamma}-1}\right)}, \tag{49}$$

which can be rewritten as:

$$\beta^2\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}} + \left(\frac{f_X}{f_D}\right)^{\frac{k\beta}{\gamma}-1}\right) > (\phi+1)^{\frac{1}{\beta}}\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}-1} \tag{50}$$

By inspection, the inequality holds for ϕ close enough to autarky ($\phi = 0$). For free trade ($\phi = 1$) the condition may or may not hold depending on parameter values.

A.5 Proof of Proposition 6

First, the emission intensity of non-exporters is given by:

$$\frac{\overline{e}^D}{\overline{x}} = \alpha\kappa t^{\alpha-1} f_D^{-\rho\alpha} \overline{a}_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left(\frac{\beta}{1-\beta}\right)^{\rho\alpha} a^{\frac{(1-\alpha)}{\beta}} \tag{51}$$

Differentiation w.r.t. ϕ gives

$$\frac{d\frac{\overline{e}^D}{\overline{x}}}{d\phi} = \frac{d\frac{\overline{e}^D}{\overline{x}}}{d\overline{a}_D} \frac{d\overline{a}_D}{d\phi} > 0, \tag{52}$$

since $\alpha, \beta < 1$ and $\frac{d\overline{a}_D}{d\phi} < 0$ from (47).

Next, the emission intensity of exporters is given by:

$$\frac{\overline{e}^X}{\overline{x}} = \alpha\kappa t^{\alpha-1} f_D^{-\rho\alpha} \left(1+\phi\right)^{-\frac{\rho\alpha}{\beta}} \overline{a}_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left(\frac{\beta}{1-\beta}\right)^{\rho\alpha} a^{\frac{(1-\alpha)}{\beta}} \tag{53}$$

Differentiation w.r.t. ϕ gives:

$$\begin{aligned}
\frac{d\frac{\overline{e}^X}{\overline{x}}}{d\phi} &= \frac{d\frac{\overline{e}^X}{\overline{x}}}{d\phi} + \frac{d\frac{\overline{e}^X}{\overline{x}}}{d\overline{a}_D} \frac{d\overline{a}_D}{d\phi} \\
&= -\frac{\overline{e}^X}{\overline{x}} \frac{1}{\beta} \left(\frac{\rho\alpha}{1+\phi} + \frac{(1-\beta)(1-\alpha)}{\overline{a}_D} \frac{d\overline{a}_D}{d\phi} \right) \\
&= -\frac{\overline{e}^X}{\overline{x}} \frac{1}{\beta} \left(\frac{\rho\alpha}{1+\phi} - \frac{(1-\beta)(1-\alpha)\left((\phi+1)^{\frac{1}{\beta}} - 1\right)^{\frac{k\beta}{\gamma}-1} (\phi+1)^{\frac{1}{\beta}-1}}{k\gamma\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)^{\frac{k\beta}{\gamma}} + f_D^{1-\frac{k\beta}{\gamma}} f_X^{\frac{k\beta}{\gamma}-1}\right)} \right)
\end{aligned}$$

The differential is negative as long as the expression inside the parenthesis is negative:

$$\rho\alpha > \frac{(1-\beta)(1-\alpha)\left((\phi+1)^{\frac{1}{\beta}} - 1\right)^{\frac{k\beta}{\gamma}-1} (\phi+1)^{\frac{1}{\beta}}}{k\gamma\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)^{\frac{k\beta}{\gamma}} + f_D^{1-\frac{k\beta}{\gamma}} f_X^{\frac{k\beta}{\gamma}-1}\right)}$$

Now using that $\beta \equiv 1 - \alpha\rho(\sigma-1) < 1$, and $\gamma \equiv (1-\alpha)(\sigma-1) > 0$, this allows us to simplify the expression

$$k > \frac{\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}-1}(\phi+1)^{\frac{1}{\beta}}}{\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}}+f_D^{1-\frac{k\beta}{\gamma}}f_X^{\frac{k\beta}{\gamma}-1}\right)},$$

which can be rewritten according to

$$k > \frac{\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{-1}(\phi+1)^{\frac{1}{\beta}}}{\left(1+\frac{f_D^{1-\frac{k\beta}{\gamma}}f_X^{\frac{k\beta}{\gamma}-1}}{\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}}}\right)} = \frac{\frac{1}{\left(1-\frac{1}{(\phi+1)^{\frac{1}{\beta}}}\right)}}{\left(1+\frac{f_D^{1-\frac{k\beta}{\gamma}}f_X^{\frac{k\beta}{\gamma}-1}}{\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{\gamma}}}\right)} = \frac{(\phi+1)^{\frac{1}{\beta}}\frac{f_X}{f_D\left((\phi+1)^{\frac{1}{\beta}}-1\right)}}{\frac{f_X}{f_D}+\left(\frac{f_X}{f_D\left((\phi+1)^{\frac{1}{\beta}}-1\right)}\right)^{\frac{k\beta}{\gamma}}}$$

Note now that we have assumed that $\frac{f_X}{f_D\left((1+\phi)^{\frac{1}{\beta}}-1\right)} > 1$, and that $\frac{k\beta}{\gamma} > 1$. We can therefore write the condition as:

$$\frac{k}{(\phi+1)^{\frac{1}{\beta}}} > 1 > \frac{\frac{f_X}{f_D\left((\phi+1)^{\frac{1}{\beta}}-1\right)}}{\frac{f_X}{f_D}+\left(\frac{f_X}{f_D\left((\phi+1)^{\frac{1}{\beta}}-1\right)}\right)^{\frac{k\beta}{\gamma}}}$$

This implies that $k > (\phi+1)^{\frac{1}{\beta}}$ is a sufficient condition for $\frac{d\frac{\overline{e}^X}{\overline{x}}}{d\phi} < 0$.

