Heterogeneous firms, exports and Pigouvian pollution tax: does the abatement technology matter?

Abstract:
This work investigates how and to what extent firms with varying productivity are influenced by an environmental Pigouvian tax on their technology and trade decisions. By using an international trade model that accounts for the heterogeneity of firms in terms of productivity, it is theoretically examined the decision of introducing a green technology or keeping a pollutant less advanced technology. If all firms adopt a pollutant technology, the eco-tax lowers emissions through a selection mechanism because the least productive firms are forced to leave the market. By imposing higher compliance costs to active firms, export propensity is negatively influenced as well. When abatement technologies can be adopted, an additional source of pollution reduction is obtained. The environmental tax will positively affect eco-innovation propensity and, indirectly, export propensity. However, since the positive effect will strictly depend on the amount of firm productivity, environmental tax and costs of clean technology, the Pigouvian tax can foster eco-innovation across the largest and most productive firms only. Productivity enhancing policies tailored to firm characteristics, especially size, may be more successful in the diffusion of cleaner technologies across all firms.

Keywords: Export; Heterogeneous productivity; Environmental tax; Abatement technology

1. Introduction

Since 1990's globalization has assumed an important role in the economy and the volume of trade has been largely increased. However, these positive trends have been accompanied by a deterioration of the environment, in terms of both increased pollution and intensive use of natural resources. A sustainable development needs to be implemented as a priority for all countries. By considering this scenario, authorities are promoting sustainability through the introduction of regulations that foster all economic agents to revise their behaviour toward a more efficient use of resources' disposals and a greener production and consumption. These policies should not only impose quantitative restrictions or standards to emissions but also boost innovation, which could guarantee better economic and environmental performances.

In view of this important and debated topic, this paper aims at investigating the role of firms' productivity heterogeneity and environmental taxation on the relationship between trade and innovation decisions at micro level. Using the Helpman (2006) version of Melitz (2003) international trade model, it is theoretically studied the firm-level effect of a Pigouvian tax on technology and exporting decisions. In this setting firms are heterogeneous in terms of productivity and operate in a monopolistically competitive market.

This work is strictly related to the theoretical literature on partial equilibrium models studying the incentives generated by environmental regulations for the introduction and diffusion of abatement technologies. Among others, Milliman and Prince (1989) and Jung et al. (1996) have pointed out that the incentives to introduce new abatement technologies depend on different types of green policies. Specifically, taxes or charges generate a better incentive for firms to be eco-innovative than other kinds of policy. A detailed survey on this literature is Requate (2005). A second relevant strand of the literature concerns the analysis of international trade patterns by accounting for firms' productivity heterogeneity [Melitz (2003)]. Depending on their productivity, firms show different export propensity in the presence of economies of scale. Generally, the most productive firms sell their goods to both domestic and foreign markets, while less productive ones serve the domestic market only. In this literature, Bustos (2011) has accounted for firm's technology decision in a Melitz (2003) trade model. Under trade integration, exporters tend to implement a more advanced technology, so the most productive firms both export and innovate. Third, the present paper is also related to the literature on the Porter Hypothesis. Borne at the beginning of 90s, this hypothesis underlines the positive effect of environmental policies on the adoption of eco-innovation and, dynamically, on firms' economic and environmental performance [Porter (1991), Porter and Van Der Linde (1995), Jaffe and Palmer (1997)].

The most part of neoclassical research on the effect of environmental regulations on innovation propensity of firms, has assumed that the output market is perfectly competitive [Milliman and Prince (1989), Jung et al. (1996) and Requate and Unold (2003)]; one exception is the monopolistic setting considered by Petrakis and Xepapadeas (1999). Recent theoretical models have analysed exporting propensity, environmental regulation and firms' environmental performance in a context of heterogeneous productivity across firms and monopolistic competition [Kreickermeier and Richter (2014), Forslid et al. (2018), Cui (2017)]. All these studies evaluate innovation decisions in a Melitz (2003) framework and share a common result. The most productive firms introduce an abatement technology and serve both domestic and foreign markets, thus their emitted pollution is lower than less efficient ones. Anoulìes (2017) has focused on a cap-and-trade system in a similar international trade framework. Differently from them, this paper contributes to the literature into many directions. First, the technological adoption framework by Bustos (2011) has been reinterpreted in terms of different environmental technologies by distinguishing among three kinds of innovation (dirty, clean-type 1 and clean-type 2); each one assumes a different level of variable and fixed costs. Cui (2017) has also exploited Bustos (2011) framework, but his focus is on emission permits when two types of technology (dirty and clean) are admitted. Second, it has been introduced a Pigouvian environmental tax into a partial equilibrium model of international trade to specifically study the effect of eco-taxes on profits and export propensity at firm level when different abatement technologies can be adopted. Cao et al. (2016) and Forslid et al. (2018) also account for a tax policy but they have focused on the effect on productivity and emission levels for the entire economy. In line with them, the introduction of a pollution tax increases the environmental propensity of the most productive firms in this paper, by adopting abatement technologies. By assuming a finite number of green and dirty technologies, this contribution identifies the exact conditions under which some firms prefer to introduce an abatement technology and others keep producing with a pollutant one and paying for the eco-tax. Intuitively, the green technology will be adopted when its cost is more than compensated by the (avoided) tax burden. The latter one varies across firms depending on their productivity level. Finally, this paper contributes to the Porter Hypothesis literature. The theoretical model proposed by Qui et al. (2018) and the empirical evidence reported by Lanoie et al. (2011) and Rammer (2017) have shown controversial results about the Porter Hypothesis when trade flows are used as a measure of competitiveness. By theoretically analysing the effect of an environmental tax on abatement technology adoption and exporting performance, this paper posits a crucial role of productivity heterogeneity as a potential driver of the Porter Hypothesis. There exists both positive and negative effects of eco-regulation on export and innovation decisions and the net effect strictly depends on firm's efficiency. Specifically, on one hand, the least productive firms adopt a polluting technology, so the negative effect prevails. On the other hand, the most productive firms implement eco-friendly technology, thus the positive effect prevails. The overall effect will depend on their distribution and importance on the whole economy.

The reminder of this paper is organized as follows. Section 2 presents the basic model setup, distinguishing between two groups: non-exporters and exporters, and it states the equilibrium conditions for three different technologies: dirty-type, clean-type 1, and clean-type 2. In Section 3, a pairwise comparison of alternative technologies is made. Section 5 concludes.

2. Theoretical Model

In this Section a partial equilibrium model, which is strictly connected with the international trade model of Melitz (2003), is presented. Specifically, it refers to the revised version proposed by Helpman (2006). Let consider a small economy where firms are heterogeneous, produce differentiated goods and sell in a market of monopolistic competition. There are no entry barriers, so firms can freely enter the market. Each firm has a production function characterized by increasing returns to scale. It is assumed that labour is the only factor of production, so variable costs of production are related to the wage rate. This wage rate depends on workers' skills: skilled workers receive a higher wage than unskilled workers. Production needs both skilled and unskilled workers. Furthermore, variable costs depend on the productivity of labour. Firms do not know *ex ante* their productivity, but they discover it after entering the market and paying for sunk fixed costs. The level of productivity is an exogenous and random variable chosen from a generic statistical distribution function. By observing their productivity level, firms decide whether to exit the market or to start producing.

Production creates pollution and it is assumed that firms emit it as a *by-product*. This means that for each unit of output produced, firms emit exactly one unit of pollution. Firms decide, first, which technology to be adopted; second, whether to supply both domestic and foreign markets or the domestic market only. The exporting decision is analysed with reference to two groups of firms characterized by different levels of technology: dirty-type firms (d), that do not adopt an abatement technology, and clean-type firms (c), which adopt an emission abatement technology. In this model, technologies are modelled following Bustos (2011), thus dirty-type firms use a baseline technology, while clean-type firms use an upgraded technology. Being a dirty-type or a clean-type firm has an important effect on the composition of skilled and unskilled labour force and requires different levels of fixed and variable costs. Clean-type technology requires more skilled workers and asks for higher fixed costs and lower variable costs than dirty-type technology. This implies that the clean-type technology generates a higher efficiency of production. It is also supposed that the government implements an exogenous Pigouvian tax *t* for each unit of pollution firms emit. The implementation of a clean-type technology is examined through two alternatives. First, it is admitted that this kind of technology requires only higher fixed costs than dirty-type technology. These firms are classified as clean-type 1 firms (c_1). As a second step, the assumption of lower variable costs is added; in this case, firms are considered of clean-type 2 (c_2). Clean-type 2 firms pay for higher fixed costs than clean-type 1 firms. In both cases, it is extremely supposed that clean-type firms' tax outlay is zero since they are able to totally abate pollution.

The demand-side is characterized by a group of consumers that have identical preferences. The market demand of a generic good *X* of a firm *j* can be expressed with the following function:

(1) $$X_j = Ap_j^{-\varepsilon}$$

where *A* represents the dimension of the market, which is exogenous at firm level and endogenous for the industry; p_j is the price of the good and ε is the elasticity of substitution between two differentiated goods. ε is equal to $1/(1-\alpha)$, with $0 < \alpha < 1$, so that $\varepsilon > 1$. Both dirty-type and clean-type firms face the same demand.

