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International trade, eco-innovation and pollution emissions: theoretical and empirical analysis at firm and country level

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Summary

Thesis Abstract

Since 1990's, environmental deterioration has obtained an increasing interest and it is one of the most important issue in the policy debate at the international level. Nevertheless, improvements have been made through, though this kind of problems still have negative effects on human and natural survival. Considering this scenario, governments have done important efforts in order to coordinate their policies towards the promotion of a sustainable development, by fostering an efficient use of natural resources and a reduction of emissions. This process is a long-term mechanism that needs changes in both consumption and production behaviours. Concerning production side, many studies have investigated the relationship between environmental issues, green policies and different economic factors, and many hypotheses have been formulated (Porter Hypothesis, Pollution Haven, etc.). Among these factors, trade and innovation have a relevant effect, so authorities should apply policies that encourage trade and innovation in a sustainable perspective. It is also true that empirical researches have underlined that the relationship among trade, innovation and environment is multi-directional. This means that producers have to manage trade and innovation by considering the environmental scenario but they should also take economic advantage from being green. In view of this, it is evident that the relationship among trade, innovation and sustainability is complex and requires an intensive collaboration between all stakeholders, from governments to consumers and firms.

By considering the worldwide importance of this relation, the present thesis aims at deeply investigating the interplay of environmental policies with the adoption of innovation and trade decision at firm level. It also has the objective of analysing the effect of trade and innovation on country level emissions. The thesis is divided into three chapters. In the first two chapters,

micro level analyses have been conducted, both from theoretical and empirical perspectives, while in the third one a cross-country study has been done. The three chapters are hereafter described.

The first essay theoretically investigates the role of firm heterogeneity into the Porter Hypothesis dynamics. By using the version of Melitz's international trade model proposed by Helpman (2006), we study the effects of the introduction of an environmental tax on technology and trade decisions of firms. Specifically, we suppose that firms could be dirty or clean, depending on the adopted technology, when the government introduces an environmental tax. Clean firms adopt a total abatement technology so that they do not pay the tax. Firms can choose among three types of technology (dirty-type, clean-type 1 and clean-type 2), which require a different amount of fixed and variable costs. Clean-type 2 technology is more complex than clean-type 1 one. Technology decision has an impact on firms’ productivity, which subsequently affects their exporting propensity. This chapter suggests four important results. First, in a situation where all firms are dirty, governments could use the environmental tax as a good instrument for reducing pollution because it forces the least productive firms to leave the market, with a reduction of emissions and an improvement of the average productivity. Second, if firms may choose between a dirty and a clean technology, they are encouraged to adopt a clean technology when the value of the tax is sufficiently high. Since this kind of technology requires a higher level of fixed costs for its implementation, these costs can be compensated by some tax savings. Third, if we consider a scenario with clean-type 1 and clean-type 2 technologies, firms will opt for a more advanced technology if it is economically convenient. This means that firms introduce a complex abatement technology only when a highly-efficient firm is able to cope with it. Finally, in a scenario where all types of technology can be chosen by firms, the international organisation of production and technology adoption will depend on different aspects, such as the amount of the environmental tax, the relationship between variable and fixed costs that each technology requires.

The second study is conducted in order to empirically analyse Pollution Havens and Porter Hypothesis by accounting for the role of firm heterogeneity in trade, innovation and environmental regulation. Specifically, we econometrically test, with reference to CIS2008 and CIS2014 manufacturing German firms, the hypothesis of a negative impact of environmental regulation on exporting propensity and the vision of a positive effect of regulation on innovation and, indirectly, on trade performance. The empirical analysis demonstrates that the hypothesis of the Pollution Haven Effect is confirmed for German firms in CIS2014 and when an environmental taxation is implemented. Differently from the existing literature, which suggests that the introduction of an eco-regulation entails some additional compliance costs and, correspondingly, a decreases competitiveness, a not significant effect of policy on exporting propensity of firms is obtained for CIS2008 and CIS2014. Since we expect that regulations have a higher impact on firms' competitiveness in more pollutant sectors, we admit heterogeneous coefficients of the eco-regulation variable by sector emission intensity. Specifically, sectors are classified as green, grey and brown and results suggest that eco-regulation has a negative effect on exporting propensity in brown sectors only, though losing robustness over time from CIS2008 to CIS2014.

Moreover, we have found that eco-innovation positively affects the probability of exporting. Another important result concerns the effect of environmental regulation on eco-innovation adoption. In line with the related literature on the well-known *weak* Porter Hypothesis, we find that regulation is a fundamental driver of innovation; the introduction of a new or a stringent environmental policy represents an incentive for firms to be innovative.

Since policy makers should consider that firms could react differently to regulation in the eco-regulation drawing process, the two perspectives are also tested on three subsamples: small, medium and large firms. This analysis is important because size represents another measure of firm's productivity, so of its efficiency level and competitive capacity. Concerning small firms, environmental policies do not affect trade propensity but are relevant for the introduction of eco-innovation. However, the latter positive effect of regulations must be associated with public financial incentives. For medium and large firms, we can state that the existence of a green policy brings firms to be non-exporters. In other words, medium, either brown or grey, firms are less competitive if an eco-regulation is imposed. However, environmental innovation adoption is driven by eco-regulation and is itself a driver for being an exporter.

The thesis is completed by a third macroeconomic level study, that aims at analysing different country characteristics, such as internationalisation and innovation profiles, which affect greenhouse gases and acidifying gases emissions in European Union countries. We decompose the overall level of emissions in scale, composition and technique effects by the Log Mean Divisia Index method. Then we investigate the determinants of each component by implementing a fixed effect Seemingly Unrelated Regression estimation. The analysis of different components is conducted through three steps. First, we investigate the effect of per capita income on air emissions. Specifically, we test the Environmental Kuznets Curve hypothesis, which underlines an inverted U-shaped relationship between income and pollution. By following the literature, as a second step, we account for the direct impact of other important economic factors in affecting the shape and turning point of the Kuznets curve, such as trade, eco-innovation, relative factor abundance and renewable energy use. Eco-innovation and renewable energy use can capture the technological progress of a country and the efficient use of resources. We expect that both variables positively contribute to the reduction of pollution. Furthermore, relative factor endowments, together with eco-innovation, is a fundamental measure of country comparative advantage. Trade has been taken into account because, as the existing empirical evidence shows, its effect on emission can be ambiguous, it could either increase or decrease pollution. Finally, as a third step, since trade has also an indirect effect on pollution through scale, composition and technique effects, we measure the trade-induced impact by adding some interaction terms. The econometric analysis of European Union countries data over 2008-2014 years show that all described economic factors differently affect the three above-mentioned effects and results are strictly related to the analysed type of pollutant. For greenhouse gases, the Environmental Kuznets Curve hypothesis cannot be rejected and is totally driven by the scale effect. This result is not verified for acidifying gases emissions. Furthermore, trade directly increases the level of both air pollutants and this is connected with the scale effect. This means that trade contributes to an increase of domestic economic activity which is reflected into an expansion of production and emissions. Trade also has an indirect impact through income, relative factors endowments and renewable energy use on air emissions, which may be either positive or negative. As a final important result, we obtain that both pollutants show a general reduction over time, common to all European Union countries, and this trend is mainly driven by the technique effect. Thus, we can argue that the European Union common policy tools fostering environmental friendly technology have contributed to improve air quality, although the 2008 worldwide crisis has certainly contributed to this decreasing trend.

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

1. Introduction

Since 1990's, globalization has assumed an important role in the global economy and the volume of trade has been largely increased. However, globalization and international trade have been accompanied by a deterioration of the environment, in terms of both increased pollution and intensive use of natural resources, so 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 behaviours 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 the implementation of 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 into the relationship between trade and innovation decisions at micro level. Specifically, by using the Helpman (2006) version of Melitz (2003) international trade model, we theoretically study the effects of the introduction of a Pigouvian tax on firms' technology and exporting decisions when they are heterogeneous in terms of productivity and operate in a monopolistic competitive market.

This work is strictly connected to different aspects of the literature on the relationship among green regulations, international trade and technology adoption at firm level. First, it refers to the theoretical literature on partial equilibrium models that studies the incentives generated by environmental regulations for the introduction and diffusion of abatement technologies by firms[1]. For example, Milliman and Prince (1989) and Jung et al. (1996), by considering different types of green policies, have pointed out that firms have different incentives to introduce abatement innovation depending on regulation. Specifically, taxes or charges generate a better incentive for firms to be eco-innovative than other kinds of policies. A second relevant branch of the literature concerns the theoretical works that analyse the international trade patterns by accounting for firms' productivity heterogeneity [Melitz (2003), Helpman (2006)]. These models have demonstrated that depending on their productivity, firms that operate in a monopolistically competitive market can have different export propensity. Generally, the least productive firms leave the market because of negative profits, while more productive firms decide among serving only the domestic market. The most productive firms sell their goods to or both domestic and foreign markets. Furthermore, among this literature, a relevant work for this chapter is represented by the paper by Paula Bustos of 2011, who has studied the firm technology decision in a Melitz (2003) trade model. Through her study, she has obtained that the growth of profits produced by trade integration can induce exporters to implement more advanced technology, so the most productive firms both export and adopt advanced innovation. Third, the present paper is related to the literature on the Porter Hypothesis. This idea is borne at the beginning of 90s and underlines the positive effect of environmental policies on the adoption of eco-innovation and, dynamically, on firms' economic and environmental performance, so on their competitiveness [Porter (1991), Porter and Van Der Linde (1995), Jaffe and Palmer (1997)]. This work is finally and especially related to more recent theoretical models that analyse the relationship of exporting propensity with environmental regulation and firms' environmental performance, in a context of heterogeneous productivity across firms and monopolistic competition [Kreickermeier and

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[1] For a detailed survey on this literature see Requate (2005).

Richter (2014), Cao et al. (2016), Holladay (2016), Forslid et al. (2018), Anoulìes (2017), Cui et al. (2017)].

This paper contributes to the existing literature into many directions. First, it is analysed the relationship between environmental tax and technology adoption by assuming that firms operate in a monopolistic competitive market. Many neoclassical researches have assumed that the output market is perfectly competitive [Milliman and Prince (1989), Jung et al. (1996) and Requate and Unold (2003)]; only Petrakis and Xepapadeas (1999) has considered an imperfect competitive market, namely monopoly. Second, it has been introduced a Pigouvian environmental tax into a partial equilibrium model of international trade in order to understand the effect of different abatement technologies on productivity and exporting propensity at firm level. Cao et al. (2016) and Forslid et al. (2018) also account for a tax policy but they have focused on the determination of the optimal abatement investment level, and its effect on productivity and emission levels for the entire economy. We both find that the introduction of a pollution tax increases the environmental propensity of the most productive firms, by adopting abatement technologies. By assuming that tax affects dirty firms only, we identify the exact conditions under which some firms prefer to introduce an abatement technology. Intuitively, this is the case when the costs associated with the adoption of a clean technology compensate the tax burden. The latter one varies across firms depending on their productivity level. Anoulìes (2017) has focused on a cap-and-trade system in a similar international trade framework. Third, 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 requires a different level of variable and fixed costs. Cui et al. (2012) has also exploited Bustos (2011) framework, but their interest is concentrated on emission permits when two types of technology are admitted (dirty and clean). Finally, this paper can contribute to the Porter Hypothesis literature by theoretically analysing the effect of environmental policy on abatement technology adoption and exporting performance, by admitting firms' productivity heterogeneity as a driver of a positive overall effect of such environmental policy. Lanoie et al. (2011) and Rammer (2017) have studied this hypothesis from an empirical perspective capturing competitiveness by trade measures. These micro studies have shown controversial results about the Porter Hypothesis. Results depend on several aspects such as the adopted measures, analysed data and econometric models. The reminder of this paper is organized as follows. Section 2 presents the basic model setup, distinguishing between two groups: non-exporters and exporters. Section 3 states the equilibrium conditions for three different technologies: dirty, clean 1, and clean 2. In Section 4, a pairwise comparison of all possible technologies has been made and, in Section 5, all types of environmental technology are considered. Section 6 concludes.