A.6 Proposition 9

$$\begin{aligned}
\overline{E}_X &= \frac{\alpha(\sigma-1)}{\sigma\left(\left(\frac{f_X}{f_D}\right)^{\frac{k\beta}{\gamma}-1}(1+\phi)^{-\frac{1}{\beta}}\left((1+\phi)^{\frac{1}{\beta}}-1\right)^{1-\frac{k\beta}{\gamma}}+\frac{\phi}{(1+\phi)}\right)}t^{-1}\mu L \\
&= \alpha\left(\frac{\sigma-1}{\sigma}\right)t^{-1}\mu L\left(\left(\frac{f_X}{f_D}\right)^{\frac{k\beta}{\gamma}-1}(1+\phi)^{-\frac{1}{\beta}}\left((1+\phi)^{\frac{1}{\beta}}-1\right)^{1-\frac{k\beta}{\gamma}}+\frac{\phi}{(1+\phi)}\right)^{-1} \\
&= \Psi\left(\Theta(1+\phi)^{-\frac{1}{\beta}}\left((1+\phi)^{\frac{1}{\beta}}-1\right)^{1-\frac{k\beta}{\gamma}}+\frac{\phi}{(1+\phi)}\right)^{-1} \qquad (54)
\end{aligned}$$

where $\Psi \equiv \alpha\left(\frac{\sigma-1}{\sigma}\right)t^{-1}\mu L$ and $\Theta \equiv \left(\frac{f_X}{f_D}\right)^{\frac{k\beta}{\gamma}-1}$ are parameters. Differentiation w.r.t. ϕ

gives:

$$\frac{d\overline{E}_X}{d\phi} = -\Psi \left(\Theta \left(1+\phi\right)^{-\frac{1}{\beta}} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{1-\frac{k\beta}{\gamma}} + \frac{\phi}{(1+\phi)} \right)^{-2} K \tag{55}$$

where

$$K \equiv \begin{array}{c} \Theta \left\{ -\tfrac{1}{\beta} \left(1+\phi\right)^{-\frac{1}{\beta}-1} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{1-\frac{k\beta}{\gamma}} \right. \\ \left. + \left(1+\phi\right)^{-\frac{1}{\beta}} \left(1 - \tfrac{k\beta}{\gamma}\right) \left(\tfrac{1}{\beta}(1+\phi)^{\frac{1}{\beta}-1}\right) \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{-\frac{k\beta}{\gamma}} \right\} + \tfrac{1}{(1+\phi)^2} \end{array}$$

$\iff$

$$K \equiv \Theta \frac{1}{\beta} \left\{ - \left(1+\phi\right)^{-\frac{1}{\beta}-1} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{1-\frac{k\beta}{\gamma}} - \left(\frac{k\beta}{\gamma} - 1\right)(1+\phi)^{-1} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{-\frac{k\beta}{\gamma}} \right\} + \frac{1}{\left(1+\phi\right)^2}$$

$\iff$

$$K \equiv (1+\phi)^{-1} \left(\Theta \frac{1}{\beta} \left\{ - \left(1+\phi\right)^{-\frac{1}{\beta}} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{1-\frac{k\beta}{\gamma}} - \left(\frac{k\beta}{\gamma} - 1\right) \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{-\frac{k\beta}{\gamma}} \right\} + \frac{1}{(1+\phi)} \right)$$

$\iff$

$$K \equiv (1+\phi)^{-1} \left(\frac{1}{(1+\phi)} - \Theta \frac{1}{\beta} \left\{ \left(1+\phi\right)^{-\frac{1}{\beta}} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{1-\frac{k\beta}{\gamma}} + \left(\frac{k\beta}{\gamma} - 1\right) \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{-\frac{k\beta}{\gamma}} \right\} \right) \tag{56}$$

From (55) $\frac{d\overline{E}_X}{d\phi} > 0$ when $K < 0$, that is, when

$$\frac{1}{(1+\phi)} - \Theta \frac{1}{\beta} \left\{ \left(1+\phi\right)^{-\frac{1}{\beta}} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{1-\frac{k\beta}{\gamma}} + \left(\frac{k\beta}{\gamma} - 1\right) \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{-\frac{k\beta}{\gamma}} \right\} < 0 \tag{57}$$

Substituting in $\Theta \equiv \left(\frac{f_X}{f_D}\right)^{\frac{k\beta}{\gamma}-1}$ and rearranging (57) implies that $\frac{d\overline{E}_X}{d\phi} > 0$ when

$$\left(\frac{f_X}{f_D}\right)^{\frac{k\beta}{\gamma}-1} \frac{(1+\phi)}{\beta} \left\{ \left(1+\phi\right)^{-\frac{1}{\beta}} \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{1-\frac{k\beta}{\gamma}} + \left(\frac{k\beta}{\gamma} - 1\right) \left(\left(1+\phi\right)^{\frac{1}{\beta}} - 1 \right)^{-\frac{k\beta}{\gamma}} \right\} > 1$$

$\iff$

$$\left\{ \frac{\left(1+\phi\right)^{1-\frac{1}{\beta}}}{\beta} \left(\frac{f_X}{f_D} \frac{1}{(1+\phi)^{\frac{1}{\beta}} - 1} \right)^{\frac{k\beta}{\gamma}-1} + \left(\frac{k}{\gamma} - \frac{1}{\beta}\right) \left(\frac{f_X}{f_D}\right)^{-1} (1+\phi) \left(\frac{f_X}{f_D} \frac{1}{(1+\phi)^{\frac{1}{\beta}} - 1} \right)^{\frac{k\beta}{\gamma}} \right\} > 1$$

$\iff$

$$\left(\frac{f_X}{f_D}\frac{1}{(1+\phi)^{\frac{1}{\beta}}-1}\right)^{\frac{k\beta}{\gamma}-1}\left\{\frac{(1+\phi)^{1-\frac{1}{\beta}}}{\beta}+(\frac{k}{\gamma}-\frac{1}{\beta})\left(\frac{(1+\phi)}{(1+\phi)^{\frac{1}{\beta}}-1}\right)\right\}>1 \tag{58}$$