Given the demand for each product, X_j, firms choose the level of price p_j that maximizes their profits π_j^m, where $m = d, c_n$ identifies the implemented technology. d and c_n indicate the adopted technology: *d* refers to dirty-type technology and c_n to clean-type technology; *n* can be equal to 1 or 2; if $n = 1$ we will refer to clean-type 1 firms, if $n = 2$ we are considering clean-type 2 firms. Dirty-type firms pay a fixed environmental tax *t* for each unit of output produced and clean-type firms do not because there is total pollution abatement.

Let start with dirty-type firms. They must pay an initial fixed cost to observe their productivity level. Once productivity is observed, they decide whether production is profitable, so maximizing price p_j is calculated, given the domestic demand of good, X_j. The problem can be analytically described as follows:

(2) $$p_j = \begin{cases} \max\ \pi_j^d = p_j X_j - (c^d/\varphi_j)X_j - tX_j - f^d \\ \quad u.c. X_j = Ap_j^{-\varepsilon} \end{cases}$$

where π_j^d is dirty-type firm's profit function, φ_j is the level of productivity, c^d is variable cost and f^d is fixed cost of production.

This problem can be also drawn for clean-type firms. It is expressed as:

(3) $$p_j = \begin{cases} \max\ \pi_j^{c_n} = p_j X_j - (c^s/\varphi_j)X_j - f^s \\ \quad u.c. X_j = Ap_j^{-\varepsilon} \end{cases}$$

where $\pi_j^{c_n}$ is clean-type firm's profit function, c^s is variable cost and f^s is fixed cost of production.
As for dirty-type firm's profit function, marginal costs are equal to $[(c^d/\varphi_j) + t]$. They are affected by three parameters. First, they are positively related to the variable production cost c^d, which depends on the share of skilled and unskilled workers; second, they inversely depend on firm's labour productivity, φ_j; third, variable costs are positively affected by the environmental tax *t*. When the abatement technology completely destroys pollution then no environmental tax is paid. The corresponding clean-type firm marginal cost is (c^s/φ_j). It is assumed that $c^s = c^d$ and $f^s = f^{c_1}$ for the clean-type 1 technology; $c^s = c^c$ and $f^s = f^{c_2}$ for the clean-type 2 technology.
Following Helpman (2006) and by imposing the profit maximization condition, *ex post* domestic profits for dirty-type and clean-type firms are obtained for all productivity levels:

(4) $$\pi_j^d = A\left[(1/\alpha)\left((c^d/\varphi_j) + t\right)\right]^{1-\varepsilon}(1-\alpha) - f^d$$
(5) $$\pi_j^{c_1} = A(c^d/\alpha\varphi_j)^{1-\varepsilon}(1-\alpha) - f^{c_1}$$
(6) $$\pi_j^{c_2} = A(c^c/\alpha\varphi_j)^{1-\varepsilon}(1-\alpha) - f^{c_2}$$

π_j^d refers to dirty-type firms, $\pi_j^{c_1}$ to clean-type 1 firms and $\pi_j^{c_2}$ to clean-type 2 firms. For a detailed examination of the profit maximization problem, see Appendixes A.1, B.1 and C.1. All domestic *ex post* profit functions are continuous and depend on the following variables: productivity, market dimension, variable and fixed costs of production, environmental tax. The latter variable appears in dirty-type firms' *ex post* profits only because clean-type firms adopt environmental technologies which are able to abate all pollutants. Given these results, it can be shown that:

Proposition 1. *Ex post domestic profits positively depend on the market dimension and firm's productivity and negatively on production costs, for any technology level*

Proof. The statement follows from *ex post* domestic profit functions (4), (5), and (6). Specifically, concerning the market dimension, an increase of *A* generates higher profits for firms. A larger profit is also obtained when the productivity level is higher. This is evident by differentiating profits with respect to φ_j:

(7) $$\frac{d\pi_j^d}{d\varphi_j} = B(c^d/\varphi_j)^{-\varepsilon}(c^d/\varphi_j^2) > 0$$
(8) $$\frac{d\pi_j^{c_1}}{d\varphi_j} = B(c^d/\varphi_j)^{-\varepsilon}(c^d/\varphi_j^2) > 0$$
(9) $$\frac{d\pi_j^{c_2}}{d\varphi_j} = B(c^c/\varphi_j)^{-\varepsilon}(c^c/\varphi_j^2) > 0$$

where $B = A(1-\alpha)(\varepsilon-1)(1/\alpha)^{\varepsilon-1}$.

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With reference to dirty-type firms, it can be shown the negative effect of the environmental tax on profits.

Proposition 2. *The environmental tax has a negative effect on dirty-type firms' ex post domestic profits*

Proof. The statement follows directly from dirty-type firms' *ex post* domestic profits. Marginal costs in the presence a Pigouvian tax are higher than without it. Without the environmental tax, marginal costs are equal to c^d/φ_j; otherwise, if a positive tax rate is considered, they are equal to $(c^d/\varphi_j) + t$.

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Since the foreign market is symmetric to the domestic one, the effect of changes of demand A and Pigouvian tax on foreign and domestic profits are identical. However, domestic and foreign markets are segmented: firms must pay additional fixed and variable trade costs. Additional fixed costs are related to distribution costs in foreign markets while, additional marginal costs refer to *iceberg trade costs*, τ_j. Modelling additional variable costs as *iceberg trade costs* means that firms produce a quantity greater than 1 to sell 1 unit to foreign customers. These costs are assumed to be homogeneous across destination countries and higher than 1. As a result of all assumptions about fixed costs, we can rank them as follows: $f^d < f^{c_1} < f^{c_2}$ and $f^{d^*} < f^{c_1^*} < f^{c_2^*}$. As in the domestic market, every firm j chooses the price that maximizes its profits, given the foreign demand of a generic good X_j^* equal to $A(p_j^*)^{-\varepsilon}$, where p_j^* is the price of a good delivered to foreign market.
Concerning dirty-type firms, the maximization problem can be represented as follows:

$$(10) \qquad p_j^* = \begin{cases} \max\ \pi_j^{d^*} = p_j^* X_j^* - (c^d \tau_j/\varphi_j) X_j^* - t X_j^* - f^{d^*} \\ \qquad\qquad u.c.\ X_j^* = A(p_j^*)^{-\varepsilon} \end{cases}$$

while for clean-type firms it corresponds to:

$$(11) \qquad p_j^* = \begin{cases} \max\ \pi_j^{c_n^*} = p_j^*\, X_j^* - (c^c \tau_j/\varphi_j)\, X_j^* - f^{s^*} \\ \qquad\qquad u.c.\ X_j^* = A(p_j^*)^{-\varepsilon} \end{cases}$$

By comparing domestic and foreign markets, an important result can be stated:

Proposition 3. *For a given level of productivity and technology, the foreign price is higher than the domestic price due to the existence of trade costs.*

Proof. By solving (2), (3), (10) and (11), domestic and foreign optimal prices for each technology can be obtained. See Appendixes A.1-C.2 for a detailed calculus. It is easy to see that foreign prices are higher than domestic ones because trade costs increase variable costs of production.

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By substituting the optimal price into profit functions, *ex post* foreign profits can be obtained as follows:

$$(12) \qquad \pi_j^{d^*} = A\big[(1/\alpha)\big((c^d \tau_j/\varphi_j) + t\big)\big]^{1-\varepsilon}(1-\alpha) - f^{d^*}$$

$$(13) \qquad \pi_j^{c_1^*} = A\big(c^d \tau_j/\alpha\varphi_j\big)^{1-\varepsilon}(1-\alpha) - f^{c_1^*}$$

$$(14) \qquad \pi_j^{c_2^*} = A\big(c^c \tau_j/\alpha\varphi_j\big)^{1-\varepsilon}(1-\alpha) - f^{c_2^*}$$

All foreign *ex post* profits are continuous functions; see Appendixes A.2, B.2 and C.2 for details. By comparing them with ex post domestic profits, Proposition 1 and 2 are confirmed for export sales. *Ex post* foreign profits positively depend on productivity and market dimension, and negatively on production variable costs and eco-taxes. Finally, *ex post* foreign profits depend on trade costs; this relationship can be summarized as follows:

Proposition 4. *The higher are fixed and variable trade costs, the lower are ex post foreign profits*

Proof. The statement follows directly from *ex post* foreign profit functions.

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Parameters	Description
c^d	Dirty-type and clean-type 1 firms marginal costs
c^c	Clean-type 2 firms marginal costs
f^d	Domestic fixed cost for dirty-type firms
f^{c_1}	Domestic fixed cost for clean-type 1 firms
f^{c_2}	Domestic fixed cost for clean-type 2 firms
f^{d^*}	Foreign fixed cost for dirty-type firms
$f^{c_1^*}$	Foreign fixed cost for clean-type 1 firms
$f^{c_2^*}$	Foreign fixed cost for clean-type 2 firms
τ	Variable trade cost
A	Market dimension
ε	Elasticity of substitution
$\alpha = (\varepsilon - 1)/\varepsilon$	Inverse of the mark-up
t	Environmental tax rate

Table 1. Description of structural parameters

2.1 Cut-Off Productivity and Pigouvian Tax in Domestic and Foreign Markets

By imposing a zero-profit condition to both *ex post* domestic and foreign profits, domestic and foreign marginal (or cut-off) productivity are respectively found. These values identify which firms exit the market and which ones serve domestic market only or both domestic and foreign markets. If a firm draws a productivity lower than the domestic marginal value, it will exit the market because domestic profits are negative; otherwise, if a firm has a productivity higher than the domestic cut-off, it will supply goods to the domestic market because it can bear fixed costs. If firm's productivity level lies between the domestic cut-off and the foreign cut-off, that firm will serve the domestic market only, while, if the productivity is higher than the foreign cut-off it will supply goods to both domestic and foreign markets.