2. Theoretical Model

In this Section, a partial equilibrium model is presented, which is strictly connected with the international trade model of Melitz (2003). Specifically, it refers to the revised version of Helpman (2006). Consider a small economy where firms are heterogeneous in terms of their productivity level, produce differentiated goods and sell in a monopolistic competition market[2], so 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

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[2] This market structure shows the following characteristics: firms supply differentiated product, so product are not perfectly substitutes and firms need to find new ways to attract consumers, which could generate lower marginal profits but higher sales; there are enough firms in the industry, thus a decision made by a firm does not affect other firms reactions; it is a more efficient market structure than monopoly but less than perfect competition.

productivity, but they discover it after entering the market and paying sunk fixed costs, which represent a partial entry barrier. 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 immediately exit the market or to start producing.

Production creates pollution and we assume that firms emit it as a *by-product*. This means that for each unit of output produced, firms emit exactly one unit of pollution. We also suppose that the government implements an exogenous Pigouvian tax t for each unit of pollution. In this model, technologies are modelled following Bustos (2011), thus dirty-type firms use a baseline or low-level technology, while clean-type firms use upgraded technologies. 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.

Firms decide, first, which type of technology to be adopted; second, whether it will supply its variety to both domestic and foreign markets or to the domestic market only. The analysis of the firm's optimal choice is necessarily backward. We start by considering how much to produce and what are the served markets, domestic and foreign ones. The decision to export is analysed with reference to two groups of firms characterized by different levels of technology: dirty-type firms (d), which do not adopt an abatement technology, and clean-type firms (c), which adopt an emission abatement technology. The adoption of a clean-type technology asks for higher fixed costs and lower variable costs than the adoption of a dirty-type technology. The implementation of a clean-type technology is examined through two alternatives. First, we will suppose that the clean technology requires higher fixed costs than dirty-type technology, all else equal. When firms adopt this kind of clean technology, we will refer to clean-type 1 firms (c_1). As a second step, the assumption of lower variable costs is added to a larger fixed cost than the dirty technology; in this case, firms are labelled clean-type 2 (c_2). Following Helpman, Melitz and Yeaple (2004), clean-type 2 firms also have higher fixed costs than clean-type 1 firms. In both cases, we extremely suppose that clean-type firms do not pay the Pigouvian tax since they are able to totally abate pollution.

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

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

where *A* represents the dimension of the market, which is exogenous for firms 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 $\frac{1}{1-\alpha}$, 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; while c_n concerns 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 are implicitly emissions free.

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

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

where π_j^d are dirty-type firm's profits function, φ_j is the level of productivity, c^d are variable costs of production and f^d are fixed costs of production. This problem can be also drawn for clean-type firms. It is expressed as:

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

where $\pi_j^{c_n}$ are clean-type firm's profits function, c^s are variable costs of production and f^s are fixed costs of production.

As for dirty-type firm's profit function, marginal costs are equal to $(\frac{c^d}{\varphi_j} + t)$. They are affected by three parameters. First, they are positively related to variable production costs c^d, which are exogenous and depend on the share of skilled and unskilled workers; second, they inversely depend by firm's labour productivity, φ_j; third, variable costs are positively connected to the environmental tax *t*. By assuming that clean-type firms adopt an abatement technology to completely avoid the payment of the environmental tax, marginal costs of a clean-type firm are equal to $\frac{c^s}{\varphi_j}$. $c^s = c^d$ and $f^s = f^{c_1}$ if we are referring to clean-type 1 technology; otherwise, if we consider the clean-type 2 technology $c^s = c^c$ and $f^s = f^{c_2}$. As we have disclosed before, we analyse the adoption of a clean-type technology through two steps. First, we assume 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, we are imposing 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 $f^d < f^{c_1} < f^{c_2}$.

Following Helpman (2006) and by imposing the profit maximization condition[3], we can get *ex post* domestic profits for dirty-type and clean-type firms, for all productivity levels:

$$(4) \qquad \pi_j^d = A\left[\frac{1}{\alpha}\left(\frac{c^d}{\varphi_j}+t\right)\right]^{1-\varepsilon}(1-\alpha)-f^d$$

$$(5) \qquad \pi_j^{c_1} = A\left(\frac{c^d}{\alpha\varphi_j}\right)^{1-\varepsilon}(1-\alpha)-f^{c_1}$$

$$(6) \qquad \pi_j^{c_2} = A\left(\frac{c^c}{\alpha\varphi_j}\right)^{1-\varepsilon}(1-\alpha)-f^{c_2}$$

π_j^d refers to dirty-type firms, $\pi_j^{c_1}$ concerns clean-type 1 firms and $\pi_j^{c_2}$ is related to clean-type 2 firms[4].

We can see that profits depend on productivity, market dimension, variable and fixed costs of production and the environmental tax. The latter variable appears only in dirty-type firms' *ex post* profits because clean-type firms abate all pollutants by adopting a clean environmental technology. Given these results, we can show that:

Proposition 1. *Ex post domestic profits positively depend on the market dimension A and productivity* φ_j *and negatively on production costs (*$c^d, c^c, f^d, f^{c_1}, f^{c_2}$*), for any technology level*

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

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[3] See Appendix A.1, B.1 and C.1 for a detailed examination of the profit maximization problem.

[4] All domestic *ex post* profits' functions are continuous

(7) $$\frac{d\pi_j^d}{d\varphi_j} = B\left(\frac{c^d}{\varphi_j} + t\right)^{-\varepsilon}\left(\frac{c^d}{\varphi_j^2}\right) > 0$$

(8) $$\frac{d\pi_j^{c_1}}{d\varphi_j} = B\left(\frac{c^d}{\varphi_j}\right)^{-\varepsilon}\left(\frac{c^d}{\varphi_j^2}\right) > 0$$

(9) $$\frac{d\pi_j^{c_2}}{d\varphi_j} = B\left(\frac{c^c}{\varphi_j}\right)^{-\varepsilon}\left(\frac{c^c}{\varphi_j^2}\right) > 0$$

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

If we solely consider dirty-type firms, we can also show that:

Proposition 2. *The environmental tax t has a negative effect on dirty-type firms' ex post domestic profits*

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

Since the foreign market is symmetric to the domestic market, the dimension of the demand A and the applied Pigouvian tax *t* to dirty-type firms are the same. 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 market[5] 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.

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[5] 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 $A(p_j^*)^{-\varepsilon}$. p_j^* is the price of a good delivered to the foreign market

Concerning dirty-type firms, the maximization problem can be represented as follows:

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

while for clean-type firms it corresponds to:

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

By comparing domestic and foreign markets, we can state an important result:

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

Proof. By solving (2), (3), (10) and (11), we obtain domestic and foreign optimal prices for each technology[6]. It is easy to see that foreign prices are higher than domestic ones because trade costs increase variable costs of production.

By substituting the optimal price into profit functions, we can obtain *ex post* foreign profits[7] as follows[8]:

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[6] See Appendix sections A1-C2

[7] All foreign *ex post* profits' functions are continuous.

[8] See Appendix A.2, B.2 and C.2 for a deeper examination.

$$(12) \quad \pi_j^{d^*} = A\left[\frac{1}{\alpha}\left(\frac{c^d\tau_j}{\varphi_j} + t\right)\right]^{1-\varepsilon}(1-\alpha) - f^{d^*}$$

$$(13) \quad \pi_j^{c_1^*} = A\left(\frac{c^d\tau_j}{\alpha\varphi_j}\right)^{1-\varepsilon}(1-\alpha) - f^{c_1^*}$$

$$(14) \quad \pi_j^{c_2^*} = A\left(\frac{c^c\tau_j}{\alpha\varphi_j}\right)^{1-\varepsilon}(1-\alpha) - f^{c_2^*}$$

By analysing these equations, Proposition 1 and 2 are confirmed also for *ex post* foreign profits. They positively depend on productivity and market dimension and negatively on production' variable costs and environmental tax. Finally, *ex post* foreign profits also depend on trade costs; their effects on profits can be summarized as follows:

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

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

3. Cut-Off Productivity and Pigouvian Environmental Tax: Domestic and Foreign Markets

By imposing a zero-profit condition to both *ex post* domestic and foreign profits, we find domestic and foreign marginal or cut-off productivity, respectively. These values are useful because they identify which firms leave the market and which ones serve the 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 less than 0; otherwise, if a firm has a productivity higher than the domestic cut-off level, 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 foreign cut-off level, a firm will serve the domestic market only, while, if the productivity is higher than the foreign cut-off the firm will supply goods both to domestic and foreign markets.

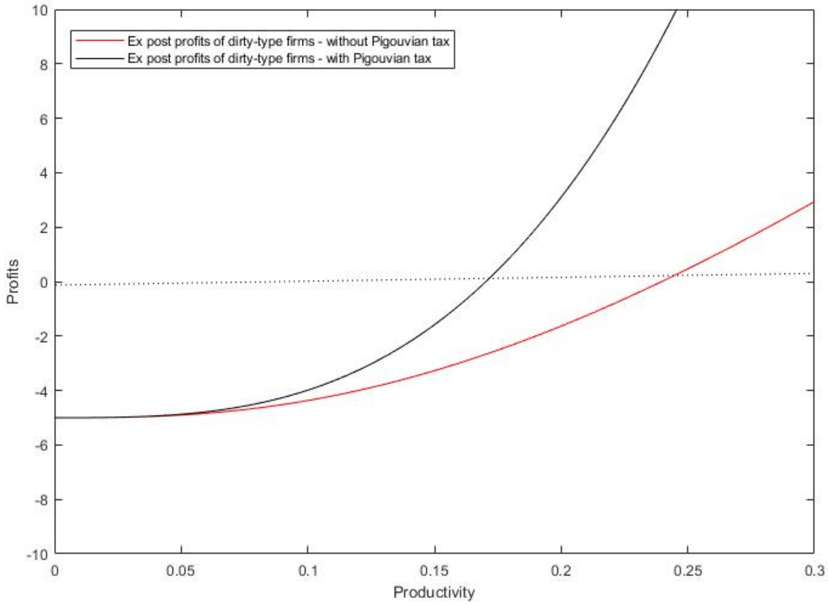
In this work, the analysis of marginal productivity is developed through three steps.

As a first step, we analyse cut-off productivity for the domestic market when a Pigouvian environmental tax is introduced and firms implement dirty-type technology. By considering these assumptions, it is possible to show that

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

Proof. If dirty-type firms have to pay a tax, zero-profit condition is satisfied when $\varphi_j = DD_t = c^d \left\{ \alpha \left[\frac{f^d}{A(1-\alpha)} \right]^{\frac{1}{1-\varepsilon}} - t \right\}^{-1}$ while, if the tax rate t is zero, $\varphi_j = DD_0 = \frac{c^d}{\alpha} \left[\frac{f^d}{A(1-\alpha)} \right]^{\frac{1}{\varepsilon-1}}$. As Graph 1 shows, the introduction of an environmental tax will increase the marginal productivity of dirty-type firms, thus all firms with a productivity between DD_0 and DD_t will exit the domestic market.