We have assumed that $\frac{f_X}{f_D\left((1+\phi)^{\frac{1}{\beta}}-1\right)}>1$, which implies that exporters are more productive than non-exporters, and the first term in (58) is therefore larger than one. Moreover, the last term in the parenthesis $\left(\frac{(1+\phi)}{(1+\phi)^{\frac{1}{\beta}}-1}\right)>\left(\frac{(1+\phi)}{(1+\phi)-1}\right)=\frac{1+\phi}{\phi}=1+\frac{1}{\phi}>1$ since $\beta<1$, and $(\frac{k}{\gamma}-\frac{1}{\beta})>0$ since we have assumed that $\frac{k\beta}{\gamma}>1$. A sufficient condition for $\frac{d\overline{E}_X}{d\phi}>0$ is therefore that

$$\left\{\frac{(1+\phi)^{1-\frac{1}{\beta}}}{\beta}+(\frac{k}{\gamma}-\frac{1}{\beta})\right\}>1 \tag{59}$$

Rewriting gives

$$\left\{(1+\phi)^{1-\frac{1}{\beta}}+\frac{k\beta}{\gamma}\right\}>1+\beta \tag{60}$$

which always holds since $0<\beta<1$.

A.7 Sector classification

SNI 2007	Manufacturing industry
10	Manufacture of food products
11	Manufacture of beverages
12	Manufacture of tobacco products
13	Manufacture of textiles
14	Manufacture of wearing apparel
15	Manufacture of leather and related products
16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw an
17	Manufacture of paper and paper products
18	Printing and reproduction of recorded media
19	Manufacture of coke and refined petroleum products
20	Manufacture of chemicals and chemical products
21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
22	Manufacture of rubber and plastic products
23	Manufacture of other non-metallic mineral products
24	Manufacture of basic metals
25	Manufacture of fabricated metal products, except machinery and equipment
26	Manufacture of computer, electronic and optical products
27	Manufacture of electrical equipment
28	Manufacture of machinery and equipment n.e.c.
29	Manufacture of motor vehicles, trailers and semi-trailers
30	Manufacture of other transport equipment
31	Manufacture of furniture
32	Other manufacturing
33	Repair and installation of machinery and equipment

A.8 NOT FOR PUBLICATION, Solving for Symmetric countries

Assume symmetric taxes and labour supply (L) so that $B = B^*$.

A.8.1 Cut-off productivities

Optimal abatement investments are derived in Section 3.4 in the main text:

$$f_A^D = \left\{ \frac{1}{B} \left(a^{1-\alpha} t^{\alpha} \right)^{\sigma-1} \frac{1}{1-\beta} \right\}^{-\frac{1}{\beta}} \tag{61}$$

$$f_A^X = \left\{ \frac{1}{(B+\phi B)} \left(a^{1-\alpha} t^{\alpha} \right)^{\sigma-1} \frac{1}{1-\beta} \right\}^{-\frac{1}{\beta}} \tag{62}$$

where $B \equiv \frac{\kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}\mu L}{P^{1-\sigma}}$ is exogenous to the firm. Now calculate relative abatement investments:

$$\frac{f_A^X}{f_A^D} = \left\{ \frac{1}{(1+\phi)} \right\}^{-\frac{1}{\beta}} \tag{63}$$

The Cut-off conditions are found in the main text text in Section 3.5 and are given by:

$$\left(a_D^{1-\alpha} \left(\frac{t}{(f_A^D)^{\rho}} \right)^{\alpha} \right)^{1-\sigma} B = f_D + f_A^D \tag{64}$$

$$\left(a_X^{1-\alpha} \left(\frac{t}{(f_A^X)^{\rho}} \right)^{\alpha} \right)^{1-\sigma} \phi B + \left(a_X^{1-\alpha} \left(\frac{t}{(f_A^X)^{\rho}} \right)^{\alpha} \right)^{1-\sigma} B - \left(a_X^{1-\alpha} \left(\frac{t}{(f_A^D)^{\rho}} \right)^{\alpha} \right)^{1-\sigma} B = f_X + f_A^X - f_A^D \tag{65}$$

Substituting (61) into (64) gives.

$$\left(a_D^{1-\alpha} \left(\frac{t}{\left\{ \frac{1}{B} \left(a_D^{1-\alpha} t^{\alpha} \right)^{\sigma-1} \frac{1}{1-\beta} \right\}^{-\frac{\rho}{\beta}}} \right)^{\alpha} \right)^{1-\sigma} B = f_D + \left\{ \frac{1}{B} \left(a_D^{1-\alpha} t^{\alpha} \right)^{\sigma-1} \frac{1}{1-\beta} \right\}^{-\frac{1}{\beta}} \tag{66}$$

Simplifying and rewriting (66) gives us an expression for B as a function of a_D and t:

$$B = \frac{f_D^{\beta} a_D^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)}}{\left(\left(\frac{1}{1-\beta} \right)^{\frac{\rho}{\beta}\alpha(1-\sigma)} - \left(\frac{1}{1-\beta} \right)^{-\frac{1}{\beta}} \right)^{\beta}} = \frac{f_D^{\beta} a_D^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)}}{\varkappa^{\beta}} \tag{67}$$

where $\varkappa \equiv \left(\frac{1}{1-\beta} \right)^{\frac{\rho}{\beta}\alpha(1-\sigma)} - \left\{ \frac{1}{1-\beta} \right\}^{-\frac{1}{\beta}} = (1-\beta)^{\frac{1-\beta}{\beta}} - \{1-\beta\}^{\frac{1}{\beta}} > 0$.