In this work, it is fundamental to understand which is the effect of different technologies on productivity and consequently on trade decisions, by analysing marginal productivity levels. It requires three steps. As a first step, dirty-type firms' domestic cut-off productivity with a positive Pigouvian environmental tax is determined. It is shown that

Proposition 5. *The introduction of a Pigouvian environmental tax by the government forces the least productive dirty-type firms to exit the market.*

Proof. If dirty-type firms pay for a tax, the zero-profit condition is satisfied when $\varphi_j = DD_t = c^d\{\alpha[f^d/(A(1-\alpha))]^{1/(1-\varepsilon)} - t\}^{-1}$; if the tax rate t is zero, $\varphi_j = DD_0 = c^d/\alpha\,[f^d/(A(1-\alpha))]^{1/(\varepsilon-1)}$. DD_t and DD_0 are dirty-type firm's marginal productivity with and without the environmental tax, respectively. In Figure 1, the corresponding ex post domestic profit functions are depicted as increasing convex curves. Specifically, the solid-type curve is the ex post domestic profit if the Pigouvian tax is positive, corresponding to equation (4); the dash-type curve refers to ex post domestic profits when no tax is imposed by authorities ($t = 0$). The introduction of an environmental tax will increase the marginal productivity of dirty-type firms from DD_0 and DD_t; all firms with a productivity level between DD_0 and DD_twill exit the domestic market.

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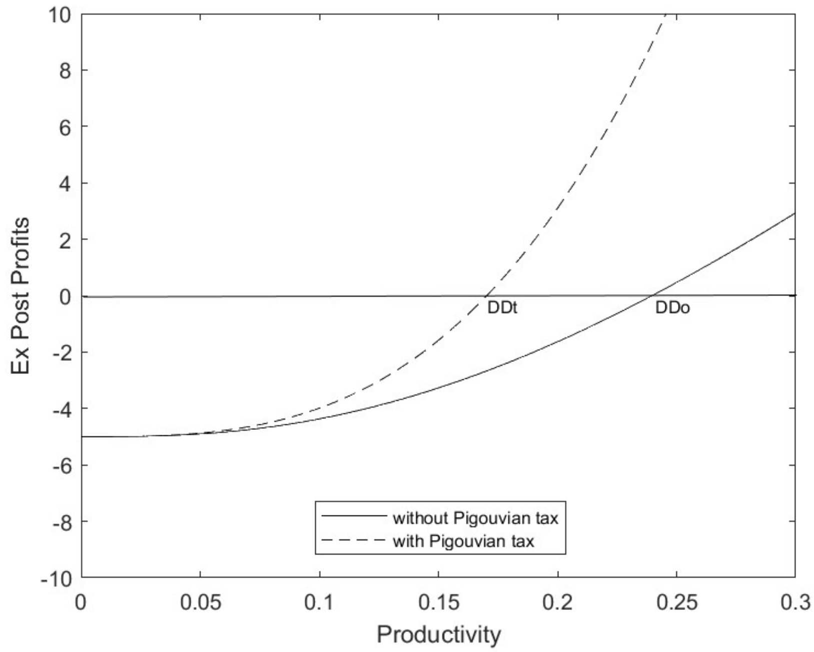

Figure 1. Dirty-type firms' ex-post domestic profit with and without the Pigouvian tax. Specification: equation (4), numerical simulation in MatLab environment by using parameters reported in Section 4.

From an environmental policy point of view, if all firms adopt a dirty-type technology, the government can use the environmental tax in order to reduce emissions because it forces some dirty-type firms to leave the market. However, the least efficient firms, so the smallest ones, exit the market. In other words, the effect of the introduction of a Pigouvian tax on the decrease of environmental emissions is limited because it involves small firms only. An environmental tax can persuade pollutant firms to switch from a pollutant technology to a cleaner one. The analysis of domestic profits corresponding to clean technologies is then required.

As a second step, by calculating zero-profit conditions for clean-type firms, the following cut-off productivity levels are obtained:

(15) $CD_1 = c^d/\alpha\,[f^{c_1}/(A(1-\alpha))]^{1/(\varepsilon-1)}$

(16) $CD_2 = c^c/\alpha\,[f^{c_2}/(A(1-\alpha))]^{1/(\varepsilon-1)}$

where CD_1 refers to clean-type 1 firms and CD_2 to clean-type 2 firms. When the productivity is lower than the marginal domestic productivity, firms exit; if their productivity is higher than the cut-off level, they decide to be active and serve the domestic market.

As a third step, foreign cut-off productivity levels for all technologies are:

(17) $DF = c^d\tau_j\left\{\alpha\left[f^{d^*}/(A(1-\alpha))\right]^{1/(1-\varepsilon)} - t\right\}^{-1}$

(18) $CF_1 = (c^d\tau_j/\alpha)\left[f^{c_1^*}/(A(1-\alpha))\right]^{1/(\varepsilon-1)}$

(19) $CF_2 = (c^c\tau_j/\alpha)\left[f^{c_2^*}/(A(1-\alpha))\right]^{1/(\varepsilon-1)}$

where DF concerns dirty-type firms, CF_1 clean-type 1 firms and CF_2 clean-type 2 firms. If firms have a productivity level lower than the foreign cut-off productivity, they sell in the domestic market only because they cannot bear export fixed costs, while, if their productivity is higher than the foreign marginal productivity, they decide to export. With regards to dirty-type firms' foreign cut-off productivity, in line with Proposition 5, the introduction of a Pigouvian tax lowers export propensity by forcing the least productive firms to exit foreign markets and concentrate their sales in the domestic market only.
For each kind of technology, if domestic and foreign marginal productivity levels are analysed together, it is possible to conclude that

Proposition 6. *The following firms' sorting is confirmed for each technology:*

a. *The least productive firms exit the domestic market.*
b. *Firms that have a productivity within domestic and foreign cut-off levels supply their goods to the domestic market.* The entity of the range depends on the adopted technology; for dirty-type firms, it is equal to $DD_t - DF$, for clean-type 1 firms $CD_1 - CF_1$ and, for clean-type 2 firms $CD_2 - CF_2$.
c. *The most productive firms serve both the domestic and foreign markets.* Specifically, dirty-type firms decide to export if $\tau > \left[\left(\alpha\left(A(1-\alpha)/f^{d^*}\right)^{1/(\varepsilon-1)} - t\right)/\left(\alpha\left(A(1-\alpha)/f^{d}\right)^{1/(\varepsilon-1)} - t\right)\right]$, clean-type 1 if $\tau > \left(f^{c_1}/f^{c_1^*}\right)^{1/(\varepsilon-1)}$ and clean-type 2 if $\tau > \left(f^{c_2}/f^{c_2^*}\right)^{1/(\varepsilon-1)}$.

Proof. By comparing domestic and foreign cut-off productivities for each technology, it is easy to demonstrate the above Proposition as drawn by Melitz (2003).

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3. Technology adoption

So far, each type of technology in domestic and foreign markets has been analysed separately. In this Section, a combined comparison of different kinds of technology is presented to understand what firms' characteristics affect the choice between pollutant and clean technologies. Specifically, in Section 3.1, it is supposed that firms can decide between dirty-type technology and one of the clean-type technologies; in Section 3.2, a firm is asked to choose between two clean-type technologies and, in Section 3.3, among dirty-type, clean-type 1 and clean-type 2 ones.

3.1 Dirty–type technology and clean-type 1 technology

Firstly, the comparison between dirty-type and clean-type cut-off productivity allows to understand how the decision about technology depends on productivity. Specifically, dirty-type and clean-type 1 technologies can be chosen by firms. In this scenario, results are highly affected by the environmental tax, which has a direct impact on dirty-type firms' cut-off productivity. By focusing on the domestic market, it can be shown that the $DD_t$is lower than CD_1 when t is less then $T_1 = G\left[(f^d)^{1/(1-\varepsilon)} - (f^{c_1})^{1/(1-\varepsilon)}\right]$, where $G = \alpha[1/A(1-\alpha)]^{1/(1-\varepsilon)}$. Economically, firms have the incentive to substitute the dirty-type technology with a clean-type one on the domestic market, only if the productivity is sufficiently high ($t > T_1$). Otherwise, the least productive active firms will adopt the dirty-type technology and more efficient firms will adopt the clean-type technology. Similarly, as for the foreign cut-off productivity, if $t < T_1^* = G\left[\left(f^{d^*}\right)^{1/(1-\varepsilon)} - \left(f^{c_1^*}\right)^{1/(1-\varepsilon)}\right]$, $DF < CF_1$.Exporters have the incentive to substitute the dirty-type technology with a clean-type 1 on the foreign market, only if the productivity is sufficiently high ($t > T_1^*$). Otherwise, the least productive exporters will keep adopting the dirty-type technology and the most efficient exporters only will adopt the clean-type technology. In view of this result and depending on fixed costs of production, it is possible to say that:

Proposition 7. *Firm's sorting is guaranteed by $t < T_1$. Specifically, two types of sorting can be obtained depending on the value of the Pigouvian tax:*

SORTING 1: Firm's <u>*foreign sorting*</u> *for a low eco-tax, if the following conditions are satisfied:*

a) $0 < t < T_1^*$
b) $\tilde{\varphi}_{DD-CD_1} > DF$
c) $\left(c^d + t\varphi_j\right)^{-\varepsilon} + \tau\left(c^d\tau + t\varphi_j\right)^{-\varepsilon} > (c^d)^{-\varepsilon}$