Graph 1. Effect of a Pigouvian tax on dirty-type firms' ex-post domestic profits



Specification: Graph 1 is drawn by using the numerical simulation of Section 5. The Pigouvian tax t is fixed at 0.85.

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.

As a second step, we have analysed the marginal domestic productivity of the three technologies. By calculating zero-profit conditions for each kind of firm, the following cut-off productivities are obtained:

$$(15) \qquad DD_t = c^d \left\{ \alpha \left[\frac{f^d}{A(1-\alpha)} \right]^{\frac{1}{1-\varepsilon}} - t \right\}^{-1}$$

$$(16) \qquad CD_1 = \frac{c^d}{\alpha} \left[\frac{f^{c_1}}{A(1-\alpha)} \right]^{\frac{1}{\varepsilon-1}}$$

$$(17) \qquad CD_2 = \frac{c^c}{\alpha} \left[\frac{f^{c_2}}{A(1-\alpha)} \right]^{\frac{1}{\varepsilon-1}}$$

where DD_t refers to dirty-type technology, CD_1 to clean-type 1 firms and CD_2 to clean-type 2 firms. When firms have a productivity lower than the marginal domestic productivity, they exit from the domestic market; while, if their productivity is higher than the cut-off level, they decide to produce and serve the market.

As a third step, a similar analysis is repeated for foreign cut-off productivities, which are identified by:

$$DF = c^d \tau_j \left\{ \alpha \left[\frac{f^{d^*}}{A(1-\alpha)} \right]^{\frac{1}{1-\varepsilon}} - t \right\}^{-1} \tag{18}$$

$$CF_1 = \frac{c^d \tau_j}{\alpha} \left[\frac{f^{c_1^*}}{A(1-\alpha)} \right]^{\frac{1}{\varepsilon-1}} \tag{19}$$

$$CF_2 = \frac{c^c \tau_j}{\alpha} \left[\frac{f^{c_2^*}}{A(1-\alpha)} \right]^{\frac{1}{\varepsilon-1}} \tag{20}$$

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 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 marginal productivity, they decide to export.

Through an analysis of dirty-type firms' foreign cut-off productivity, it is possible to conclude that, in line with Proposition 5, the introduction of a Pigouvian tax forces the least productive firms to exit foreign markets.

For each kind of technology, if we analyse domestic and foreign marginal productivities together, we can conclude that

Preposition 6. *The following firms' sorting drawn by Melitz (2003) is confirmed:*

a. least productive firms exit the market because their profits are negative

b. firms that have a productivity within domestic and foreign cut-off level supply only the domestic market[9]

c. *most productive firms supply both domestic and foreign markets*[10].

Proof. By comparing domestic and foreign cut-off productivities for each technology, it is easy to demonstrate the above Proposition.

4. Pairwise technology comparison: theoretical results

Until now, it has been analysed each type of technology, in domestic and foreign markets, separately. In this Section, a combined theoretical analysis of the different kinds of technology is conducted. Specifically, in Section 4.1, it is supposed that firms can decide between dirty-type technology and one of the clean-type technologies; in Section 4.2, a situation where only clean-type technologies can be chosen has been studied and, finally, in Section 4.2, all technologies coexist, so firms can choose among dirty-type, clean-type 1 and clean-type 2 technology.

4.1 Dirty–type technology and Clean-type 1 technology

Firstly, dirty-type and clean-type 1 cut-off (or equivalently marginal) productivity levels are compared. In this situation, results are affected by the value of the environmental tax, which influences cut-off productivities of

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[9] The range depends on adopted technology. For dirty-type technology, it is represented by $DD_t - DF$; for clean-type 1 technology it is characterized by $CD_1 - CF_1$ and, for clean-type 2 technology, by $CD_2 - CF_2$

[10] Dirty-type firms decide to export if $\tau > \left\{\frac{\alpha\left[\frac{A(1-\alpha)}{f^{d*}}\right]^{\frac{1}{\varepsilon-1}} - t}{\alpha\left[\frac{A(1-\alpha)}{f^{d}}\right]^{\frac{1}{\varepsilon-1}} - t}\right\}$, clean-type 1 firms if $\tau > \left(\frac{f^{c_1}}{f^{c_1^*}}\right)^{\frac{1}{\varepsilon-1}}$ and clean type 2 firms if $\tau > \left(\frac{f^{c_2}}{f^{c_2^*}}\right)^{\frac{1}{\varepsilon-1}}$.

dirty-type firms. By focusing on the domestic market, it can be shown that the marginal domestic productivity of dirty-type firms is lower than the marginal domestic productivity of clean-type 1 firms, $DD_t < CD_1$, when the environmental tax $t < T_1$, where $T_1 = G\left[(f^d)^{\frac{1}{1-\varepsilon}} - (f^{c_1})^{\frac{1}{1-\varepsilon}}\right]$[11]. In words, on the domestic market, firms have the incentive to implement a clean-type 1 technology, instead of a dirty-type technology, only if the environmental tax is sufficiently high. Similarly, we can examine foreign cut-off productivities. We find that $DF < CF_1$, when $t < T_1^*$, where $T_1^* = G\left[\left(f^{d^*}\right)^{\frac{1}{1-\varepsilon}} - \left(f^{c_1^*}\right)^{\frac{1}{1-\varepsilon}}\right]$. This means that, if we only consider the foreign market, a low value of Pigouvian tax brings exporting firms to adopt clean-type 1 technology. T_1 can be higher or lower than T_1^* but we assume that the former is higher than the latter, $T_1 > T_1^*$.

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:*

1) *Firm's foreign sorting for a low eco-tax, if the following conditions are satisfied:*

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

2) *Firm's domestic sorting for a high eco-tax, that is guaranteed if*

    a) $T_1^* < t < T_1$;

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[11] $G = \alpha\left[\frac{1}{A(1-\alpha)}\right]^{\frac{1}{1-\varepsilon}}$.

b) $\tilde{\varphi}_{DD-CD_1} < DF$.

Proof. Proposition 7 can be proven by making a comparison between marginal productivities of dirty-type and clean-type 1 firms and the position of the adoption cut-off productivity, $\tilde{\varphi}_{DD-CD_1}$, with respect to the foreign cut off productivity of dirty type firms, DF[12]. Given that $T_1 > T_1^*$ by assumption, three situations can emerge depending on the value of the environmental tax t[13]. First, t can be lower than T_1^*. This condition can guarantee a foreign sorting (hereafter SORTING 1) when the adoption cut-off productivity $\tilde{\varphi}_{DD-CD_1}$ is lower than DF and dirty-type *ex post* profit function is steeper than 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 clean-type 1 firms' domestic *ex post* profits function, $\pi_j^{c_1}$. This condition is verified when $\left[\left(c^d + t\varphi_j\right)^{-\varepsilon} + \tau\left(c^d\tau + t\varphi_j\right)^{-\varepsilon}\right] > (c^d)^{-\varepsilon}$[14].

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 a productivity level between DD_t and DF;
c. dirty-type firms that serve both domestic and foreign markets, for a productivity level between CD_1 and $\tilde{\varphi}_{DF-CF_1}$[15];

---

[12] $\tilde{\varphi}_{DD-CD_1}$ represents the productivity such that dirty-type firms' domestic profits (π_j^D) are equal to clean-type 1 firms' domestic profits ($\pi_j^{c_1}$).

[13] Since $t > 0$, we can demonstrate that the domestic cut-off productivity of clean-type 1 firms is always lower than foreign cut-off productivity of dirty-type firms. See Appendix D for the examination.

[14] See Appendix E for the examination.

[15] $\tilde{\varphi}_{DF-CF_1}$ represents the adoption cut-off productivity such that the sum of domestic and foreign profits of dirty-type firms ($\pi^{d\,SUM}$) are equal to the sum of profits 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 $\tilde{\varphi}_{DF-CF_1}$.

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.

Second, if $T_1^* < t < T_1$, we can have a domestic sorting (hereafter SORTING 2) where domestic firms can decide to adopt either a dirty-type or a clean-type technology and all exporting firms, so the most productive, adopt the clean-type technology. In this case, the adoption cut-off productivity $\tilde{\varphi}_{DD-CD_1}$ is higher than the foreign marginal productivity of dirty-type firms, DF. Under SORTING 2, firms are classified as follows:

a. exiter firms, for a productivity level lower than DD_t;
b. dirty-type firms that serve the domestic market, for a productivity level between DD_t and $\tilde{\varphi}_{DD-CD_1}$;
c. clean-type 1 firms that serve the domestic market, for a productivity level 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.

Provided that 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, we can say that the higher the environmental tax the higher the probability of having SORTING 2 and exporters adopt the upgraded abatement technology only.

Third, if $t > T_1$, 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 more than compensated by the environmental tax savings due to abated pollutants. In this situation, all firms will adopt clean-type 1 technology.

Similar results can be easily shown by comparing dirty-type and clean-type 2 profits.

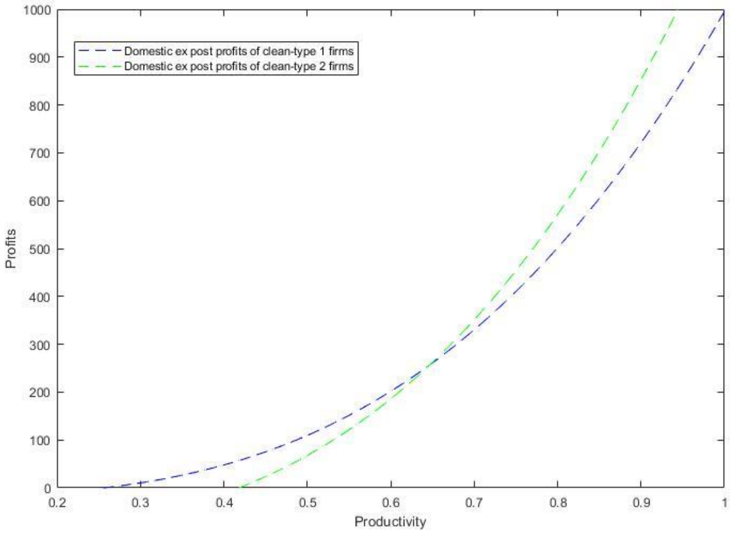
4.2 Clean-type 1 technology and Clean-type 2 technology

In this Section, we compare the two clean-type technology by accounting for firm productivity and exporting decision. A detailed comparison between cut-off productivities of clean-type 1 and clean-type 2 firms is then required. If we consider an economy with clean-type firms only, which abate all emitted pollution and pay no environmental taxes, results are only affected by the level of variable and fixed costs of production. Concerning the domestic market and given these assumptions, we can show 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* $\frac{f^{c_2}}{f^{c_1}} > \left(\frac{c^d}{c^c}\right)^{\varepsilon-1}$

Proof. Zero-profit condition for clean-type 1 firms in domestic market is verified when productivity $\varphi_i = CD_1$; 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 marginal productivities, $CD_1 < CD_2$ when $\frac{f^{c_2}}{f^{c_1}} > \left(\frac{c^d}{c^c}\right)^{\varepsilon-1}$. This conclusion is graphically reported in Graph 2.