Next we substitute (61) and (62) into (65) to get

$$\begin{aligned}
&\left(a_X^{1-\alpha}\left(\frac{t}{\left\{\frac{1}{B(1+\phi)}\left(a_X^{1-\alpha}t^{\alpha}\right)^{\sigma-1}\frac{1}{1-\beta}\right\}^{-\frac{\rho}{\beta}}}\right)^{\alpha}\right)^{1-\sigma} B\left(\phi+1\right) \\
&-\left(a_X^{1-\alpha}\left(\frac{t}{\left\{\frac{1}{B}\left(a_X^{1-\alpha}t^{\alpha}\right)^{\sigma-1}\frac{1}{1-\beta}\right\}^{-\frac{\rho}{\beta}}}\right)^{\alpha}\right)^{1-\sigma} B \\
&= f_X + \left\{\frac{1}{B(1+\phi)}\left(a_X^{1-\alpha}t^{\alpha}\right)^{\sigma-1}\frac{1}{1-\beta}\right\}^{-\frac{1}{\beta}} - \left\{\frac{1}{B}\left(a_X^{1-\alpha}t^{\alpha}\right)^{\sigma-1}\frac{1}{1-\beta}\right\}^{-\frac{1}{\beta}},
\end{aligned} \tag{68}$$

which we can simplify and rewrite so as to get B as function of a_x and t:

$$B = \frac{a_X^{(1-\alpha)(\sigma-1)}t^{\alpha(\sigma-1)}f_X^{\beta}}{\left((1+\phi)^{\frac{1}{\beta}}-1\right)^{\beta}\varkappa^{\beta}} \tag{69}$$

Using (67) and (69) gives the relative cut-off condition ratio:

$$\frac{a_X^{(1-\alpha)(\sigma-1)}}{a_D^{(1-\alpha)(\sigma-1)}} = \left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\beta}\frac{f_D^{\beta}}{f_X^{\beta}} \tag{70}$$

Next solve the free entry condition

$$\begin{aligned}
f_E = &\int_0^{a_X}\left(\left(a^{1-\alpha}\left(\frac{t}{(f_A^X)^{\rho}}\right)^{\alpha}\right)^{1-\sigma}B(1+\phi) - f_D - f_X - f_A^X\right)dG(a) \\
&+\int_{a_X}^{a_D}\left[\left(a^{1-\alpha}\left(\frac{t}{(f_A^D)^{\rho}}\right)^{\alpha}\right)^{1-\sigma}B - f_D - f_A^D\right]dG(a)
\end{aligned} \tag{71}$$

Using (14) and (15) to substitute, we get

$$\begin{aligned}
&f_E + a_X^k(f_D+f_X) + (a_D^k - a_X^k)f_D \\
&= B^{\frac{1}{\beta}}(1+\phi)^{\frac{1}{\beta}}t^{-\frac{\alpha(\sigma-1)}{\beta}}\varkappa k\int_0^{a_X} a^{-\frac{(1-\alpha)(\sigma-1)}{\beta}}a^{k-1}da + B^{\frac{1}{\beta}}t^{-\frac{\alpha(\sigma-1)}{\beta}}\varkappa k\int_{a_X}^{a_D} a^{-\frac{(1-\alpha)(\sigma-1)}{\beta}}a^{k-1}da
\end{aligned} \tag{72}$$

Solving the integral we get

$$
\begin{aligned}
& f_E + a_X^k(f_D + f_X) + (a_D^k - a_X^k) f_D \\
&= B^{\frac{1}{\beta}}(1+\phi)^{\frac{1}{\beta}} t^{-\frac{\alpha(\sigma-1)}{\beta}} \varkappa \frac{k\beta}{k\beta - (1-\alpha)(\sigma-1)} a_X^{k-\frac{(1-\alpha)(\sigma-1)}{\beta}} \\
&+ B^{\frac{1}{\beta}} t^{-\frac{\alpha(\sigma-1)}{\beta}} \varkappa \frac{k\beta}{k\beta - (1-\alpha)(\sigma-1)} \left(a_D^{k-\frac{(1-\alpha)(\sigma-1)}{\beta}} - a_X^{k-\frac{(1-\alpha)(\sigma-1)}{\beta}} \right)
\end{aligned}
\tag{73}
$$

and substituting in the solutions for B, (67) and (69):

$$
\begin{aligned}
& f_E + a_X^k(f_D + f_X) + (a_D^k - a_X^k) f_D \\
&= \left(\frac{a_X^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)} f_X^{\beta}}{\left((1+\phi)^{\frac{1}{\beta}} - 1\right)^{\beta} \varkappa^{\beta}} \right)^{\frac{1}{\beta}} (1+\phi)^{\frac{1}{\beta}} t^{-\frac{\alpha(\sigma-1)}{\beta}} \varkappa \frac{k\beta}{k\beta - (1-\alpha)(\sigma-1)} a_X^{k-\frac{(1-\alpha)(\sigma-1)}{\beta}} \\
&+ \left(\frac{f_D^{\beta} a_D^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)}}{\varkappa^{\beta}} \right)^{\frac{1}{\beta}} t^{-\frac{\alpha(\sigma-1)}{\beta}} \varkappa \frac{k\beta}{k\beta - (1-\alpha)(\sigma-1)} a_D^{k-\frac{(1-\alpha)(\sigma-1)}{\beta}} \\
&- \left(\frac{a_X^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)} f_X^{\beta}}{\left((1+\phi)^{\frac{1}{\beta}} - 1\right)^{\beta} \varkappa^{\beta}} \right)^{\frac{1}{\beta}} t^{-\frac{\alpha(\sigma-1)}{\beta}} \varkappa \frac{k\beta}{k\beta - (1-\alpha)(\sigma-1)} a_X^{k-\frac{(1-\alpha)(\sigma-1)}{\beta}}
\end{aligned}
$$

gives

$$
f_E + a_X^k f_X \left(-\frac{(1-\alpha)(\sigma-1)}{k\beta - (1-\alpha)(\sigma-1)} \right) + a_D^k f_D \left(-\frac{(1-\alpha)(\sigma-1)}{k\beta - (1-\alpha)(\sigma-1)} \right) = 0 \tag{74}
$$