SORTING 2: Firm's <u>*domestic sorting*</u> *for a high eco-tax, if the following conditions are satisfied:*

a) $T_1^* < t < T_1$
b) $\tilde{\varphi}_{DD-CD_1} < DF$

Proof. In order to prove Proposition 7, it is necessary to make a combined comparison of dirty-type and clean-type 1 firms' domestic and foreign cut-off productivity and the relative position of the adoption cut-off productivity, $\tilde{\varphi}_{DD-C\ 1}$, with respect to the foreign cut-off productivity DF. $\tilde{\varphi}_{DD-C\ 1}$ represents the productivity level such that π_j^D is equal to $\pi_j^{c_1}$. By assuming $T_1 > T_1^*$ and since $t > 0$, CD_1 is always lower than DF (see Appendix D). If t is lower than T_1^*, SORTING 1 is obtained when $\tilde{\varphi}_{DD-CD_1}$ is lower than DF and the dirty-type *ex post* profit function is steeper than the clean-type 1 one. Specifically, in order to get SORTING 1, the slope of the function $\pi^{d\ SUM}$, which is the sum of domestic and foreign profits of dirty-type firms ($\pi_j^d + \pi_j^{d^*}$), must be higher than the slope of $\pi_j^{c_1}$. This condition is verified when $\left[\left(c^d + t\varphi_j\right)^{-\varepsilon} + \tau\left(c^d\tau + t\varphi_j\right)^{-\varepsilon}\right] > (c^d)^{-\varepsilon}$. For a detailed examination, see Appendix E.
Under SORTING 1, firms can be ranked into four categories:

a. firms that exit the market, for productivity levels lower than DD_t;
b. dirty-type firms that serve the domestic market, for productivity levels between DD_t and DF;
c. dirty-type firms that serve both domestic and foreign markets, for productivity levels between CD_1 and $\tilde{\varphi}_{DF-C\ 1}$. This latter value represents the adoption cut-off productivity such that $\pi^{d\ SUM}$ is total profit of clean-type 1 firms, $\pi^{c_1\ SUM} = \pi_j^{c_1} + \pi_j^{c_1^*}$.
d. clean-type 1 firms that supply goods to both domestic and foreign markets, for productivity levels higher than $\tilde{\varphi}_{DF-C\ 1}$.

Under SORTING 1, the most productive firms, serving both the domestic and foreign markets, have the incentive to adopt an abatement technology, while all non-exporters implement the dirty-type technology.
Conversely, if $T_1^* < t < T_1$, SORTING 2 is obtained and non-exporters can decide to adopt either a dirty-type or a clean-type technology and all exporting firms, so the most productive ones, adopt the

clean-type technology. In this case, $\tilde{\varphi}_{DD-CD_1}$ is higher than DF. Under SORTING 2, firms are classified as follows:

a. firms that exit the market, for productivity levels lower than DD_t;
b. dirty-type firms that serve the domestic market, for productivity levels between DD_t and $\tilde{\varphi}_{DD-CD_1}$;
c. clean-type 1 firms that serve the domestic market, for productivity levels between $\tilde{\varphi}_{DD-CD_1}$ and CF_1;
d. clean-type 1 firms that serve both domestic and foreign markets, for productivity levels higher than CF_1.

Since the scenario with $t < T_1^* < T_1$ is associated to SORTING 1 and the scenario with $T_1^* < t < T_1$ implies SORTING 2, the higher the environmental tax the higher the probability of having SORTING 2 and exporters adopt the upgraded abatement technology only.

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When $t > T_1$, clean-type 1 technology is more convenient than dirty-type technology because the higher fixed costs, associated to the adoption of clean-type 1 technology, will be compensated by the environmental tax savings due to abated pollutants. In this case, all firms will adopt clean-type 1 technology. Furthermore, by assuming $T_1 < T_1^*$ SORTING 1 is confirmed but SORTING 2 is not a possible scenario anymore.
Similar results can be easily shown by comparing dirty-type and clean-type 2 profits.

3.2 Clean-type 1 technology and clean-type 2 technology

In this Section, clean-type 1 and clean-type 2 technologies are compared by accounting for firm's productivity and exporting decision. As it is disclosed before, the adoption of a clean-type technology has been analysed through two steps. First, it is assumed that clean-type firms have higher fixed costs than dirty-type firms, but identical variable production costs. Second, lower variable production costs and higher fixed costs are assumed ($c^c < c^d$). By assuming lower variable production costs, it is imposed that clean-type 2 technology is more complex than both dirty-type and clean-type 1 technologies, thus it requires a higher share of skilled workers. The analysis will assume that $f^d < f^{c_1} < f^{c_2}$. If an economy with clean-type firms only is considered, all emitted pollution is abated and none firms pay for the environmental tax, results are affected by the level of variable and fixed costs of production only. Concerning domestic market and given these assumptions, it can be shown that

Proposition 8. M*arginal domestic productivity of a clean-type 2 firm is higher than the marginal domestic productivity of a clean-type 1 firm when* $(f^{c_2}/f^{c_1}) > (c^d/c^c)^{\varepsilon-1}$

Proof. Zero-profit condition for clean-type 1 firms in domestic market is verified when $\varphi_i = CD_1$; while, for clean-type 2 firms' profit is equal to zero when $\varphi_i = CD_2$. The trade-off between variable and fixed costs of the two clean-type technologies plays a relevant role on production's decision. By comparing (15) and (16), $CD_1 < CD_2$ when $(f^{c_2}/f^{c_1}) > (c^d/c^c)^{\varepsilon-1}$. This conclusion is graphically reported in Figure 2. The figure shows ex post domestic profits of clean-type 1 and clean-type 2 firms, respectively identified by (5) and (6). The full convex curve refers to clean-type 1 firms, while the dotted convex curve concerns clean-type 2 firms.

■

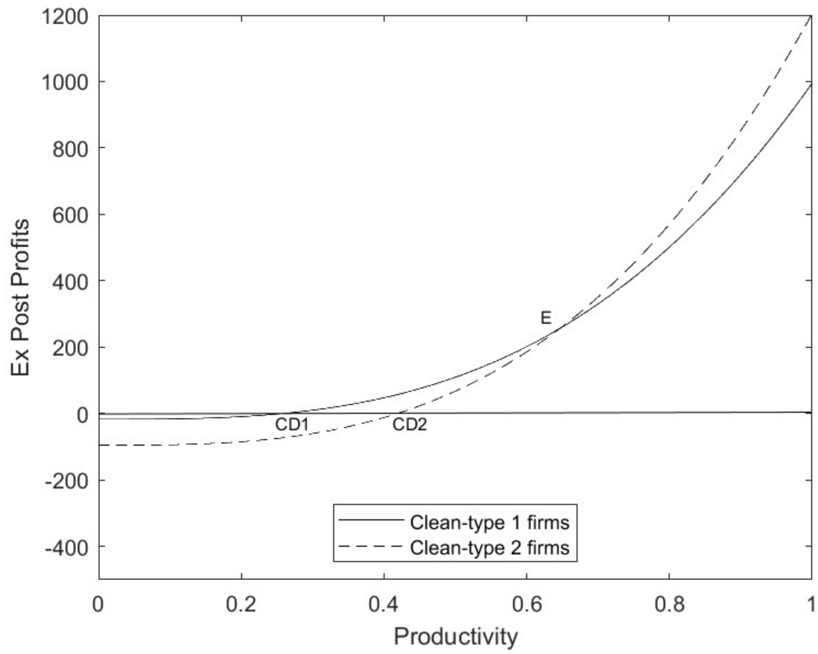

Figure 2. Ex post domestic profits of clean-type 1 and clean-type 2 firms. Specification: equations (5) and (6), numerical simulation in MatLab environment using parameters reported in Section 4.

Furthermore, similar conclusions about marginal productivity can be done referring to the foreign market. Specifically, if $(f^{c_2^*}/f^{c_1^*}) > (c^d/c^c)^{\varepsilon-1}$, so $CF_1 < CF_2$, clean-type 2 technology requires a higher productivity level in order to supply goods to foreign markets, so the adoption of the clean-type 2 technology brings more firms to exit the foreign market, due to a higher value of the marginal productivity.

Given that a more complex abatement innovation, which is identified by clean-type 2 technology, requires lower marginal costs and higher fixed costs than simple abatement innovation, identified by clean-type 1 technology, clean-type 2 abatement technology is more convenient than clean-type 1 if and only if productivity is much higher, so the production volume and sales are sufficiently high to cope with the higher fixed cost.

By examining both domestic and foreign markets cut-off productivities and by assuming $(f^{c_2}/f^{c_1}) > (f^{c_2^*}/f^{c_1^*})$, it is easy to demonstrate that

Proposition 9. *Firm's sorting exists when* $(f^{c_2}/f^{c_1}) > (c^d/c^c)^{\varepsilon-1}$. *Two kinds of sorting can be obtained:*

SORTING 3: Firm's <u>foreign sorting</u>, which is guaranteed when:

a) $0 < (c^d/c^c)^{\varepsilon-1} < (f^{c_2^*}/f^{c_1^*})$

b) $\tau < \{(f^{c_1} - f^{c_2})/[f^{c_1^*}[(c^d)^{1-\varepsilon} - (c^c)^{1-\varepsilon}]]\}^{1/(\varepsilon-1)}/c^d$, which implies $\tilde{\varphi}_{CD_1-C_2} > CF_1$. $\tilde{\varphi}_{CD_1-CD_2}$ is the productivity level such that $\pi_j^{c_1}$ is equal to $\pi_j^{c_2}$. This condition corresponds to point E in Figure 2. A detailed analysis is reported in Appendix F.

c) $\tau < [(c^d/c^c)^{\varepsilon-1} - 1]^{1/(1-\varepsilon)}$

SORTING 4: Firm's <u>domestic sorting</u>, that results if:

a) $(f^{c_2^*}/f^{c_1^*}) < (c^d/c^c)^{\varepsilon-1} < (f^{c_2}/f^{c_1})$;
b) $\tilde{\varphi}_{CD_1-CD_2} < CF_1$.