Graph 2. Domestic ex post profits of clean-type 1 and clean-type 2 firms: a comparison



Specification. Graph 2 is drawn by using the numerical simulation of Section 5

Furthermore, similar conclusions about marginal productivities can be done referring to the foreign market. Specifically, if $\frac{f^{c_2^*}}{f^{c_1^*}} > \left(\frac{c^d}{c^c}\right)^{\varepsilon-1}$, 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 marginal productivity.

Given that more complex abatement innovation (clean-type 2 technology) requires lower marginal costs and higher fixed costs than simple abatement innovation (clean-type 1 technology), previous results underline that the first could bring to a higher selection of firms only if the fixed costs required by its implementation are much higher than the ones needed for the simple abatement technology.

By examining both domestic and foreign markets cut-off productivities and by assuming $\frac{f^{c_2}}{f^{c_1}} > \frac{f^{c_2^*}}{f^{c_1^*}}$, we can show the next proposition.

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

1) *<u>Firm's foreign sorting</u>, which is guaranteed when:*

   a) $0 < \left(\frac{c^d}{c^c}\right)^{\varepsilon-1} < \frac{f^{c_2^*}}{f^{c_1^*}}$;

   b) $\tau < \frac{\left\{\frac{f^{c_1} - f^{c_2}}{f^{c_1^*}\left[\left(c^d\right)^{1-\varepsilon} - \left(c^c\right)^{1-\varepsilon}\right]}\right\}^{\frac{1}{\varepsilon-1}}}{c^d}$*, which implies* $\tilde{\varphi}_{CD_1-CD_2} > CF_1$;

   c) $\tau < \left[\left(\frac{c^d}{c^c}\right)^{\varepsilon-1} - 1\right]^{\frac{1}{1-\varepsilon}}$.

2) *<u>Firm's domestic sorting</u>, that results if:*

   a) $\frac{f^{c_2^*}}{f^{c_1^*}} < \left(\frac{c^d}{c^c}\right)^{\varepsilon-1} < \frac{f^{c_2}}{f^{c_1}}$;

   b) $\tilde{\varphi}_{CD_1-CD_2} < CF_1$[16].

Proof. As we have seen in Section 4.1, it is fundamental to compare marginal productivities of clean-type 1 and clean-type2 technologies and the adoption cut-off productivity, $\tilde{\varphi}_{CD_1-CD_2}$[17]. Their values depend on marginal and fixed costs of production. Given that $\frac{f^{c_2^*}}{f^{c_1^*}}$ is lower than $\frac{f^{c_2}}{f^{c_1}}$, three situations can be obtained depending on the value of relative marginal costs, $\left(\frac{c^d}{c^c}\right)^{\varepsilon-1}$. First, if

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[16] $\tau > \frac{\left\{\frac{f^{c_1} - f^{c_2}}{f^{c_1^*}\left[\left(c^d\right)^{1-\varepsilon} - \left(c^c\right)^{1-\varepsilon}\right]}\right\}^{\frac{1}{\varepsilon-1}}}{c^d}$

[17] Specifically, $\tilde{\varphi}_{CD_1-CD_2}$ is the productivity level such that clean-type 1 firms' *ex post* domestic profits ($\pi_j^{c_1}$) are equal to clean-type 2 firms' *ex post* domestic profits ($\pi_j^{c_2}$). See Appendix F for the calculation of $\tilde{\varphi}_{CD_1-CD_2}$.

$0 < \left(\frac{c^d}{c^c}\right)^{\varepsilon-1} < \frac{f^{c_2^*}}{f^{c_1^*}}$, a foreign sorting (hereafter SORTING 3) is guaranteed. In order to obtain SORTING 3, it also necessary that the adoption cut-off productivity, $\tilde{\varphi}_{CD_1-CD_2}$, is higher than marginal foreign productivity of clean-type 1 firms, CF_1. The latter condition is satisfied when $\tau < \frac{\left\{\frac{f^{c_1}-f^{c_2}}{f^{c_1^*}\left[\left(c^d\right)^{1-\varepsilon}-\left(c^c\right)^{1-\varepsilon}\right]}\right\}^{\frac{1}{\varepsilon-1}}}{c^d}$. Furthermore, the grade of the function $\pi^{SUM\ c_1}$, which defines the sum between *ex post* domestic and foreign profits of clean-type 1 firms, $\pi^{c_1} + \pi^{c_1^*}$, must be greater than the grade of the *ex post* domestic profits of clean-type 2 firms, π^{c_2}. The latter condition is verified when $\tau < \left[\left(\frac{c^d}{c^c}\right)^{\varepsilon-1} - 1\right]^{\frac{1}{1-\varepsilon}}$[18]. SORTING 3 shows that clean-type 2 technology is adopted by exporting firms only and brings to the following classification of firms:

a. exiter firms, whose profits are negative, for productivity levels lower than CD_1;
b. clean-type 1 firms that supply goods to the domestic market, for a productivity level between CD_1 and CF_1;
c. clean-type 1 firms that serve both domestic and foreign markets, for a productivity level between $CF_1$and $\tilde{\varphi}_{CF_1-CF_2}$[19];
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 $\frac{f^{c_2^*}}{f^{c_1^*}} < \left(\frac{c^d}{c^c}\right)^{\varepsilon-1} < \frac{f^{c_2}}{f^{c_1}}$ a domestic sorting (hereafter SORTING 4) can be obtained. Under SORTING 4, domestic firms can implement a clean-

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[18] See Appendix G for details on this condition.

[19] $\tilde{\varphi}_{CF_1-CF_2}$ identifies the adoption cut-off productivity such that the sum of profits of clean-type 1 firms ($\pi^{SUM\ c_1}$) are equal to the sum of profits of clean-type 2 firms ($\pi^{SUM\ c_2} = \pi_j^{c_2} + \pi_j^{c_2^*}$).
See Appendix H for the examination of $\tilde{\varphi}_{CF_1-CF_2}$.

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. exiter firms, whose profits are negative, for productivity levels lower than CD_1;
b. clean-type 1 firms that supply goods to the domestic market, for a productivity level between CD_1 and $\tilde{\varphi}_{CD_1-CD_2}$;
c. clean-type 2 firms that serve the domestic market, for a productivity level 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.

It is possible to assert that, if the fixed costs borne by clean-type 2 firms are not so high as fixed costs payed by clean-type 1 firms, SORTING 4 prevails on SORTING 3.

Third, if $\left(\frac{c^d}{c^c}\right)^{\varepsilon-1} > \frac{f^{c_2}}{f^{c_1}}$, clean-type 2 technology prevails on clean-type 1 technology, thus there are only clean-type 2 firms in the economy.

5. A comparison between all types of technology: the role of the Pigouvian tax, costs of production and the adoption cut-off productivity

In previous sections, the model accounts for a single technology or for pairwise combinations of technologies; in this Section, the aim is to understand what happens when firms can choose among all types of technology; so dirty-type, clean-type 1 and clean-type 2 abatement innovations are implemented into the theoretical model.

The pairwise technology comparisons have underlined that multiple scenarios can be obtained depending on different aspects, such as the Pigouvian tax, the relationship among marginal and fixed costs of production, the slope of profit functions and the technology adoption cut-off. In view of this, it has been chosen to study SORTING 2 by adding SORTING 3. This combination allows for both domestic and foreign firms' sorting.

Now, the assumptions of the model are explained through a deeper analysis of the above-mentioned aspects[20]. First, the value of the Pigouvian tax t must lie between T_1^* and T_1, in order to get SORTING 2. Second, the following relationship among marginal and fixed costs of production of clean-type 1 and clean-type 2 firms must be verified to ensure SORTING 3: $0 < \left(\frac{c^d}{c^c}\right)^{\varepsilon-1} < \frac{f^{c_2^*}}{f^{c_1^*}}$. Third, as it is reported in Section 4.2, the slope of clean-type firm profits' functions must be considered. Specifically, we assume that trade costs τ are lower than $\left[\left(\frac{c^d}{c^c}\right)^{\varepsilon-1} - 1\right]^{\frac{1}{1-\varepsilon}}$. Finally, we consider the already know assumptions on adoption cut-off productivities:

a) $\tilde{\varphi}_{DD-CD_1}$ must be lower than the cut-off productivity DF in order to get SORTING 2;
b) SORTING 3 is guaranteed if the adoption cut-off productivity $\tilde{\varphi}_{CD_1-CD_2} > CF_1$;

combined with the following further condition:

c) the adoption cut-off productivity $\tilde{\varphi}_{CF_1-CF_2}$ have to be higher than both $\tilde{\varphi}_{DD-CD_1}$and $\tilde{\varphi}_{CD_1-CD_2}$;

As already stated in Section 4, we can analytically calculate the adoption cut-off productivities between clean-type 1 and clean-type 2 technologies ($\tilde{\varphi}_{CD_1-CD_2}$ and $\tilde{\varphi}_{CF_1-CF_2}$), but we cannot do the same with adoption cut-off productivity between dirty-type and clean-type 1 technology ($\tilde{\varphi}_{DD-CD_1}$), so it is required to approximate it through a numerical simulation.

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[20] See Appendix I for a detailed table of assumptions

5.1 Numerical simulation of the adoption cut-off productivity $\tilde{\varphi}_{DD-CD_1}$

The productivity level $\tilde{\varphi}$ represents the productivity level at the intersection between the total *ex post* profit of dirty-type and clean-type 1 firms.
Total *ex post* profits[21] of a firm are equal to:

$$(21) \quad \pi^{TOT^m} = max\{0, \pi^m\} + max\{0, (\pi^{m^*})\} \qquad m = d, c_1$$

This equation can be also expressed for dirty-type firms as

$$(22) \quad \pi^{TOT^d} \begin{cases} 0 \; if \; \varphi \leq DD_t \\ \pi^d \; if \; DD_t < \varphi \leq DF_t \\ \pi^{d\,SUM} \;\; if \; \varphi > DF_t \end{cases}$$

and, for clean-type 1 firms, as

$$(23) \quad \pi^{TOT^{c_1}} \begin{cases} 0 \; if \; \varphi \leq CD_1 \\ \pi_j^{c_1} \; if \; CD_1 < \varphi \leq CF_1 \\ \pi^{c_1\,SUM} \;\; if \; \varphi > CF_1 \end{cases}$$

π^d, $\pi_j^{c_1}$, $\pi_j^{d^*}$ and $\pi_j^{{c_1}^*}$ are all continuous functions so, it is easy to verify that both π^{TOT^d} and $\pi^{TOT^{c_1}}$ are continous too. In order to find the exact value of $\tilde{\varphi}$, 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 $\tilde{\varphi}$. This means that, the following *well-posedness* problem have to be discussed.
Given the function

$$(24) \quad F(\varphi) = \pi^{TOT^{c_1}} - \pi^{TOT^d}$$

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[21] For sake of simplicity, *j*'s subscript is dropped.

we can affirm that

Proposition 10. *There exists a unique root* $\tilde{\varphi} \in (0, \infty)$ *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 $\pi^{TOT^{d}}$ and $\pi^{TOT^{c_1}}$ are continuous. Moreover, $F(\varphi) < 0$ for $\varphi \in (DD_t, CD_1)$[22]. Finally, is not difficult to verify that $F(\varphi)$ is strictly increasing and the following limit holds:

$$(25) \qquad \lim_{\varphi=+\infty} F(\varphi) = \lim_{\varphi=+\infty} [(\pi^{c_1\,SUM}) - (\pi^{d\,SUM})] = +\infty$$

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

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

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

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[22] This is verified because we have assumed that $t < T_1$, so $DD_t < CD_1$.