Now substitute out a_X using (70) to get

$$
\begin{aligned}
& f_E + a_D^k \left((\phi+1)^{\frac{1}{\beta}} - 1 \right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}} \frac{f_D^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}{f_X^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}} f_X \left(\frac{-(1-\alpha)(\sigma-1)}{k\beta - (1-\alpha)(\sigma-1)} \right) \\
& + a_D^k f_D \left(\frac{-(1-\alpha)(\sigma-1)}{k\beta - (1-\alpha)(\sigma-1)} \right) = 0.
\end{aligned}
$$

and rewrite to get an expression for a_D^k, which gives the equilibrium cut-off productivity for domestic producers

$$\overline{a}_D^k = \frac{f_E}{\left(\frac{(1-\alpha)(\sigma-1)}{k\beta-(1-\alpha)(\sigma-1)}\right) f_D \left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}} f_D^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1} f_X^{1-\frac{k\beta}{(1-\alpha)(\sigma-1)}}+1\right)} \tag{75}$$

Using (70) gives the corresponding equilibrium cut-off productivity for exporters in the symmetric case:

$$\overline{a}_X^k = \frac{f_E}{\left(\frac{(1-\alpha)(\sigma-1)}{k\beta-(1-\alpha)(\sigma-1)}\right) f_X \left(1+\frac{1}{\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}} f_X^{1-\frac{k\beta}{(1-\alpha)(\sigma-1)}} f_D^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}}\right)} \tag{76}$$

A.8.2 Calculate the price index (P)

We now calculate the price index for the symmetric case. We have that $B \equiv \frac{\kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}\mu L_j}{P_j^{1-\sigma}} = \frac{\varsigma\mu L_j}{P_j^{1-\sigma}}$, where $\varsigma \equiv \kappa^{1-\sigma}\sigma^{-\sigma}\left(\sigma-1\right)^{\sigma-1}$. According to (67) we have that

$$B = \frac{f_D^\beta a_D^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)}}{\varkappa^\beta} = \frac{\varsigma\mu L_j}{P_j^{1-\sigma}} \tag{77}$$

which can be rewritten as

$$P = \left(\frac{\varsigma\mu L_j \varkappa^\beta}{f_D^\beta a_D^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)}}\right)^{\frac{1}{1-\sigma}} = \left(\frac{\varkappa}{f_D}\right)^{\frac{\beta}{1-\sigma}} \left(\varsigma\mu\right)^{\frac{1}{1-\sigma}} L_j^{\frac{1}{1-\sigma}} a_D^{(1-\alpha)} t^\alpha,$$

and substituting in for a_D^k using (75) gives the price index

$$\overline{P} = \left(\frac{\varkappa}{f_D}\right)^{\frac{\beta}{1-\sigma}} \left(\varsigma\mu\right)^{\frac{1}{1-\sigma}} L_j^{\frac{1}{1-\sigma}} t^\alpha \cdot \tag{78}$$

$$\left(\frac{f_E}{\left(\frac{(1-\alpha)(\sigma-1)}{k\beta-(1-\alpha)(\sigma-1)}\right) f_D \left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}} f_D^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1} f_X^{1-\frac{k\beta}{(1-\alpha)(\sigma-1)}}+1\right)}\right)^{\frac{(1-\alpha)}{k}}$$

A.8.3 Calculating number of firms in the symmetric case ($n = n^*$)

The price of an individual variety of a non-exporter is given by (from the main text):

$$p = \frac{\sigma}{\sigma-1}\kappa\left(\frac{t}{f_A^{\rho}}\right)^{\alpha} a^{(1-\alpha)} = \frac{\sigma}{\sigma-1}\kappa t^{\alpha}\left(\overline{f}_A^D\right)^{\rho\alpha} a^{(1-\alpha)}$$

After substituting in$\overline{f}_A^D$ from (14) we get the non-export price

$$p = \frac{\sigma}{\sigma-1}\kappa B^{-\frac{\rho\alpha}{\beta}}\left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} t^{\frac{(1-\beta)\alpha}{\beta}+\alpha} a^{(1-\alpha)+\frac{(1-\alpha)(1-\beta)}{\beta}} = \frac{\sigma}{\sigma-1}\kappa B^{-\frac{\rho\alpha}{\beta}}\left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}} \tag{79}$$

The price of exporters is derived in the same fashion

$$\begin{aligned} p^* &= \frac{\sigma}{\sigma-1}\kappa\left(B+\phi B\right)^{-\frac{\rho\alpha}{\beta}}\left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} t^{\frac{(1-\beta)\alpha}{\beta}+\alpha} a^{(1-\alpha)+\frac{(1-\alpha)(1-\beta)}{\beta}} \\ &= \frac{\sigma}{\sigma-1}\kappa\left(B+\phi B\right)^{-\frac{\rho\alpha}{\beta}}\left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}} \end{aligned} \tag{80}$$