Proof. As seen in Section 4.1, it is fundamental to compare marginal productivity levels of clean-type 1 and clean-type2 technologies and the adoption cut-off productivity $\tilde{\varphi}_{CD_1-CD_2}$. Their values depend on marginal and fixed costs of production. Given that $f^{c_2^*}/f^{c_1^*}$ is lower than f^{c_2}/f^{c_1}, different situations can be obtained depending on the value of relative marginal costs, $(c^d/c^c)^{\varepsilon-1}$. First, if $0 < (c^d/c^c)^{\varepsilon-1} < (f^{c_2^*}/f^{c_1^*})$, SORTING 3 is guaranteed. In order to obtain this specific sorting, $\tilde{\varphi}_{CD_1-CD_2}$ must be higher than CF_1. The latter condition is satisfied when $\tau < \{(f^{c_1} - f^{c_2})/[f^{c_1^*}[(c^d)^{1-\varepsilon} - (c^c)^{1-\varepsilon}]]\}^{1/(\varepsilon-1)}/c^d$. Furthermore, the slope of the function $\pi^{SUM\ c_1}$ must be greater than the slope of π^{c_2} function. This condition is verified when $\tau < [(c^d/c^c)^{\varepsilon-1} - 1]^{1/(1-\varepsilon)}$. Mathematical steps are reported in Appendix G. Under SORTING 3, clean-type 2 technology is adopted by exporting firms only and brings to the following classification of firms:

a. firms that exit the market, for productivity levels lower than CD_1;
b. clean-type 1 firms that supply goods to the domestic market, for productivity levels between CD_1 and CF_1;
c. clean-type 1 firms that serve both domestic and foreign markets, for productivity levels between CF_1 and $\tilde{\varphi}_{CF_1-CF_2}$. $\tilde{\varphi}_{CF_1-CF_2}$ is the adoption cut-off such that $\pi^{SUM\ c_1}$ is total profit of clean-type 2 firms, $\pi^{SUM\ c_2} = \pi_j^{c_2} + \pi_j^{c_2^*}$;
d. clean-type 2 firms that serve both domestic and foreign markets, for productivity levels higher than $\tilde{\varphi}_{CF_1-CF_2}$.

Second, if $(f^{c_2^*}/f^{c_1^*}) < (c^d/c^c)^{\varepsilon-1} < (f^{c_2}/f^{c_1})$ SORTING 4 can be obtained. Under SORTING 4, domestic firms can implement a clean-type 2 abatement technology instead of a clean-type 1 technology. Moreover, all exporting firms opt for a clean-type 2 technology. SORTING 4 guarantees the existence of the following classification of firms:

a. firms that exit the market, for productivity levels lower than CD_1;
b. clean-type 1 firms that supply goods to the domestic market, for productivity levels between CD_1 and $\tilde{\varphi}_{CD_1-CD_2}$;
c. clean-type 2 firms that serve the domestic market, for productivity levels between $\tilde{\varphi}_{CD_1-CD_2}$ and CF_2;
d. clean-type 2 firms that serve both domestic and foreign markets, for productivity levels higher than CF_2.

If the adoption of clean-type 2 technology is accompanied by a higher volume of production, related to higher fixed costs but lower variable costs, SORTING 4 prevails on SORTING 3.

■

When $(c^d/c^c)^{\varepsilon-1} > (f^{c_2}/f^{c_1})$, clean-type 2 technology is more profitable than clean-type 1 technology, thus there are only clean-type 2 firms in the economy.

Cut-off	Description
DD_t	Domestic cut-off productivity for dirty-type firms
DF	Foreign cut-off productivity for dirty-type firms
CD_1	Domestic cut-off productivity for clean-type 1 firms
CF_1	Foreign cut-off productivity for clean-type 1 firms
CD_2	Domestic cut-off productivity for clean-type 2 firms
CF_2	Foreign cut-off productivity for clean-type 2 firms
$\widetilde{\varphi}_{DD-CD_1}$	Adoption cut-off such that $\pi^D = \pi^{c_1}$
$\widetilde{\varphi}_{DF-CF_1}$	Adoption cut-off such that $\pi^{SUM\ D} = \pi^{SUM\ c_1}$
$\widetilde{\varphi}_{CD_1-CD_2}$	Adoption cut-off such that $\pi^{c_1} = \pi^{c_2}$
$\widetilde{\varphi}_{CF_1-CF_2}$	Adoption cut-off such that $\pi^{SUM\ c_1} = \pi^{SUM\ c_2}$

Table 2. Description of productivity cut-offs

3.3 A comparison among all types of technology

In Sections 2, 3.1 and 3.2, the model is analysed by accounting for a single technology or for pairwise combinations of technologies; in this Section it is supposed that firms can choose among all types of technology: dirty-type, clean-type 1 and clean-type 2 abatement innovations. Since this work studies the conditions under which both domestic and foreign firms' sorting are verified, the combination SORTING 2-SORTING 3 has been chosen among all possible scenarios. As demonstrated by the pairwise technology comparisons, results depend on different aspects related to the environmental tax rate, imposed by the government, and the production advantages in terms of fixed and variable costs, which affect firms' profits and adoption cut-off productivities. In order to get both types of sorting, the following conditions must be satisfied:

a. $T_1^* < t < T_1$
b. $0 < (c^d/c^c)^{\varepsilon-1} < (f^{c_2^*}/f^{c_1^*})$
c. $\tau^{1/(1-\varepsilon)} + 1 < (c^d/c^c)^{\varepsilon-1}$

Condition (a) defines the value of the environmental tax rate such that domestic sorting of dirty-type and clean-type 1 firms exists. Condition (b) allows for the existence of foreign sorting of clean-type 1 and clean-type 2 firms, and underlines that a production advantage for clean-type 1 firms, in terms of lower foreign fixed costs, must exist. Finally, condition (c) refers to the slope of clean-type firm

profit functions. Specifically, it is assumed that both clean-type 1 and 2 firms are active in the foreign market.
These conditions bring to the following results on the adoption cut-off productivities:

d. $\tilde{\varphi}_{DD-C\ 1} < DF$
e. $\tilde{\varphi}_{CD_1-CD_2} > CF_1$
f. $\tilde{\varphi}_{CF_1-CF_2} > \tilde{\varphi}_{DD-CD_1}$
g. $\tilde{\varphi}_{CF_1-CF_2} > \tilde{\varphi}_{CD_1-C\ 2}$

which give both domestic and foreign firm sorting.
As already stated in Section 3.1 and 3.2, the adoption cut-off productivity levels $\tilde{\varphi}_{CD_1-CD_2}$ and $\tilde{\varphi}_{CF_1-CF_2}$ can be analytically calculated. This is not possible for $\tilde{\varphi}_{DD-CD_1}$, so it must be approximated through a numerical simulation reported below.

3.3.1 Numerical simulation of the adoption cut-off productivity $\tilde{\varphi}_{DD-C\ 1}$

The productivity level $\tilde{\varphi}_{DD\ \ \ 1}$ is the productivity level such that a firm is indifferent between dirty type and clean type 1 technologies. Graphically, this corresponds to the intersection point of dirty-type total *ex post* profit curve with clean-type 1 one (point H in Figure 3).
For sake of simplicity, *j*' subscript is dropped, thus total *ex post* profit is:

$$(20)\quad \pi^{TOT^m} = max\{0, \pi^m\} + max\{0, (\pi^{m^*})\} \qquad m = d, c_1$$

This equation can be also expressed for a dirty-type firm as

$$(21)\quad \pi^{TOT^d} \begin{cases} 0\ if\ \varphi \leq DD_t \\ \pi^d\ if\ DD_t < \varphi \leq DF_t \\ \pi^{d\ SUM}\ \ if\ \varphi > DF_t \end{cases}$$

and, for a clean-type 1 firm as

$$(22)\qquad \pi^{TOT^{c_1}} \begin{cases} 0\ if\ \varphi \leq CD_1 \\ \pi_j^{c_1}\ if\ CD_1 < \varphi \leq CF_1 \\ \pi^{c_1\ SUM}\ \ if\ \varphi > CF_1 \end{cases}$$

π^d, $\pi_j^{c_1}$, $\pi_j^{d^*}$ and $\pi_j^{c_1{}^*}$ are all continuous functions; it is easy to verify that both π^{TOT^d} and $\pi^{TOT^{c_1}}$ are continuous too. It is firstly necessary to prove that a unique root between π^{TOT^d} and $\pi^{TOT^{c_1}}$ exists and that is represented by $\tilde{\varphi}_{DD-CD_1}$. This means that, the following *well-posedness* problem must be discussed.
Given the function

$$(23)\qquad F(\varphi) = \pi^{TOT^{c_1}} - \pi^{TOT^d}$$

it is affirmed that

Proposition 10. *There exists a unique root* $\tilde{\varphi}_{DD-C\ 1} \in (0, \infty)$ *for function* $F(\varphi)$*, which is the intersection between total ex post profits of dirty-type and clean-type 1 firms.*

Proof. Notice that the function $F(\varphi)$ is continuous over the whole domain $[0, +\infty[$, because both π^{TOT^d} and $\pi^{TOT^{c_1}}$ are continuous. Moreover, $F(\varphi) < 0$ for $\varphi \in (DD_t, CD_1)$. This is verified because $t < T_1$ is assumed. Finally, it is easy to verify that $F(\varphi)$ is strictly increasing and the following limit holds:

$$(24) \quad \lim_{\varphi=+\infty} F(\varphi) = \lim_{\varphi=+\infty} [(\pi^{c_1\,SUM}) - (\pi^{d\,SUM})] = +\infty$$

then the well-known theorem of zeros for continuous function assures the existence and uniqueness of a root for function $F(\varphi)$.