through different steps. Starting from an interval $I_0 = [a, b] \in \mathbb{R}$, this method creates a sequence of subinterval $I_k = \left[a^{(k)}, b^{(k)}\right]$, where $k \geq 0$, with $I_k \subset I_{k-1}$, $k \geq 1$, and applies the property that $f\left(a^{(k)}\right) f\left(b^{(k)}\right) < 0$. 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 $\varphi^0 = \frac{(a^0 + b^0)}{2}$ is defined. It represents the mean of I_0; then, for $k \geq 0$ set a new interval equal to:

$$(26) \quad \begin{cases} a^{(k+1)} = a^{(k)}, b^{(k+1)} = \varphi^{(k)} & if\ f\left(\varphi^{(k)}\right) f\left(a^{(k)}\right) < 0 \\ a^{(k+1)} = \varphi^{(k)}, b^{(k+1)} = b^{(k)} & if\ f\left(\varphi^{(k)}\right) f\left(b^{(k)}\right) < 0 \end{cases}$$

Finally, set $\varphi^{(k+1)} = \frac{\left(a^{(k+1)} + b^{(k+1)}\right)}{2}$. The iteration terminates at the *n*-th step for which $\left|\varphi^n - \tilde{\varphi}_{DD-CD_1}\right| \leq |I_n| \leq \xi$, 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 model's parameters, which are listed in Column 1 of Table 1. Values are chosen with respect to the theoretical conditions explained at the beginning of this Section but further specifications about some parameters are necessary. Trade costs τ, equal to 1.41, are obtained by adapting the formula proposed by Bernard et al. (2007) $\frac{\tau^{1-\varepsilon}}{1+\tau^{1-\varepsilon}}$, which identifies the average fraction of exports in firm sales, to our data. Specifically, we use the mean of the share of total turnover from sales to clients outside the country (0.2758)[23]. The elasticity of substitution ε, has been set equal to 4 by following Bernard et al. (2003). Consequently, the parameter α is equal to 0.75.

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[23] This parameter refers to German firms data of Community Innovation Survey 2014 - eurostat

Table 1. Fixed and simulated parameters of numerical simulation

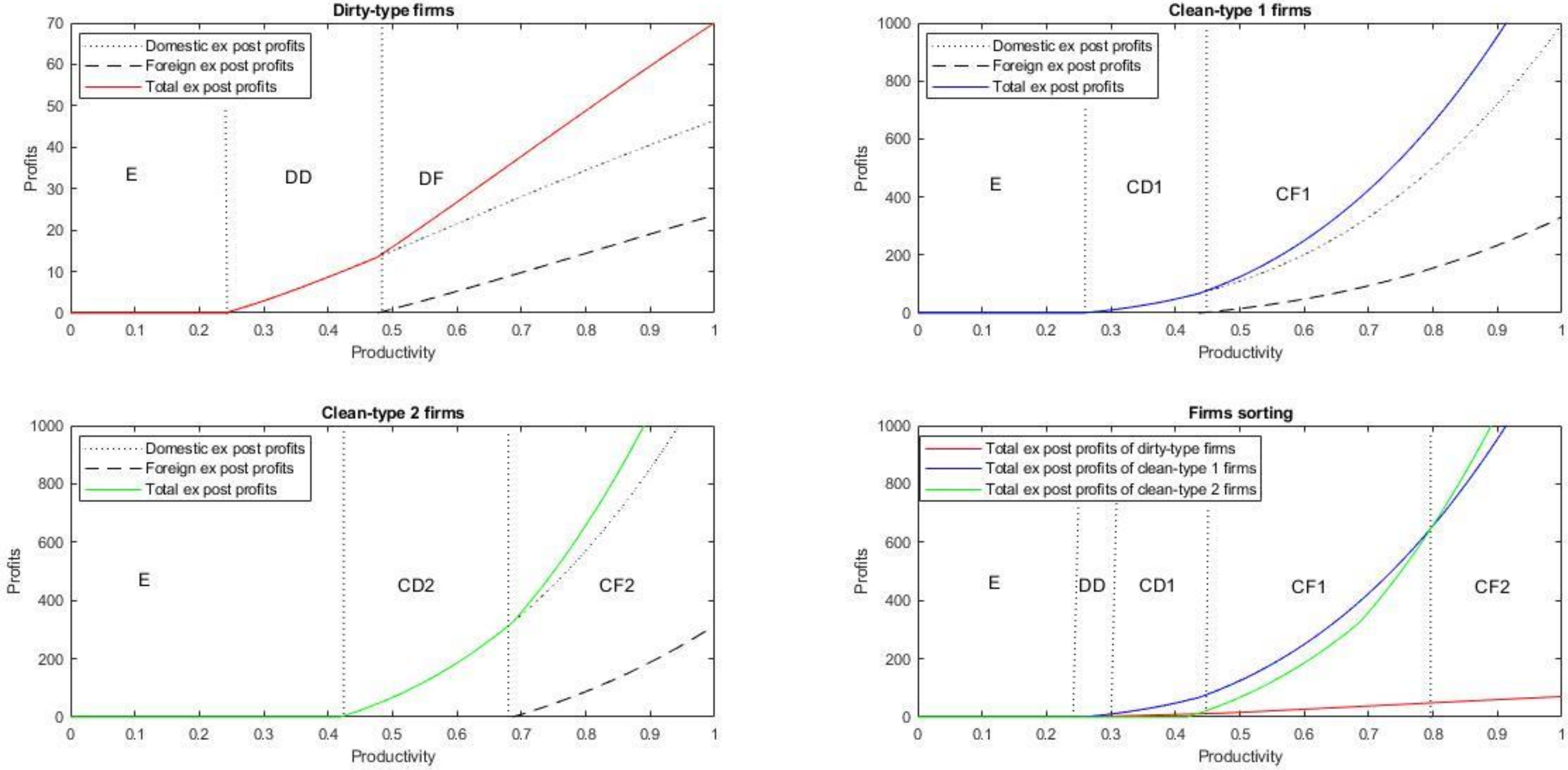
Fixed Parameters	Value	Simulated Parameters	Value
Marginal costs c^d	0.50	T_1	0.9835
Marginal cost c^c	0.46	T_1^*	0.7146
Domestic fixed cost for dirty-type firms f^d	5	DD_t	0.2397
Domestic fixed cost for clean-type firms 1 f^{c_1}	17	DF	0.4762
Domestic fixed cost for clean-type 2 firms f^{c_2}	95	CD_1	0.2561
Foreign fixed cost for dirty-type firms f^{d^*}	10	CF_1	0.4363
Foreign fixed cost for clean-type 1 firms $f^{c_1^*}$	30	CD_2	0.4180
Foreign fixed cost for clean-type 2 firms $f^{c_2^*}$	150	CF_2	0.6864
Trade costs τ	1.41	$\tilde{\varphi}_{DD-CD_1}$	**0.2611**
Market dimension A	1200	$\tilde{\varphi}_{CF_1-CF_2}$	0.7975
Elasticity of substitution ε	4	$\tilde{\varphi}_{CD_1-CD_2}$	0.6472
α	0.75		
Pigouvian environmental tax t	0.85		

The parameters obtained through the numerical simulation are reported in Column 2 of Table 1. By analysing these values, we can see that all the necessary conditions are verified, so the merging of SORTING 2 and SORTING 3 gives both domestic and foreign sorting. Specifically, firms are classified as follows:

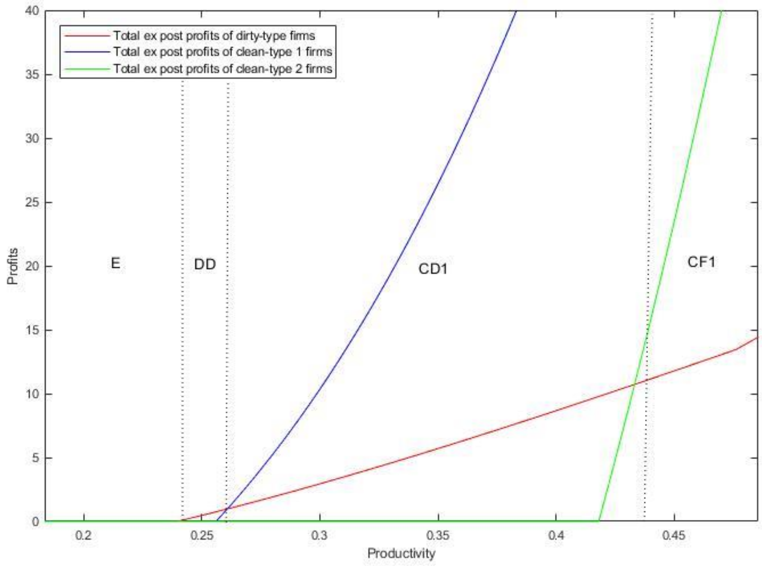
a. firms that exit the market, which have a productivity lower than DD_t;
b. firms that serve domestic market only and adopt dirty-type technology. These firms have a productivity that lies among DD_t and $\tilde{\varphi}_{DD-CD_1}$;
c. firms that supply domestic market only and adopt a clean-type 1 technology. The level of their productivity lies inside the range $\tilde{\varphi}_{DD-CD_1}$ and CF_1;
d. clean-type 1 firms that serve both domestic and foreign markets. They have a productivity between CF_1 and $\tilde{\varphi}_{CF_1-CF_2}$;
e. clean-type 2 firms that supply domestic and foreign market. The productivity of these firms is higher than $\tilde{\varphi}_{CF_1-CF_2}$.

Different conclusions can be summarized as follows. First, for a relatively low value of the environmental tax, domestic firms can adopt a dirty-type technology or a clean-type 1 technology, which is more complex than the former. Second, exporting firms never adopt a dirty-type technology but only clean-type technologies. This assertion underlines that abating firms can compensate the higher fixed costs of a complex technology. Third, the most productive firms export and implement the most complex abatement technology, the clean-type 2 technology.

Graph 3. Firms' sorting obtained by numerical simulation – SORTING 2 and SORTING 3



Graph 4. Focus on domestic sorting – SORTING 2 and SORTING 3



6. Conclusions

Given the increasing interest of researchers on the effect of environmental regulation on environmental innovation and trade performance, this work theoretically investigates the role of firm’s productivity heterogeneity in the adoption of an abatement technology and the 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 firms’ cut-off productivity for dirty-type firms, so the lowest productive pollutant firms leave the market due to the introduction of the Pigouvian tax. This result implies that, if all firms adopt a dirty-type technology, the government can use the tax as an instrument for reducing emissions. 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, in the presence of an alternative clean technology (clean-type 1 or 2), a sufficiently large environmental tax brings firms to adopt the abatement technology because the higher fixed costs, associated with a clean-type technology, can be compensated by environmental tax savings. Third, by considering a scenario where firms can adopt clean-type 1 and clean-type 2 technology, due to a higher complexity of clean-type 2 technology, which requires higher fixed costs, it is implemented also by less productive firms if and only if 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. Ex post productivity is affected by Pigouvian tax and (variable and fixed) trade and technological costs. These variables affect the slope of domestic and foreign profit functions, and correspondingly domestic, foreign and technology cut-offs. The conditions under which the lowest productive firms adopt a dirty-type technology and exclusively sell to domestic consumers have been identified. By focusing on the combination between SORTING 2 and SORTING 3, a low value of the tax brings domestic firms to adopt a dirty-type technology and exporting firms implement clean-type innovations only. The most productive firms export and use the clean-type 2 technology, which is the most complex one.