Next the price index is given by

$$P = \left(n\int_0^{a_D} p^{1-\sigma} dG + \phi n\int_0^{a_X} p*^{1-\sigma}\, dG\right)^{\frac{1}{1-\sigma}}$$

and substituting in for prices in the domestic and foreign market, we get

$$P = n^{\frac{1}{1-\sigma}}\frac{\sigma}{\sigma-1}\kappa B^{-\frac{\rho\alpha}{\beta}}\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}}\left(\int_0^{a_D} a^{\frac{(1-\alpha)}{\beta}(1-\sigma)} dG + \phi\left(1+\phi\right)^{\frac{1-\beta}{\beta}}\int_0^{a_X} a^{\frac{(1-\alpha)}{\beta}(1-\sigma)} dG\right)^{\frac{1}{1-\sigma}}$$

$$\begin{aligned} P^{1-\sigma} = n &\left(\frac{\sigma}{\sigma-1}\kappa B^{-\frac{\rho\alpha}{\beta}}\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}}\right)^{1-\sigma} a_D^{\frac{(1-\alpha)(1-\sigma)}{\beta}} \cdot \\ &\left(\frac{\beta k}{(1-\alpha)(1-\sigma)+\beta k} + \phi\left(1+\phi\right)^{\frac{1-\beta}{\beta}}\frac{\beta k}{(1-\alpha)(1-\sigma)+\beta k}\left(\frac{a_X}{a_D}\right)^{k+\frac{(1-\alpha)(1-\sigma)}{\beta}}\right) \end{aligned}$$

where we in turn can substitute in a_X/a_D from (70) to get

$$P^{1-\sigma} = nB^{-\frac{\rho\alpha(1-\sigma)}{\beta}} \left(\frac{\sigma}{\sigma-1}\kappa\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}}\right)^{1-\sigma} a_D^{\frac{(1-\alpha)(1-\sigma)}{\beta}} \cdot$$
$$\frac{\beta k}{(1-\alpha)(1-\sigma)+\beta k}\left(1+\phi(1+\phi)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)$$

Now we substitute in for B (67)

$$P^{1-\sigma} = na_D^{-(1-\alpha)(\sigma-1)}t^{-\alpha(\sigma-1)}f_D^{1-\beta}\varkappa^{\beta-1}\left(\frac{\sigma}{\sigma-1}\kappa\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}}\right)^{1-\sigma} \cdot$$
$$\frac{\beta k}{(1-\alpha)(1-\sigma)+\beta k}\left(1+\phi(1+\phi)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)$$

From definition of B and (67) $P_j^{1-\sigma} = \varsigma\mu L_j\varkappa^{\beta}f_D^{-\beta}a_D^{(1-\alpha)(1-\sigma)}t^{\alpha(1-\sigma)}$ which allows us to write:

$$\varsigma\mu L_j\varkappa^{\beta}f_D^{-\beta}a_D^{(1-\alpha)(1-\sigma)}t^{\alpha(1-\sigma)} = na_D^{-(1-\alpha)(\sigma-1)}t^{-\alpha(\sigma-1)}f_D^{1-\beta}\varkappa^{\beta-1}\left(\frac{\sigma}{\sigma-1}\kappa\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}}\right)^{1-\sigma} \cdot$$
$$\frac{\beta k}{(1-\alpha)(1-\sigma)+\beta k}\left(1+\phi(1+\phi)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)$$

with $\varsigma \equiv \kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}$, $\varkappa \equiv (1-\beta)^{\frac{1-\beta}{\beta}} - (1-\beta)^{\frac{1}{\beta}}$, and $\beta \equiv 1-\alpha\rho(\sigma-1)$, and to rewrite to get an expression for equilibrium number of firms

$$n = \frac{\beta\mu L}{f_D\sigma\frac{\beta k}{(1-\alpha)(1-\sigma)+\beta k}\left(1+\phi(1+\phi)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)} \tag{81}$$

A.8.4 Non-exporter emissions

Emission intensity is given by (from the main text):

$$\frac{e}{x} = \alpha\kappa t^{\alpha-1}f_A^{-\rho\alpha}a^{1-\alpha}$$

Substituting optimal abatement investments from (14)

$$f_A^D = \left\{\frac{1}{B}\left(a^{1-\alpha}t^{\alpha}\right)^{\sigma-1}\frac{1}{\alpha\rho(\sigma-1)}\right\}^{\frac{1}{\alpha\rho(\sigma-1)-1}}$$

gives

$$e^D = \alpha\kappa t^{\frac{\alpha-\beta}{\beta}} B^{-\frac{\rho\alpha}{\beta}} \left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}} x \tag{82}$$

First, derive the equilibrium emission intensity of non-exporters in the symmetric case. Substituting for B from (67) gives

$$e^D = \alpha\kappa t^{\frac{\alpha-\beta}{\beta}-\frac{\alpha(1-\beta)}{\beta}} f_D^{-\rho\alpha} \varkappa^{\rho\alpha} a_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}} x$$

with $\varsigma \equiv \kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}$, $\varkappa \equiv (1-\beta)^{\frac{1-\beta}{\beta}} - (1-\beta)^{\frac{1}{\beta}}$, and $\beta = 1-\alpha\rho(\sigma-1)$. We rewrite so that

$$\frac{e^D}{x} = \alpha\kappa t^{\frac{\alpha-\beta}{\beta}-\frac{\alpha(1-\beta)}{\beta}} f_D^{-\rho\alpha} a_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left((1-\beta)^{\frac{1-\beta}{\beta}} - (1-\beta)^{\frac{1}{\beta}}\right)^{\rho\alpha} \left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}}$$

and simplify to get

$$\frac{\overline{e}^D}{x} = \alpha\kappa t^{\alpha-1} f_D^{-\rho\alpha} a_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left(\frac{\beta}{1-\beta}\right)^{\rho\alpha} a^{\frac{(1-\alpha)}{\beta}} \tag{83}$$

For exporters we can calculate the equilibrium emission intensity in a similar fashion:

$$\frac{\overline{e}^X}{x} = \alpha\kappa t^{\alpha-1} f_D^{-\rho\alpha} (1+\phi)^{-\frac{\rho\alpha}{\beta}} a_D^{-\frac{(1-\beta)}{\beta}(1-\alpha)} \left(\frac{\beta}{1-\beta}\right)^{\rho\alpha} a^{\frac{(1-\alpha)}{\beta}} \tag{84}$$