■

Anyway, as above-mentioned, the model does not admit a simple closed-form solution for $\tilde{\varphi}_{DD-CD_1}$, because the intersection between total ex post profits lies on the domestic part of both total *ex post* profits, therefore the numerical approximation represents the only way of obtaining quantitative results. The bisection method has been implemented as an iterative numerical approximation. Bisection sequences are iterated in Excel environment. Before proceeding with the application of this numerical approach, a brief description of the method is given.

3.3.1.1 The Bisection Method

The bisection method is based on the theorem of zeros for continuous function and, as described by Quarteroni et al. (2000), it is implemented through the following steps. Starting from an interval $I_0 = [a, b] \in \mathbb{R}$, this method creates a sequence of subinterval $I_k = [a^{(k)}, b^{(k)}]$, where $k \geq 0$, with $I_k \subset I_{k-1}$, $k \geq 1$, and applies the property that $f(a^{(k)})f(b^{(k)}) < 0$. In other words, as a first step the initial interval I_0 is set: a is set equal to a^0 and b equal to b^0. As a second step, a new variable $\varphi^0 = (a^0 + b^0)/2$ is defined. It represents the mean of I_0; then, for $k \geq 0$ set a new interval equal to:

$$(25) \quad \begin{cases} a^{(k+1)} = a^{(k)}, b^{(k+1)} = \varphi^{(k)} & if\ f(\varphi^{(k)})f(a^{(k)}) < 0 \\ a^{(k+1)} = \varphi^{(k)}, b^{(k+1)} = b^{(k)} & if\ f(\varphi^{(k)})f(b^{(k)}) < 0 \end{cases}$$

Finally, set $\varphi^{(k+1)} = (a^{(k+1)} + b^{(k+1)})/2$. The iteration terminates at the *n*-th step for which $|\varphi^n - \tilde{\varphi}_{DD-CD_1}| \leq |I_n| \leq \xi$, where $\tilde{\varphi}_{DD-CD_1}$ is the root of the continuous function $F(\varphi)$, ξ is a fixed value of tolerance and $|I_n| = |a^{(n)} - b^{(n)}|$ represents the length of I_n.

In order to apply the bisection method, it is fundamental to set specific values of structural parameters, which are listed in Table 3, Column 1. Values are chosen in order to satisfy the theoretical conditions explained at the beginning of this Section but further specifications about some parameters are necessary. Trade cost is assumed to be equal to 1.41, obtained by adapting the formula proposed by Bernard et al. (2007) $\tau^{1-\varepsilon}/(1 + \tau^{1-\varepsilon})$. The formula identifies the average fraction of exports in a given sector. The value is taken for German firms from the Eurostat Community Innovation Survey dataset 2006-2008. Specifically, the mean share of total turnover from foreign sales is 0.2758. The elasticity of substitution ε is set to 4 by following Bernard et al. (2003). Consequently, the parameter α (the inverse of mark-up) is equal to 0.75.

Fixed Parameters	**Value**
Marginal costs c^d	0.50
Marginal costs c^c	0.46
Domestic fixed cost for dirty-type firms f^d	5
Domestic fixed cost for clean-type 1 firms f^{c_1}	17
Domestic fixed cost for clean-type 2 firms f^{c_2}	95
Foreign fixed cost for dirty-type firms f^{d^*}	10
Foreign fixed cost for clean-type 1 firms $f^{c_1^*}$	30
Foreign fixed cost for clean-type 2 firms $f^{c_2^*}$	150
Variable trade cost τ	1.41
Market dimension A	1200
Elasticity of substitution ε	4
Inverse of the mark-up $\alpha = (\varepsilon - 1)/\varepsilon$	0.75
Pigouvian environmental tax t	0.85

Simulated Parameters	**Value**
T_1	0.98
T_1^*	0.71
DD_t	0.24
DF	0.48
CD_1	0.26
CF_1	0.44
CD_2	0.42
CF_2	0.69
$\widetilde{\varphi}_{DD-CD_1}$	0.26
$\widetilde{\varphi}_{CF_1-CF_2}$	0.80
$\widetilde{\varphi}_{CD_1-CD_2}$	0.65

Table 3. Fixed and simulated parameters for the numerical simulation.

The parameters obtained through the numerical simulation are reported in Column 2 of Table 1. By analysing these values, all the necessary conditions are verified. By merging SORTING 2 and SORTING 3 both domestic and foreign sorting are obtained. As it is possible to see from graph "Firm sorting" in Figure 3, which combines *ex post* total profits by technology, five groups of firms exist:

a. firms that exit the market, for productivity levels lower than DD_t;
b. firms that serve domestic market only and adopt dirty-type technology, for productivity levels between DD_t and $\tilde{\varphi}_{DD-C\ \ 1}$;
c. clean-type 1 firms that supply domestic market only, for productivity levels between $\tilde{\varphi}_{DD-CD_1}$ and CF_1;
d. clean-type 1 firms that serve both domestic and foreign markets, for productivity levels between CF_1 and $\tilde{\varphi}_{CF_1-CF_2}$;
e. clean-type 2 firms that supply goods to domestic and foreign markets, for productivity levels higher than $\tilde{\varphi}_{CF_1-C\ \ 2}$.

By summarizing, some conclusions can be drawn. First, for a relatively low value of the environmental tax, domestic firms can adopt a dirty-type technology or a clean-type 1 technology, Since the latter is more complex and more expensive than the former one, the least productive keep using the pollutant technology. Second, exporting firms never adopt a dirty-type technology but only clean-type technologies. This means that abating firms more than compensate the higher fixed costs of a green technology. Third, the most productive firms export and implement the most complex abatement technology, the clean-type 2 technology.

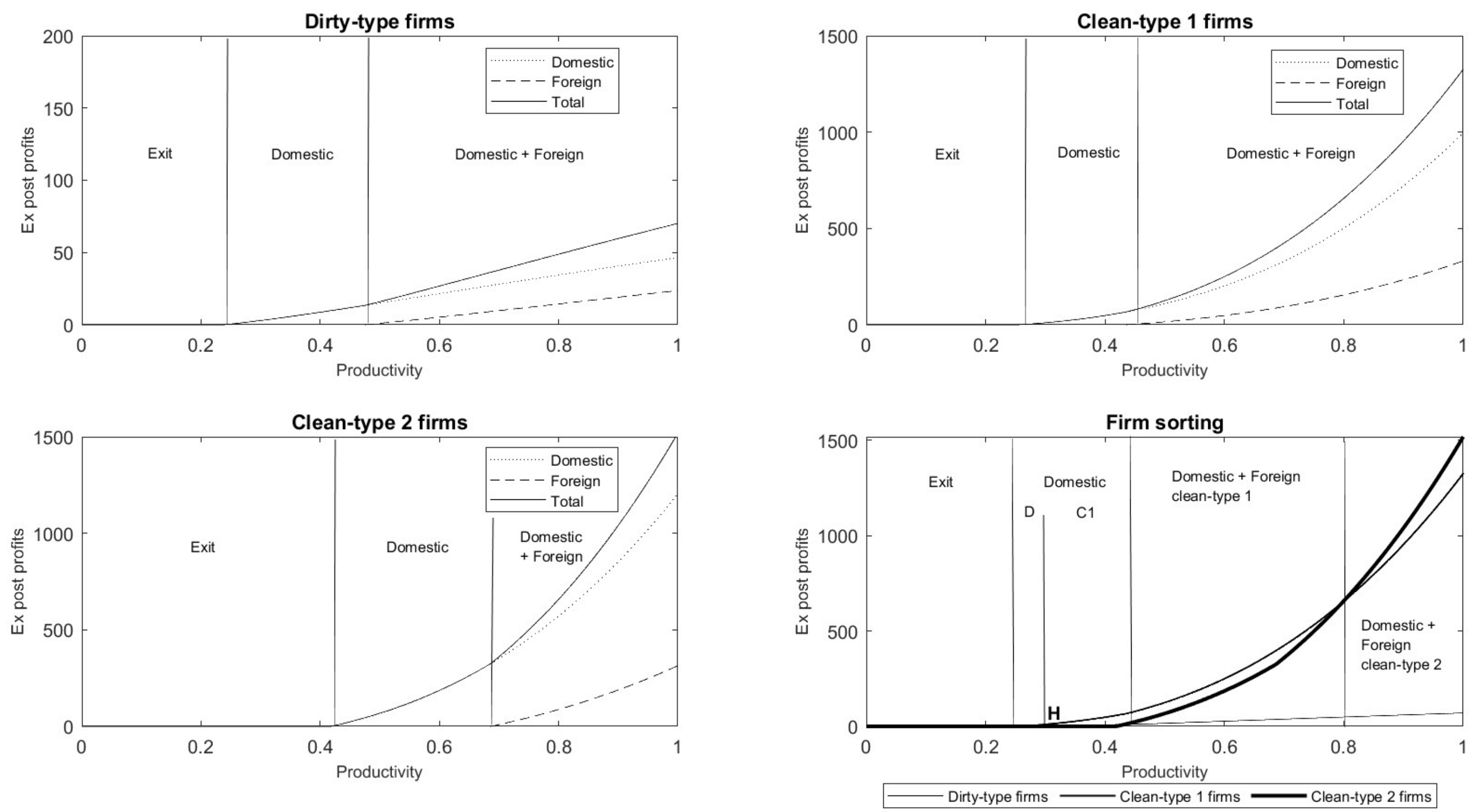

Figure 3. Firm sorting obtained by numerical simulation in MatLab environment. Parameter values are reported in Table 1.