By admitting that the complex technology involves a higher marginal cost but a lower fixed cost than the clean-type 1 technology may imply a reversed result under certain conditions, where a group of firms with a medium productivity will adopt the clean-type 2 technology, and the most productive ones using the clean-type 1 technology.

From a policy point of view, governments could introduce new environmental policies that force firms to adopt cleaner innovation because it represents a source of competitiveness. Firms tend to be more productive when using more advanced clean technologies and consequently may start exporting their products into foreign market. These regulations could be supported by subsidies or financial incentives to foster innovations.

Further investigations could be conducted by considering other types of environmental regulations because they differently affect the structure of the model. Moreover, some counterfactual analysis could be useful in order to understand how the scenario changes if some variables change too; for example, by supposing that clean-type 2 technology requires higher fixed and variable costs than clean-type 1 and dirty-type technologies.

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Appendix A – Profits Maximization of Dirty-Type Firms

A.1 Domestic

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

$$\pi_j^d = Ap_j^{1-\varepsilon} - \left(\frac{c^d}{\varphi_j} + t\right) Ap_j^{-\varepsilon} - f^d$$

Consequently, by differentiating profits function with respect to the price, we are able to apply the first order condition of maximization (first derivative must be equal to 0) in order to obtain the maximizing price p_j^d

$$\frac{d\pi_j^d}{dp_j} = A(1-\varepsilon)p_j^{-\varepsilon} + A\varepsilon p_j^{-\varepsilon-1}\left(\frac{c^d}{\varphi_j} + t\right) = 0$$

$$Ap_j^{-\varepsilon}\left[(1-\varepsilon) + \varepsilon\left(\frac{c^d}{\varphi_j} + t\right)p_j^{-1}\right] = 0$$

$$\varepsilon - 1 = \varepsilon\left(\frac{c^d}{\varphi_j} + t\right)p_j^{-1}$$

$$p_j = \frac{1}{\alpha}\left(\frac{c^d}{\varphi_j} + t\right) = p_j^d$$

where $\frac{1}{\alpha} = \frac{\varepsilon}{\varepsilon - 1}$.

By substituting this optimal price into the profit function, we will achieve the *ex post* domestic profits of dirty-type firms π_j^d, given the domestic demand:

$$\pi_j^d = A\left[\frac{1}{\alpha}\left(\frac{c^d}{\varphi_j} + t\right)\right]^{1-\varepsilon} - A\left(\frac{c^d}{\varphi_j} + t\right)\left[\frac{1}{\alpha}\left(\frac{c^d}{\varphi_j} + t\right)\right]^{-\varepsilon} - f^d$$

$$= A\left(\frac{c^d}{\varphi_j} + t\right)^{1-\varepsilon} \frac{1}{\alpha}^{-\varepsilon} \left(\frac{1}{\alpha} - 1\right) - f^d$$

$$= A\left(\frac{c^d}{\varphi_j} + t\right)^{1-\varepsilon} \frac{1}{\alpha}^{1-\varepsilon} (1-\alpha) - f^d$$

$$= A\ \left[\frac{1}{\alpha}\left(\frac{c^d}{\varphi_j}+t\right)\right]^{1-\varepsilon}(1-\alpha)-f^d$$

A.2 Foreign

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

$$\pi_j^{d^*} = Ap_j^{*^{1-\varepsilon}} - \left(\frac{c^d\tau_j}{\varphi_j}+t\right)Ap_j^{*^{-\varepsilon}} - f^{d^*}$$

By differentiating these profits with respect to the price and by imposing the first order condition we obtain the maximizing price of dirty-type firms in foreign market:

$$\frac{d\pi_j^{d^*}}{dp_j^*} = A(1-\varepsilon)p_j^{*^{-\varepsilon}} + A\varepsilon p_j^{*^{-\varepsilon-1}}\left(\frac{c^d\tau_j}{\varphi_j}+t\right) = 0$$

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

$$p_j^{d^*} = \frac{1}{\alpha}\left(\frac{c^d\tau_j}{\varphi_j}+t\right)$$

Finally, this value of the price is substituted into the profits function in order to obtain the *ex post* foreign profits of dirty-type firms:

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

Appendix B – Profits Maximization of Clean-Type 1 Firms

B.1 Domestic

Profits maximization is equal to dirty-type firms’ s option, so, in order to simplify the analysis, we will report only the results. First, by substituting the demand constraints into the profits function, we obtain:

$$\pi_j^{c_1} = Ap_j^{1-\varepsilon} - \left(\frac{c^d}{\varphi_j}\right) Ap_j^{-\varepsilon} - f^{c_1}$$

In order to satisfy first order condition of maximization, first derivative of profit with respect to the price is calculated and then it is equalized to 0. By imposing this condition, we will obtain the maximizing price:

$$p_j^{c_1} = \frac{1}{\alpha}\left(\frac{c^d}{\varphi_j}\right)$$

This value of the price is substituted into the profits function and we achieve the *ex post* domestic profits for clean-type 1 firms:

$$\pi_j^{c_1} = A\left(\frac{c^d}{\varphi_j \alpha}\right)^{1-\varepsilon} (1-\alpha) - f^{c_1}$$

B.2 Foreign

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

$$\pi_j^{{c_1}^*} = Ap_j^{*1-\varepsilon} - \left(\frac{c^d \tau_j}{\varphi_j}\right) Ap_j^{*-\varepsilon} - f^{{c_1}^*}$$

${\pi_j^{c_1}}^*$ is differentiated with respect to p_j^* and equalized to 0. The obtained result is the optimal price in foreign market for clean-type 1 firms:

$$p_j^{*c_1} = \frac{1}{\alpha}\left(\frac{c^d\tau_j}{\varphi_j}\right)$$

In order to achieve the *ex post* foreign profits of clean-type 1 firms, the optimal price is substituted into profits function:

$${\pi_j^{c_1}}^* = A\left(\frac{c^d\tau_j}{\varphi_j\alpha}\right)^{1-\varepsilon}(1-\alpha) - f^{{c_1}^*}$$

Appendix C - Profits Maximization of Clean-Type 2 Firms

C.1 Domestic

First, by substituting the demand constraint into the profits' function we obtain:

$$\pi_j^{c_2} = Ap_j^{1-\varepsilon} - \left(\frac{c^c}{\varphi_j}\right)Ap_j^{-\varepsilon} - f^{c_2}$$

In order to satisfy first order condition of maximization, first derivative of profits with respect to the price is calculated and it is equalized to 0. By imposing this condition, the maximizing price of clean-type 2 firms in domestic market:

$$p_j^{c_2} = \frac{1}{\alpha}\left(\frac{c^c}{\varphi_j}\right)$$

This value of the price is substituted into the profits and we achieve the *ex post* domestic profits for clean-type 2 firms:

$$\pi_j^{c_2} = A\left(\frac{c^c}{\varphi_j \alpha}\right)^{1-\varepsilon}(1-\alpha) - f^{c_2}$$

C.2 Foreign

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

$$\pi_j^{{c_2}^*} = Ap_j^{*1-\varepsilon} - \left(\frac{c^c \tau_j}{\varphi_j}\right)Ap_j^{*-\varepsilon} - f^{{c_2}^*}$$

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

$$p_j^{*c_2} = \frac{1}{\alpha}\left(\frac{c^c \tau_j}{\varphi_j}\right)$$

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

$$\pi_j^{{c_2}^*} = A\left(\frac{c^c \tau_j}{\varphi_j \alpha}\right)^{1-\varepsilon}(1-\alpha) - f^{{c_2}^*}$$

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

We have seen in Section 3 that the foreign cut-off productivity of dirty-type firms DF is equal to $c^d \tau_j \left\{\alpha\left[\frac{f^{d^*}}{A(1-\alpha)}\right]^{\frac{1}{1-\varepsilon}} - t\right\}^{-1}$ while, the domestic cut-off productivity of clean-type 1 firms CD_1 is equal to $\frac{c^d}{\alpha}\left[\frac{f^{c_1}}{A(1-\alpha)}\right]^{\frac{1}{\varepsilon-1}}$. If we compare these marginal productivities, we can show that $CD_1 < DF$ when

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

But, given that Proposition 7 requires that $\tau > \left(\frac{f^{c_1}}{f^{c_1^*}}\right)^{\frac{1}{\varepsilon-1}}$ the previous inequalities is always verified.

Appendix E – Dirty-type and Clean-type 1 firms: a comparison between the grade of profits function

Given domestic and foreign *ex post* profits functions of dirty-type firms, it is possible to calculate the sum of profits which is equal to the following equation

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

By differentiating $\pi^{d\,SUM}$ with respect to φ_j, we can obtain the grade of the previous function:

$$\begin{aligned}\frac{d\pi^{d\,SUM}}{d\varphi_j} = {} & A\,\alpha^{\varepsilon-1}(1-\alpha)(\varepsilon \\ & - 1)\left(\frac{c^d}{{\varphi_j}^2}\right)\left[\left(\frac{c^d}{\varphi_j}+t\right)^{-\varepsilon} + \tau\left(\frac{c^d\tau}{\varphi_j}+t\right)^{-\varepsilon}\right]\end{aligned}$$

Similarly, we can obtain the grade of the domestic *ex post* profits of clean-type 1 firms, so by differentiating with respect to φ_j the function $\pi_j^{c_1}$, we get

$$\frac{d\pi^{c_1}}{d\varphi_j} = A\,\alpha^{\varepsilon-1}(1-\alpha)(\varepsilon-1)\left(\frac{c^d}{{\varphi_j}^2}\right)\left(\frac{c^d}{\varphi_j}\right)^{-\varepsilon}$$

Now, by comparing $\frac{d\pi^{d\,SUM}}{d\varphi_j}$ and $\frac{d\pi^{c_1}}{d\varphi_j}$, it is easy to show that $\frac{d\pi^{d\,SUM}}{d\varphi_j} > \frac{d\pi^{c_1}}{d\varphi_j}$ when

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

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

In order to calculate the adoption cut-off $\tilde{\varphi}_{CD_1-CD_2}$ we compare the domestic *ex post* profits of clean-type 1 and clean-type 2 firms. As we can see from equations (5) and (6) in Section 2, these profits are equal to

$$\pi_j^{c_1} = A\left(\frac{c^d}{\alpha\varphi_j}\right)^{1-\varepsilon}(1-\alpha) - f^{c_1}$$

for clean-type 1 firms, and

$$\pi_j^{c_2} = A\left(\frac{c^c}{\alpha\varphi_j}\right)^{1-\varepsilon}(1-\alpha) - f^{c_2}$$

for clean-type 2 firms. By equalizing the equations we analytically obtain $\tilde{\varphi}_{CD_1-CD_2}$, which is equal to the following equation

$$\tilde{\varphi}_{CD_1-CD_2} = \left\{\frac{f^{c_1} - f^{c_2}}{A\,\alpha^{\varepsilon-1}(1-\alpha)[(c^d)^{1-\varepsilon} - (c^c)^{1-\varepsilon}]}\right\}^{\frac{1}{\varepsilon-1}}$$

Appendix G – Clean-type 1 and Clean-type 2 firms: a comparison between the grade of profits function

Given domestic and foreign *ex post* profits functions of clean-type 1 firms, we can calculate the sum of profits as follows

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

By differentiating $\pi^{c_1\,SUM}$ with respect to φ_j, we can obtain the grade of the function:

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

In the same way, the grade of the domestic *ex post* profits of clean-type 1 firms is obtained, so by differentiating with respect to φ_j the function $\pi_j^{c_2}$, we get

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

Now, by comparing $\frac{d\pi^{c_1\,SUM}}{d\varphi_j}$ and $\frac{d\pi^{c_2}}{d\varphi_j}$, it is easy to show that $\frac{d\pi^{c_1\,SUM}}{d\varphi_j} > \frac{d\pi^{c_2}}{d\varphi_j}$ when

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

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

In order to get the exact value of $\tilde{\varphi}_{CF_1-CF_2}$, it is necessary to calculate the sum of clean-type 1 firms and clean-type 2 firms profit. The sum of profits of clean-type 1 firms can be obtained by summarizing $\pi_j^{c_1}$ and $\pi_j^{{c_1}^*}$:

$$\begin{aligned}\pi^{c_1\,SUM} &= \pi_j^{c_1} + \pi_j^{{c_1}^*} \\ &= A\left(\frac{c^d}{\varphi_j\alpha}\right)^{1-\varepsilon}(1-\alpha) - f^{c_1} + A\left(\frac{c^d\tau_j}{\varphi_j\alpha}\right)^{1-\varepsilon}(1-\alpha) \\ &\qquad - f^{{c_1}^*} \\ &= A\left(\frac{c^d}{\varphi_j\alpha}\right)^{1-\varepsilon}(1-\alpha)\left(1+\ \tau_j^{1-\varepsilon}\right) - f^{c_1} - f^{{c_1}^*}\end{aligned}$$

In the same way we can obtained the sum of profits of clean-type 2 firms:

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

The exact value of $\hat{\varphi}$ is obtained by equalling $\pi^{c_1\,SUM}$ to $\pi^{c_2\,SUM}$ and solving by φ_j

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

Appendix I – Sorting conditions

	SORTING 2 and 3
Pigouvian tax	$T_1^* < t < T_1$
Marginal and fixed costs	$0 < \left(\frac{c^d}{c^c}\right)^{\varepsilon-1} < \frac{f^{c_2^*}}{f^{c_1^*}}$
Adoption cut-off productivity	$\tilde{\varphi}_{DD-CD_1} < DF$
	$\tilde{\varphi}_{CD_1-CD_2} > CF_1$
	$\tilde{\varphi}_{DD-CD_1} < \tilde{\varphi}_{CF_1-CF_2}$ $\tilde{\varphi}_{CD_1-CD_2} < \tilde{\varphi}_{CF_1-CF_2}$
Profit function slope	$\tau < \left[\left(\frac{c^d}{c^c}\right)^{\varepsilon-1} - 1\right]^{\frac{1}{1-\varepsilon}}$

Pollution Haven Effect and Porter Hypothesis: on the importance of firms’ heterogeneity to account for the relationship between environmental regulation, eco-innovation and exports in German manufacturing firms

1. Introduction

In the last twenty years, innovation and environmental issues have captured the international authorities’ attention, especially in a context where globalization, followed by a worldwide trade liberalization, has played a crucial role in competitiveness improvement and sustainable growth. It is important to understand that the relationship among all these aspects is complex and economists have obtained controversial results. Since firms could differently react and adapt to complexities, the present work aims at theoretically and empirically studying the role of productivity heterogeneity across firms as a crucial driver of technology adoption and exporting decisions. By studying a firm’s exporting decision in the Melitz (2003) trade model where technology can be either dirty or green, we get some theoretical predictions to be econometrically tested. Specifically, these hypotheses include a negative direct impact of environmental regulation on exporting propensity and a positive effect of regulation on innovation, with reference to CIS2008 and CIS2014 manufacturing German firms. Moreover, the indirect impact of regulation on trade performance through innovation decisions can be measured. As econometric strategy we have implemented the Endogenous Switching Model, which accounts for the dichotomous nature of export and innovation variables and the possible endogeneity of eco-innovation covariates.

This paper is closely related to different contributions of the existing literature on trade, innovation and environment debate. First, we refer to macro and micro trade theories that have studied the link between innovation and exporting decisions [Grossman and Helpman (1991), Yeaple (2005), Piccardo et al. (2013), Bustos (2011), and Tavassoli (2013)]. This literature has predicted a positive bidirectional relation between innovation and exporting, especially at firm level. A second strand of the literature concerns the impact of innovation on emissions. A huge number of works has pointed out the positive effect of innovation in diminishing environmental pollution and in preserving natural resources. In this process, governments play a fundamental role in leading countries toward a sustainable change by introducing well-designed regulations that foster innovation adoption and structural changes. Third, this paper is also connected to the literature analyzing the effect of environmental policies on eco-innovation adoption and diffusion processes, whose results are controversial. On one side, some researchers have asserted that green regulations, or more stringent ones, generate higher compliance costs of production, worsening firms' competitiveness [Tobey (1990), Grossman and Krueger (1993), Copeland and Taylor (2004)]. On the other side, some theoretical and empirical works have demonstrated that these regulations are fundamental for the adoption of abatement technologies by firms [Milliman and Prince (1989), Jung et al. (1996), Horbach (2008) and Horbach et al. (2012)]. Furthermore, at micro level, different studies have argued that environmental regulation not only causes higher costs but, these costs, will be accompanied by an improvement in economic and environmental performance, which is driven by innovation [Porter (1991), Porter and Van Der Linde (1995)]. Finally, the work is especially related to an emerging empirical and theoretical literature that accounts for firms' heterogeneity when international trade and environmental issues are debated [Kreickemeier and Ritcher (2014), Cao et al. (2016), Holladay (2016), Cui et al. (2017) and Forslid et al. (2018)]. Specifically, these studies introduce innovation decisions into the microeconomic Melitz (2003) trade model 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. Furthermore, Cao et al. (2016) explore inverted U-shaped curves for investments in abatement technology for a panel of Chinese firms, under the assumption of the heterogeneous framework of Melitz (2003). Holladay (2016) has empirically analyzed the effect of export orientation and import competition on emissions using US establishment data, with reference to the theoretical framework of Cui et al. (2012).

The paper contribution is many folds. First, though the Melitz framework has been frequently used in environmental studies, our objective is different. We aim at understanding whether productivity heterogeneity at firm level plays a relevant role in explaining controversial results about the effect of eco policies on trade and innovation decisions. Specifically, Kreickemeier and Ritcher (2014), have studied the effect of trade liberalization on aggregate emissions in a more integrated country. Forslid et. al. (2018) have analyzed which is the role of endogenous abatement investments into trade and emissions dynamics at industry level. Second, we have tested our prediction on German manufacturing firms, since Germany plays an important role in the definition of European Union policies and represents one of the most advanced economies in the European scenario, especially when environmental protection and eco-innovation investments are considered. Third, differently from previous works, that have empirically investigated a single dataset, the present analysis has been conducted on two samples, CIS2008 and more recent CIS2014 from Eurostat. Van Leeuwen and Mohnen (2017) and Rammer (2018) only have separately implemented CIS2008 and CIS2014 data, but they have specifically investigated the impact of energy policies on exporting performance of firms. Furthermore, among microeconomic studies that use the Melitz (2003) approach for explaining environmental and trade performance, no one has implemented CIS data[24]. Since we work on two dataset that cover different time period, one pre economic crisis period (2006-2008) and one after crisis period (2012-2014), we can compare the conclusions about the importance of eco-innovation

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[24] Holladay (2016) has merged National Establishment Time Series (NETS) with the EPA’s Risk-Screening Environmental Indicators (RSEI); its annuals dataset covers 1990-2006 time-period. Cao et al. (2016) have used the Energy Saving and Abatement Survey for the period 2005-2009.

adoption and environmental regulations on firms' exporting decision in time periods where priorities were different.

The remainder of the paper is organized as follows. Section 2 provides the literature review on environmental policies, eco-innovation and trade performance. In Section 3 and 4, description of the theoretical framework and the econometric model are proposed. Section 5 reports data description and Section 6 the results obtained by the endogenous switching estimation model. In Section 7, a robustness analysis is conducted by estimating the effect of environmental tax on small, medium and large firms' propensity of exporting and innovating. Section 8 concludes.

2. Literature Review

For the last thirty years, many researchers have investigated the relationship between environmental regulation and innovation, between regulation and economic performance, and among all these aspects. Considering the aim of the research, our approach essentially refers to four branches of literature. A first strand of literature concerns theoretical models on partial equilibrium analysis of different environmental policies as incentives for the adoption of innovation[25]. Specifically, our work is strictly related to models that assume an *ex ante* and myopic regulator [Milliman and Prince (1989) and Jung et al. (1996)], so it is supposed that the regulator moves as the first player, with respect to firms, and does not anticipate the new technology. These works have demonstrated that taxation produces a higher cost savings than other types of environmental policies, thus it has the strongest impact on technology decision at firm level. The second branch of literature is developed within the neoclassical framework and argues that competitiveness may be harmed by the introduction of an environmental regulation, or by a higher stringency of an existing one, due to an increase of production costs,

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[25] For a detailed survey on theoretical models with environmental policy incentives for innovation see Requate (2005).

named *compliance costs*[26]. The negative effect of a tighten pollution regulation on production costs and, consequently, on competitiveness, thus on comparative advantage and trade, is well-known as *Pollution Haven Effect*. Specifically, it states that, a more stringent environmental policy increases the costs of production and, consequently, a loss of competitiveness occurs for a given level of trade barriers. This situation entails a decrease of net exports and incoming foreign direct investments for sectors affected by regulation (polluting sectors). The *Pollution Haven Effect* is a fundamental driver of the *Pollution Haven Hypothesis*, which underlines that trade liberalization can induce a reallocation of commodities' production: more polluting industries or firms move toward countries with less stringent environmental regulation [Copeland and Taylor (2004)]. In other words, the *Pollution Haven Effect* is a necessary, but not sufficient, condition for having *Pollution Haven Hypothesis*. It becomes sufficient when it dominates the other sources of comparative advantage or these sources are absent [Taylor (2005), Cherniwchan et al. (2016)]. Nowadays, recent theoretical and empirical studies have supported the *Pollution Haven Effect*[27]. On the contrary, the evidence about the *Pollution Haven Hypothesis* still remain less robust since it underlines different results and it is theoretically contrasted by a higher relevance of other factors of comparative advantage other than environmental regulation in conditioning trade flows, such as factor endowments and technological differences [Copeland and Taylor (1994)]. Researches about Pollution Havens have been especially conducted at macro level and they can be divided into two waves. A first wave of studies argues that tighter environmental policies have a small effect on trade, even insignificant. For example, Tobey (1990), by empirically testing an extended version of the Heckscher-Ohlin-Vanek (HOV) model of international trade[28], finds that dirty industries' localization and trade patterns are not affected by the intensity of environmental regulation. Furthermore, Grossman and

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[26] At firm level, these costs bring to the adaptation of production processes or to a rethinking of the organization.

[27] See Jaffe et al. (1995), Copeland-Taylor (2004) and Taylor (2005) for *Pollution Haven Effect* review.

[28] Tobey (1990) extends the HOV model of international trade by including a qualitative measure of environmental regulation stringency.