Next, we calculate the level of total emissions. We start with non-exporters. The quantity sold domestically is:

$$x = \frac{p^{-\sigma}\mu L}{P^{1-\sigma}}$$

Non-export price

$$p = \frac{\sigma}{\sigma-1}\kappa B^{-\frac{\rho\alpha}{\beta}} \left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{(1-\beta)\alpha}{\beta}+\alpha} a^{(1-\alpha)+\frac{(1-\alpha)(1-\beta)}{\beta}} = \frac{\sigma}{\sigma-1}\kappa B^{-\frac{\rho\alpha}{\beta}} \left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}}$$

which gives

$$x = \frac{\left(\frac{\sigma}{\sigma-1}\right)^{-\sigma} \kappa^{-\sigma}\mu L B^{\frac{\sigma\rho\alpha}{\beta}} \left(\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}}\right)^{-\sigma}}{P^{1-\sigma}}. \tag{85}$$

Since $B \equiv \frac{\kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}\mu L_j}{P_j^{1-\sigma}}$, this implies that $\frac{(\sigma-1)B}{\kappa} = \frac{\kappa^{-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma}\mu L_j}{P_j^{1-\sigma}}$. which we can use to substitute into (85), to get

$$x = \frac{(\sigma-1)}{\kappa} B^{\frac{\sigma\rho\alpha}{\beta}+1} t^{-\frac{\sigma\alpha}{\beta}} a^{-\frac{\sigma(1-\alpha)}{\beta}} \left\{ \frac{1}{1-\beta} \right\}^{-\frac{\sigma\rho\alpha}{\beta}} \tag{86}$$

which we in turn substitute into (82). This gives

$$e^D = \alpha\kappa t^{\frac{\alpha-\beta}{\beta}} B^{-\frac{\rho\alpha}{\beta}} \left(\frac{1}{1-\beta} \right)^{\frac{\rho\alpha}{\beta}} a^{\frac{(1-\alpha)}{\beta}} \frac{(\sigma-1)}{\kappa} B^{\frac{\sigma\rho\alpha}{\beta}+1} t^{-\frac{\sigma\alpha}{\beta}} a^{-\frac{\sigma(1-\alpha)}{\beta}} \left\{ \frac{1}{1-\beta} \right\}^{-\frac{\sigma\rho\alpha}{\beta}}$$

which can be simplified to get

$$e^D = \alpha t^{\frac{\alpha(1-\sigma)-\beta}{\beta}} \left(\frac{1}{1-\beta} \right)^{\frac{\beta-1}{\beta}} a^{\frac{(1-\alpha)(1-\sigma)}{\beta}} (\sigma-1) B^{\frac{1}{\beta}} \quad . \tag{87}$$

Total emissions of non-exporters are (from the main text):

$$E_D = n \int_{a_X}^{a_D} e dG(a \mid a_D)$$

Solving the integral, conditional on entry gives:

$$E_D = n\alpha t^{\frac{\alpha(1-\sigma)-\beta}{\beta}} \left(\frac{1}{1-\beta} \right)^{\frac{\beta-1}{\beta}} (\sigma-1) B^{\frac{1}{\beta}} \frac{k\beta}{(1-\alpha)(1-\sigma)+k\beta} a_D^{-\frac{(1-\alpha)(\sigma-1)}{\beta}} \left(1 - \left(\frac{a_X}{a_D} \right)^{-\frac{(1-\alpha)(\sigma-1)}{\beta}+k} \right)$$

while from (70) we have that $a_X/a_D = \left((\phi+1)^{\frac{1}{\beta}} - 1 \right)^{\frac{\beta}{(1-\alpha)(\sigma-1)}} \frac{f_D^{\frac{\beta}{(1-\alpha)(\sigma-1)}}}{f_X^{\frac{\beta}{(1-\alpha)(\sigma-1)}}}$. Substitute this and n from (81) gives

$$E_D = \frac{\beta\mu L (\sigma-1) B^{\frac{1}{\beta}}}{f_D \sigma \frac{\beta k}{(1-\alpha)(1-\sigma)+\beta k} \left(1 + \phi (1+\phi)^{\frac{1-\beta}{\beta}} \left(\left((\phi+1)^{\frac{1}{\beta}} - 1 \right) \frac{f_D}{f_X} \right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1} \right)} \alpha t^{\frac{\alpha(1-\sigma)-\beta}{\beta}} \left(\frac{1}{1-\beta} \right)^{\frac{\beta-1}{\beta}}$$
$$\cdot \frac{k\beta}{(1-\alpha)(1-\sigma)+k\beta} a_D^{-\frac{(1-\alpha)(\sigma-1)}{\beta}} \left(1 - \left(\left((\phi+1)^{\frac{1}{\beta}} - 1 \right)^{\frac{\beta}{(1-\alpha)(\sigma-1)}} \frac{f_D^{\frac{\beta}{(1-\alpha)(\sigma-1)}}}{f_X^{\frac{\beta}{(1-\alpha)(\sigma-1)}}} \right)^{-\frac{(1-\alpha)(\sigma-1)}{\beta}+k} \right)$$

We use (67) to substitute for B and simplify to get

$$\overline{E}_D = \frac{\left(1 - \left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)}{\left(1 + \phi\left(1+\phi\right)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)}\mu L\alpha t^{-1}\frac{(\sigma-1)}{\sigma} \tag{88}$$

A.8.5 Exporter emissions

Next we turn to the emissions of exporters. From the main text we have that:

$$e^X = \alpha\kappa t^{\frac{\alpha-\beta}{\beta}}(1+\phi)^{-\frac{\rho\alpha}{\beta}}\overline{B}^{-\frac{\rho\alpha}{\beta}}\left(\frac{1}{1-\beta}\right)^{\frac{\rho\alpha}{\beta}} a^{\frac{1-\alpha}{\beta}}x, \tag{89}$$

where

$$x = (1+\phi)\frac{p^{-\sigma}\mu L}{P^{1-\sigma}} \tag{90}$$

Substituting (15) gives the exporter price

$$p = \frac{\sigma}{\sigma-1}\kappa\left(1+\phi\right)^{-\frac{\rho\alpha}{\beta}} B^{-\frac{\rho\alpha}{\beta}}\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}}a^{\frac{(1-\alpha)}{\beta}},$$

and substituting this into (90) gives

$$x = (1+\phi)\frac{\left(\frac{\sigma}{\sigma-1}\right)^{-\sigma}\kappa^{-\sigma}\mu L\left(1+\phi\right)^{\frac{\sigma\rho\alpha}{\beta}} B^{\frac{\sigma\rho\alpha}{\beta}}\left(\left\{\frac{1}{1-\beta}\right\}^{\frac{\rho\alpha}{\beta}} t^{\frac{\alpha}{\beta}}a^{\frac{(1-\alpha)}{\beta}}\right)^{-\sigma}}{P^{1-\sigma}} \tag{91}$$