4. Conclusions

Given the increasing interest of the economic literature on the effect of environmental regulation on environmental innovation and trade performance, this work has theoretically investigated the role of firm's productivity heterogeneity on the adoption of abatement technology and exporting propensity at firm level when a Pigouvian pollution tax is introduced.

By using a revised version of Melitz international trade model proposed by Helpman (2006) where firms may adopt dirty-type and clean-type technologies, four important results have been found. First, the introduction of a Pigouvian tax by the government generates an increase of cut-off productivity of dirty-type firms, so the lowest productive pollutant firms leave the market due to this imposed regulation. This result implies that, if all firms adopt a dirty-type technology, the government can use the tax as an instrument to reduce pollution. However, since exiters are the smallest firms, the emission reduction is limited, and active firms' costs increase due to the tax burden, with a negative effect on export propensity. Second, when alternative clean-type technologies (clean-type 1 and clean-type 2) are considered, a sufficiently large environmental tax brings firms to adopt the abatement technology because the higher fixed costs, associated with cleaner technologies, can be compensated by environmental tax savings. This reduces the share of polluters in the active firm population. Third, due to the higher complexity of the clean-type 2 technology, which requires higher fixed costs, less productive firms will adopt it provided that an advantage in terms of marginal costs exists. Finally, when all types of technology can be chosen by firms, different scenarios in terms of firm sorting may emerge, so, depending on Pigouvian tax rate and variable and fixed costs of production, domestic and foreign cut-off productivities change. Among all possible scenarios, it has been analysed the case when both domestic and foreign sorting is verified. A low value of the tax brings domestic firms to adopt a dirty-type technology or a clean-type 1 technology and exporting firms implement clean-type innovations only. More productive firms export and use abatement technology; specifically, by admitting that the complex technology (clean-type 2) involves lower marginal costs of production but larger fixed costs than the clean-type 1 one, may imply that, under certain conditions, a group of exporters with a medium productivity will adopt the clean-type 1 technology and the most productive ones use the clean-type 2 technology.

From a policy point of view, the environmental tax has a selection effect on the smallest and least productive firms, while it fosters abatement technologies for the largest and most productive firms only. Therefore, governments should introduce new environmental policies tailored on firm characteristics, especially size. Productivity enhancing policies may be more successful in the transition toward cleaner technology economies, with a particular attention on small firms.

Further investigations could be conducted by considering other types of environmental regulations, which differently affect the structure of the model. Moreover, some counterfactual analysis could be done by supposing that clean-type 2 technology requires both higher fixed and variable costs than clean-type 1 and dirty-type technologies. The theoretical analysis developed in this paper can be useful in the empirical evaluation of the effect of eco-regulation on firms' green innovation propensity and competitiveness using micro data. The environmental tax will negatively affect export propensity. Furthermore, it positively influences eco-innovation propensity, which in turn indirectly fosters export propensity. However, since these contrasting effects will strictly depend on productivity, environmental tax and cost differences across firms and technologies, an appropriate econometric strategy should be developed to account for both direct and indirect effects.

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Appendix A – Profit Maximization of Dirty-Type Firms

A.1 Domestic market

First, it is necessary to substitute the demand constraint into the profit function:

Eq. (A.1.1) $\pi_j^d = Ap_j^{1-\varepsilon} - \big((c^d/\varphi_j) + t\big)Ap_j^{-\varepsilon} - f^d$

Consequently, by differentiating profit function with respect to the price, the first order condition of maximization is applied (first derivative must be equal to 0) and the maximizing price p_j^d is obtained.

Eq. (A.1.2) $\frac{d\pi_j^d}{dp_j} = A(1-\varepsilon)p_j^{-\varepsilon} + A\varepsilon p_j^{-\varepsilon-1}\big((c^d/\varphi_j) + t\big) = 0$

Eq. (A.1.3) $Ap_j^{-\varepsilon}\big[(1-\varepsilon) + \varepsilon\big((c^d/\varphi_j) + t\big)p_j^{-1}\big] = 0$

Eq. (A.1.4) $\varepsilon - 1 = \varepsilon\big((c^d/\varphi_j) + t\big)p_j^{-1}$

Eq. (A.1.5) $p_j = 1/\alpha\,\big((c^d/\varphi_j) + t\big) = p_j^d$

where $1/\alpha = \varepsilon/(\varepsilon - 1)$.
By substituting the optimal price into the profit function, the *ex post* domestic profit of dirty-type firms π_j^d is:

Eq. (A.1.6) $$\begin{aligned}\pi_j^d &= A\big[(1/\alpha)\big((c^d/\varphi_j) + t\big)\big]^{1-\varepsilon} - A\big((c^d/\varphi_j) + t\big)\big[(1/\alpha)\big((c^d/\varphi_j) + t\big)\big]^{-\varepsilon} - f^d \\ &= A\big((c^d/\varphi_j) + t\big)^{1-\varepsilon}(1/\alpha)^{-\varepsilon}((1/\alpha) - 1) - f^d \\ &= A\big((c^d/\varphi_j) + t\big)^{1-\varepsilon}(1/\alpha)^{1-\varepsilon}(1-\alpha) - f^d \\ &= A\,\big[(1/\alpha)\big((c^d/\varphi_j) + t\big)\big]^{1-\varepsilon}(1-\alpha) - f^d\end{aligned}$$

A.2 Foreign market

Given the foreign demand X_j^*, dirty-type firms choose the price level that maximizes their profits:

Eq. (A.2.1) $\pi_j^{d^*} = Ap_j^{*1-\varepsilon} - \big((c^d\tau_j/\varphi_j) + t\big)Ap_j^{*-\varepsilon} - f^{d^*}$

By differentiating the foreign profit function with respect to the price and by imposing the first order condition, the maximizing price of dirty-type firms in foreign market will be equal to:

Eq. (A.2.2) $\frac{d\pi_j^{d^*}}{dp_j^*} = A(1-\varepsilon)p_j^{*-\varepsilon} + A\varepsilon p_j^{*-\varepsilon-1}\big((c^d\tau_j/\varphi_j) + t\big) = 0$

By solving this equation with respect to p_j^*, the optimal price in foreign market is

Eq. (A.2.3) $p_j^{d^*} = \frac{1}{\alpha}\big((c^d\tau_j/\varphi_j) + t\big)$

Finally, this value of the price is substituted back into the profit function and the *ex post* foreign profit of dirty-type firms is obtained:

Eq. (A.2.4) $\pi_j^{d^*} = A\left[(1/\alpha)\left((c^d\tau_j/\varphi_j) + t\right)\right]^{1-\varepsilon}(1-\alpha) - f^{d^*}$

Appendix B – Profit Maximization of Clean-Type 1 Firms

B.1 Domestic market

Profit maximization is identical for dirty-type and clean-type 1 firms. To simplify the analysis, final results are reported. First, by substituting the demand constraint into the profit function it is found:

Eq. (B.1.1) $\pi_j^{c_1} = Ap_j^{1-\varepsilon} - (c^d/\varphi_j)\,Ap_j^{-\varepsilon} - f^{c_1}$

By imposing the first order condition, the maximizing price for clean-type 1 firms will be equal to:

Eq. (B.1.2) $p_j^{c_1} = (1/\alpha)\,(c^d/\varphi_j)$

This price is substituted back into the profit function and the *ex post* domestic profit for clean-type 1 firms is:

Eq. (B.1.3) $\pi_j^{c_1} = A\left(c^d/\varphi_j\alpha\right)^{1-\varepsilon}(1-\alpha) - f^{c_1}$

B.2 Foreign market

Given the foreign demand, clean-type 1 firms choose the price that maximizes their profits

Eq. (B.2.1) $\pi_j^{c_1^*} = Ap_j^{*^{1-\varepsilon}} - \left((c^d\tau_j/\varphi_j)\right)Ap_j^{*^{-\varepsilon}} - f^{c_1^*}$

Given the first order condition, the optimal price in foreign market for clean-type 1 firms is:

Eq. (B.2.2) $p_j^{*c_1} = (1/\alpha)\left(c^d\tau_j/\varphi_j\right)$

Then, the *ex post* foreign profit of clean-type 1 firms is:
Eq. (B.2.3) $\pi_j^{c_1^*} = A\left(c^d\tau_j/\varphi_j\alpha\right)^{1-\varepsilon}(1-\alpha) - f^{c_1^*}$

Appendix C - Profit Maximization of Clean-Type 2 Firms

C.1 Domestic market

First, by substituting the demand constraint into the profit function the following is obtained:

Eq. (C.1.1) $\pi_j^{c_2} = Ap_j^{1-\varepsilon} - (c^c/\varphi_j)\,Ap_j^{-\varepsilon} - f^{c_2}$

By satisfying the first order condition, the maximizing price of clean-type 2 firms in domestic market is:

Eq. (C.1.2) $p_j^{c_2} = (1/\alpha)\,(c^c/\varphi_j)$

This value of the price is substituted back into profit function and the *ex post* domestic profit for clean-type 2 firms is equal to:

Eq. (C.1.3) $\pi_j^{c_2} = A\ (c^c/\varphi_j\alpha)^{1-\varepsilon}(1-\alpha) - f^{c_2}$

C.2 Foreign market

Given the foreign demand as constraint, clean-type 2 firms' profits are equal to the following equation:

Eq. (C.2.1) $\pi_j^{c_2^*} = Ap_j^{*^{1-\varepsilon}} - (c^c\tau_j/\varphi_j)\,Ap_j^{*^{-\varepsilon}} - f^{c_2^*}$

By differentiating $\pi_j^{c_2^*}$ with respect to p_j^* and by imposing zero-profits condition, the optimal price in foreign market for clean-type 2 firms is obtained:

Eq. (C.2.2) $p_j^{*c_2} = (1/\alpha)\,(c^c\tau_j/\varphi_j)$

Given the optimal price, clean-type 2 firms' *ex post* foreign profits can be obtained:

Eq. (C.2.3) $\pi_j^{c_2^*} = A\ (c^c\tau_j/\varphi_j\alpha)^{1-\varepsilon}(1-\alpha) - f^{c_2^*}$

Appendix D – Dirty-type firms' foreign cut-off productivity and Clean-type 1 firms' domestic cut-off productivity

In Section 2 it is demonstrated that foreign cut-off productivity of dirty-type firms DF is equal to $c^d\tau_j\left\{\alpha\left[f^{d^*}/(A(1-\alpha))\right]^{1/(1-\varepsilon)} - t\right\}^{-1}$, while domestic cut-off productivity of clean-type 1 firms CD_1 is equal to $c^d/\alpha\,[f^{c_1}/(A(1-\alpha))]^{1/(1-\varepsilon)}$. By comparing these marginal productivity values, it can be shown that $CD_1 < DF$ when

Eq. (D.1) $\tau > \left(f^{c_1}/f^{c_1^*}\right)^{1/(1-\varepsilon)} - t[f^{c_1}/(A(1-\alpha)\alpha^{\varepsilon-1})]^{1/(1-\varepsilon)}$

Given that Proposition 7 assumes $\tau > \left(f^{c_1}/f^{c_1^*}\right)^{1/1-\varepsilon}$ the previous inequality is always verified.

Appendix E – Dirty-type and Clean-type 1 firms: a comparison between the slopes of profit functions

Given domestic and foreign *ex post* profit functions of dirty-type firms, it is possible to calculate the total profit which is equal to

Eq. (E.1) $$\begin{aligned}\pi^{d\,SUM} &= \pi_j^d + \pi_j^{d^*}\\ &= \left\{A\,\alpha^{\varepsilon-1}(1-\alpha)\left[\left((c^d/\varphi_j)+t\right)^{1-\varepsilon} + \left((c^d\tau_j/\varphi_j)+t\right)^{1-\varepsilon}\right]\right\} - f^d - f^{d^*}\end{aligned}$$

By differentiating $\pi^{d\,SUM}$ with respect to φ_j, the slope of the previous function is obtained:

Eq. (E.2) $\frac{d\pi^{d\,SUM}}{d\varphi_j} = A\,\alpha^{\varepsilon-1}(1-\alpha)(\varepsilon-1)\,(c^d/\varphi_j{}^2)\left[\left((c^d/\varphi_j)+t\right)^{-\varepsilon}+\tau\left((c^d\tau_j/\varphi_j)+t\right)^{-\varepsilon}\right]$

Similarly, the slope of domestic *ex post* profit of clean-type 1 firms can be calculated by differentiating the function $\pi_j^{c_1}$ with respect to φ_j

Eq. (E.3) $\frac{d\pi^{c_1}}{d\varphi_j} = A\,\alpha^{\varepsilon-1}(1-\alpha)(\varepsilon-1)\,(c^d/\varphi_j{}^2)\,(c^d/\varphi_j)^{-\varepsilon}$

Now, by comparing Eq. (E.2) and Eq. (E.3), it is easy to show that $\frac{d\pi^{d\,SUM}}{d\varphi_j} > \frac{d\pi^{c_1}}{d\varphi_j}$ when

Eq. (E.4) $\left[\left(c^d+t\varphi_j\right)^{-\varepsilon}+\tau\left(c^d\tau+t\varphi_j\right)^{-\varepsilon}\right] > (c^d)^{-\varepsilon}$

Appendix F – Clean-type 1 and Clean-type 2 firms: adoption cut-off productivity $\tilde{\varphi}_{CD_1-CD_2}$

In order to calculate the adoption cut-off $\tilde{\varphi}_{CD_1-CD_2}$ is such that domestic *ex post* profit of clean-type 1 and clean-type 2 firms are identical. As shown by Equations (5) and (6) in Section 2, $\pi_j^{c_1} = A\left(c^d/\varphi_j\alpha\right)^{1-\varepsilon}(1-\alpha)-f^{c_1}$ for clean-type 1 firms, and $\pi_j^{c_2} = A\left(c^c/\varphi_j\alpha\right)^{1-\varepsilon}(1-\alpha)-f^{c_2}$ for clean-type 2 firms. The productivity level satisfying this condition is analytically calculated, $\tilde{\varphi}_{CD_1-C\ 2}$

Eq. (F.1) $\tilde{\varphi}_{CD_1-CD_2} = \{(f^{c_1}-f^{c_2})/A\,\alpha^{\varepsilon-1}(1-\alpha)[(c^d)^{1-\varepsilon}-(c^c)^{1-\varepsilon}]\}^{1/(\varepsilon-1)}$

Appendix G – Clean-type 1 and Clean-type 2 firms: a comparison between the slopes of profit functions

Given domestic and foreign *ex post* profit functions of clean-type 1 firms, total profit can be calculated as follows

Eq. (G.1)
$$\begin{aligned}\pi^{c_1\,SUM} &= \pi_j^{c_1}+\pi_j^{c_1^*}\\ &= \left[A\,\alpha^{\varepsilon-1}(1-\alpha)\left(c^d/\varphi_j\right)^{1-\varepsilon}(1+\tau^{1-\varepsilon})\right]-f^{c_1}-f^{c_1^*}\end{aligned}$$

By differentiating $\pi^{c_1\,SUM}$ with respect to φ_j, the slope of the function is equal to:

Eq. (G.2) $\frac{d\pi^{c_1\,SUM}}{d\varphi_j} = A\,\alpha^{\varepsilon-1}(1-\alpha)(1+\tau^{1-\varepsilon})(\varepsilon-1)\left(c^d/\varphi_j{}^2\right)\left(c^d/\varphi_j\right)^{-\varepsilon}$

In the same way, the slope of domestic *ex post* profit of clean-type 2 firms is obtained

Eq. (G.3) $\frac{d\pi^{c_2}}{d\varphi_j} = A\,\alpha^{\varepsilon-1}(1-\alpha)(\varepsilon-1)\left(c^c/\varphi_j{}^2\right)\left(c^c/\varphi_j\right)^{-\varepsilon}$

Now, by comparing Eq. (G.2) and Eq. (G.3), it is easy to show that the total profit function of clean-type 1 firms is steeper than the domestic profit function of clean-type 2 firms when

Eq. (G.4) $\tau < [(c^d/c^c)^{\varepsilon-1} - 1]^{1/(1-\varepsilon)}$

Appendix H - Clean-type 1 and Clean-type 2 firms: adoption cut-off productivity $\tilde{\varphi}_{CF_1-CF_2}$

The value of adoption cut-off $\tilde{\varphi}_{CF_1-C\ _2}$ is obtained when clean-type 1 firm and clean-type 2 firm total profits are identical. Clean-type 1 firm total profit is reported in Eq. (G.1). With regards to clean-type 2 firms total profit function can be obtained:

Eq. (H.1)
$$\begin{aligned} \pi^{c_2\,SUM} &= \pi_j^{c_2} + \pi_j^{c_2{}^*} \\ &= A\left(c^c/\varphi_j\alpha\right)^{1-\varepsilon}(1-\alpha) - f^{c_2} + A\left(c^c\tau_j/\varphi_j\alpha\right)^{1-\varepsilon}(1-\alpha) - f^{c_2{}^*} \\ &= A\left(c^c/\varphi_j\alpha\right)^{1-\varepsilon}(1-\alpha)\left(1+\ \tau_j^{1-\varepsilon}\right) - f^{c_2} - f^{c_2{}^*} \end{aligned}$$

The value of $\tilde{\varphi}_{CF_1-CF_2}$ is then obtained

Eq. (H.2)
$$\tilde{\varphi}_{CF_1-CF_2} = \left[(f^{c_1} + f^{c_1^*} - f^{c_2} - f^{c_2^*})/(A\,\alpha^{\varepsilon-1}(1-\alpha)(1+\tau_j^{1-\varepsilon})((c^d)^{1-\varepsilon} - (c^c)^{1-\varepsilon}))\right]^{1/(1-\varepsilon)}$$