We have that $B \equiv \frac{\kappa^{1-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma-1}\mu L_j}{P_j^{1-\sigma}}$, which implies that $\frac{(\sigma-1)B}{\kappa} = \frac{\kappa^{-\sigma}\sigma^{-\sigma}(\sigma-1)^{\sigma}\mu L_j}{P_j^{1-\sigma}}$, which we substitute into (91) to get

$$x = \frac{(\sigma-1)}{\kappa}\left(1+\phi\right)^{1+\frac{\sigma\rho\alpha}{\beta}} B^{\frac{\sigma\rho\alpha}{\beta}+1}t^{-\frac{\sigma\alpha}{\beta}}a^{-\frac{\sigma(1-\alpha)}{\beta}}\left\{\frac{1}{1-\beta}\right\}^{-\frac{\sigma\rho\alpha}{\beta}},$$

and this in turn into (89) gives $\overline{e}^X$:

$$\overline{e}^X = \alpha t^{\frac{\alpha(1-\sigma)-\beta}{\beta}}\left(\frac{1}{1-\beta}\right)^{\frac{\beta-1}{\beta}} a^{\frac{(1-\alpha)(1-\sigma)}{\beta}}\left(\sigma-1\right)\left(1+\phi\right)^{\frac{1}{\beta}}B^{\frac{1}{\beta}}$$

Now calculate total emissions from all exporters using that

$$E_X = n\int_0^{a_X} edG(a \mid a_D).$$

We solve the integral and substitute in $(a_X/a_D)^k$ from (70):

$$E_X = n\alpha t^{\frac{\alpha(1-\sigma)-\beta}{\beta}} \left(\frac{1}{1-\beta}\right)^{\frac{\beta-1}{\beta}} (\sigma-1)(1+\phi)^{\frac{1}{\beta}} (B)^{\frac{1}{\beta}} \frac{k\beta}{(1-\alpha)(1-\sigma)+k\beta} \cdot$$
$$\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}} \frac{f_D^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}{f_X^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}\right) a_X^{\frac{(1-\alpha)(1-\sigma)}{\beta}},$$

substitute $B = \frac{a_X^{(1-\alpha)(\sigma-1)} t^{\alpha(\sigma-1)} f_X^{\beta}}{\left((1+\phi)^{\frac{1}{\beta}}-1\right)^{\beta} \varkappa^{\beta}}$ from (69):

$$E_X = n\alpha t^{-1} \left(\frac{1}{1-\beta}\right)^{\frac{\beta-1}{\beta}} (\sigma-1)(1+\phi)^{\frac{1}{\beta}} \frac{f_X}{\left((1+\phi)^{\frac{1}{\beta}}-1\right)\varkappa} \frac{k\beta}{(1-\alpha)(1-\sigma)+k\beta} \cdot$$
$$\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}} \frac{f_D^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}{f_X^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}\right)$$

then we substitute in n from (81) and use that $\varkappa = (1-\beta)^{\frac{1-\beta}{\beta}} - \{1-\beta\}^{\frac{1}{\beta}}$, which after simplifying gives us

$$\overline{E}_X = \frac{\left(\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}{\sigma\left((1+\phi)^{-\frac{1}{\beta}}\left((1+\phi)^{\frac{1}{\beta}}-1\right)^{1-\frac{k\beta}{(1-\alpha)(\sigma-1)}} + \frac{\phi}{(1+\phi)}\left(\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)} \alpha t^{-1}(\sigma-1)\frac{f_X}{f_D}\mu L \tag{92}$$

A.8.6 Total emissions

We have from (88) that:

$$\overline{E}_D = \frac{\left(1-\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)}{\left(1+\phi(1+\phi)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}}-1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)} \mu L \alpha t^{-1}\frac{(\sigma-1)}{\sigma}$$

Using this and $\overline{E}_X$ from (92) gives total emissions

$$E_{tot} = E_D + E_X = \frac{\left(1 - \left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)}{\left(1 + \phi\left(1+\phi\right)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)}\mu L\alpha t^{-1}\frac{(\sigma-1)}{\sigma} +$$

$$\frac{\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}\frac{f_D^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}{f_X^{\frac{k\beta}{(1-\alpha)(\sigma-1)}}}\right)}{f_D\sigma\left(1 + \phi\left(1+\phi\right)^{\frac{1-\beta}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}\right)}\alpha t^{-1}\left(\sigma-1\right)\frac{f_X\left(1+\phi\right)^{\frac{1}{\beta}}}{\left((1+\phi)^{\frac{1}{\beta}} - 1\right)}\mu L$$

which can be simplified to be expressed by

$$\overline{E}_{tot} = \mu L\alpha t^{-1}\frac{(\sigma-1)}{\sigma}\left(\frac{1 + \left((1+\phi)^{\frac{1}{\beta}} - 1\right)\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}}{1 + \frac{\phi}{(1+\phi)}\left(1+\phi\right)^{\frac{1}{\beta}}\left(\left((\phi+1)^{\frac{1}{\beta}} - 1\right)\frac{f_D}{f_X}\right)^{\frac{k\beta}{(1-\alpha)(\sigma-1)}-1}}\right) \tag{93}$$