Krueger (1993), who investigate the determinant of Mexican trade flows, suggest that labour endowments represent a more relevant source of comparative advantage than environmental regulation. A second wave of studies underlines that previous results are preliminary and weak because of four drawbacks. First, results are strictly affected by the quality of data and the level of analysis. Van Beers and Van Den Berg (2000), by revising the gravity model of Tobey (1990) and applying it at a more disaggregated level and for different industries, find that environmental policy stringency has a positive and significant effect on exports, especially for paper sector, but this effect is not confirmed for all dirty industries (chemicals and steel). Second, focussing on gravity estimates of the effect of environmental policy stringency on trade flows, the econometric model and the corresponding assumptions are very important. Ederington and Minier (2003), by modelling environmental regulation as an endogenous variable, show that the intensity of environmental policy has a strong effect on net imports (scaled by domestic production). Furthermore, Jug and Mirza (2005), by using different data sourced by Eurostat and implementing a gravity model that admits endogeneity and measurement errors, find a negative and significant relationship between regulation and relative imports. Third, cross-country and sector heterogeneity plays a relevant role in explaining the impact of pollution policies on trade. Harris et al. (2002), construct a three-dimension gravity model that accounts for importing, exporting and time effects and they do not find any significant impact of six different environmental regulation intensity measures on net imports, but they point out that it is fundamental to consider import, export and time fixed effects to account for heterogeneity. Mulatu et al. (2003), by examining the effect of environmental abatement costs on net exports of manufacturing industry in three different countries (United States, Germany and Netherland), show that results differ across countries and sectors. Specifically, a tighten environmental policy, which requires higher capital expenditure, represents a source of comparative advantage for polluting industries in the United States, while an increase of environmental costs negatively affects the net value of exports on total value of production of polluting-intensive sectors in Germany and Netherland.

Ederington et al. (2005), who adopt pollution abatement costs as a measure of environmental regulation and net imports scaled by shipments as a measure of trade variable costs, confirm the importance of heterogeneity across industries in studying the trade-environment relationship. In other words, if we do not consider the peculiarities of each sector, we will understate the effect of the pollution policy on trade. Finally, one of the most important reasons that explain the above-mentioned divergent results is related to the measure of environmental regulation. Tsurumi et al. (2015) study the impact of three different measures of environmental policy stringency (energy intensity, abatement costs intensity, survey indices) on bilateral trade flows. The paper shows that an increase in abatement costs brings a decrease of both net exports and GDP, but energy intensities and survey indices boost trade flows.

In general, it is possible to state that environmental regulation significantly affects trade, but the sign and the magnitude of the effect could be different.

A third important part of literature is based on the *Porter Hypothesis*, which aims at demonstrating the positive effect of environmental regulation on innovation and, as a consequence, on competitiveness of firms and the market as a whole. Specifically, following the idea of Porter (1991) and Porter and Van der Linde (1995), Jaffe and Palmer (1997) has underlined three versions of this hypothesis. The *weak* Porter Hypothesis suggests that a more stringent environmental regulation, such as a command-and-control policy[29], affects "certain types" of innovation, mainly eco-innovation, but do not completely offset compliance costs. The *narrow* Porter Hypothesis points out the relevance of environmental policies that stimulate environmental innovation, specifically, Porter and Van der Linde argue that more flexible environmental policies have a higher impact on the adoption of innovation than command-and-control regulations. Furthermore, these regulations also stimulate firms' competitiveness. Finally, the third type is the *strong* Porter Hypothesis. This hypothesis allows a dynamic mechanism to evaluate the effect of environmental regulation on innovation and, in turn, on economic and

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[29] Command-and-Control environmental regulations impose specific limits for pollution emission or for the implementation of specific abatement technologies.

environmental performance. Following this version of the Porter Hypothesis, a "well-designed" environmental policy could represent an opportunity for firms: if the innovation is induced by the introduction of environmental regulation, it could generate benefits that more than compensate compliance costs, thus implying an increase in firm's competitiveness. In other words, a green policy should encourage firms to innovate and to reorganize their production in a more efficient way. This mechanism could be advantageous both socially and economically.

For the last twenty years, a huge number of researches have been empirically studying all versions of the Porter Hypothesis[30]. Concerning the *weak* Porter Hypothesis, applied researchers commonly agree on a significant and positive impact of environmental policy on eco-innovation by using different measures of environmental innovation and environmental regulation[31]. This version of the Porter Hypothesis is in line with neoclassical theoretical model that study the environmental policy incentives in adopting abatement technology. By focusing on *narrow* Porter hypothesis, a few studies have been conducted. For example, by studying the effect of environmental regulation and innovation on trade volumes in the manufacturing industry, Costantini and Mazzanti (2012) empirically show that regulation, through a positive effect on innovation, indirectly increases the competitiveness of eco-friendly industries. Furthermore, Lanoie et al. (2011) support the *narrow* Porter Hypothesis by finding that a flexible environmental policy, such as performance-based standards, has a positive effect on innovation. Finally, the most studied version of the Porter Hypothesis is the *strong* one, both at micro and macro level. Results are contrasting and depend on different aspects, such as how firms' competitiveness[32], environmental regulation, environmental

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[30] For a good review of the literature we can refer to Ambec et al. (2013). Furthermore, Cohen and Tubb (2017) make a meta-analysis of the Porter Hypothesis.

[31] Jaffe and Palmer (1997), Brunnermeier and Cohen (2003), Popp (2002), Lanoie et al. (2011), Rubashkina et al. (2015), Franco and Marin (2017) and Van Leeuwen and Mohnen (2017)

[32] See Dechezleprêtre and Sato (2014) for a review on the impacts of environmental regulations on competitiveness of firms measured by trade, employment, productivity and innovative activities.

innovation are measured[33]. In the literature about the *strong* Porter Hypothesis, a small number of studies have been focused on the connection between trade and environment. Costantini and Mazzanti (2012), who conduct an industry-level analysis across EU15 countries, support this hypothesis by concluding that environmental regulations positively and significantly affect innovation and European Union competitiveness by boosting exports. Conversely, Rammer et al. (2017), focusing on German, Swiss and Austrian firms, do not confirm the *strong* Porter hypothesis mechanism by studying the impact of energy policies on firms' exports and market position.

Finally, a fourth strand of the literature is connected to international trade theory that underlines a positive relationship between innovation and exporting performance. In 2005, Yeaple, by focusing on a general equilibrium trade model with homogeneous firms, has shown that in the presence of fixed costs associated with both technology adoption and exporting, only those firms that adopt advanced technologies start to export. Similarly, Bustos (2011) has suggested that trade liberalization can stimulate upgraded technology adoption by using a model with heterogeneous firms where the choice of technology is jointly modeled with production and export decisions. Models like Bustos (2011), that refer to Melitz's model of 2003, have been highly used in order to study the relationship between different environmental aspects and trade. For example, Kreickermeier and Richter (2014) have identified a fourth effect of trade on environmental emissions, the reallocation effect, which states that international integration increases average productivity and, subsequently, reduces the emission intensity. Nevertheless, there is another (scale) effect that causes an increase of emissions, so the net effect will be positive if and only if the emission intensity of firms strongly decreases. Moreover, Forslid et al. (2018) have constructed a theoretical model following Melitz (2003) in order to understand, through the abatement technology investments mechanism, if

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[33] Lanoie et al. (2011), Broberg et al. (2013), Rexhäuser and Rammer (2014) and Rubashkina et al. (2015) find no evidence on strong Porter Hypothesis; whereas Lanoie et al. (2008), Costantini and Mazzanti (2012), Albrizio et al. (2017) and Marin and Franco (2017) support this version of the Porter Hypothesis.

exporters have lower level of emissions due to the introduction of an environmental tax. They further investigate the effect of trade liberalization on aggregate level of emissions. Their investigation has shown that trade liberalization increases production and exporting firms become cleaner than non-exporting ones because they are induced to invest in abatement technologies.

By using the same approach of these studies, in the next section we describe the theoretical model.

3. Theoretical Framework

In this section, a theoretical model based on Melitz (2003) and Bustos (2011) is developed to allow some predictions - to be empirically tested - on the impact of environmental taxation and investment in abatement technology on export propensity at firm level. The basic framework entails international trade and heterogeneous firms where manufacturing of goods produces pollution. First, firms make the decision to invest in an abatement technology to reduce emissions or not. Then they choose to serve either the domestic market or the domestic and export markets. Firms pay an emission tax for pollution and trade costs for foreign sales. Some additional fixed costs of entry in domestic and export markets are to be paid by firms implying decreasing average costs.

Demand: consumers' preferences are described by a CES utility function. The demand function for variety j with constant elasticity of substitution ε, with ε >1, is $X_j = Ap_j^{-\varepsilon}$, where A denotes aggregate expenditure for differentiated products, which is exogenous at firm level and endogenous for the industry; p_j is variety j's price.

Entry and production: each firm will produce a differentiated product to be supplied in a monopolistically competitive market using only one factor, labor, given an inelastic labor supply L at the aggregate level. Firms are heterogeneous in their productivity for a given technology and draw a productivity φ from a cumulative probability distribution function G(φ) when a fixed entry cost f_e, expressed in units of labor, is paid. The cost function exhibits constant marginal cost with a fixed cost. However, marginal and fixed costs differ when selling to domestic customers from those to be paid to reach foreign customers when the world economy is imperfectly integrated.

Technology: we assume that one unit of pollution is emitted for each unit of output for all varieties, thereby each firm will decide to adopt an emission abatement technology or not. In the former situation, we refer to clean-type firms, in the latter one to dirty-type firms. We say that a dirty-type technology is a baseline or low-level technology, while a clean-type one is an upgraded technology. A dirty-type technology entails a Pigouvian tax for each unit of pollution, while the clean-type technology is able to completely abate pollutants, for simplicity, and asks for higher fixed costs and lower variable costs than the dirty-type one. Our model differs from Copeland and Taylor (1994) for some aspects. They have proposed a general equilibrium model with the aim of interpreting the role of comparative advantage factors and environmental emissions at country level, while our objective is to study the role of firms' heterogeneity in the regulation, innovation and trade mechanism. They consider two sectors that differ in pollution and factor intensity, in the presence of two factors of production (capital and labor). We instead concentrate on a more simplified framework that includes only one factor of production (labor) and we assume that firms can choose between abating all emitted pollution, by using clean-type technology, or do not abate at all and pay a tax. Furthermore, their work implements an endogenous regulation, while we hypothesize that the environmental tax is exogenous because the model is micro and firms take the tax as given. Our simplification allows to pay more attention on the choice of technology and to analyze firms' differences in terms of innovation.

Firm's decision: we analyze firm j's decisions of whether to enter the export market and whether to adopt technology m, where $= d, c$; subscripts d and c indicate dirty-type and clean-type technologies, respectively. We compare total profits for the two alternative technologies when the pricing rule of a fixed mark-up over marginal costs is set. In the presence of CES consumers' preferences, we can easily calculate (domestic) profits for any non-exporter with an ex-ante productivity level φ and using a technology *m* as follows (*j* subscript suppressed to simplify notation):

$$(1)\qquad \pi_m^d = A\left(\frac{c_m}{\alpha\varphi}\right)^{1-\varepsilon}(1-\alpha) - f_m \qquad\qquad m = d, c$$

where a dirty-type firm's marginal cost is $c_d = c(1+t)$. The marginal cost includes an *ad valorem* environmental tax since pollution cannot be abated. Differently, a clean-type firm's marginal cost is c_c, with $c_c < c$, assuming that pollution is totally abated. Profits depend also on industry expenditure *A*, and fixed costs of production, f_d or f_c, with $f_c > f_d$.

In the presence of variable (iceberg) trade costs τ, with $\tau > 1$, a firm can get additional variable profits by selling to foreign customers. However, fixed costs of exporting f_m^* are to be paid. For any exporter and for a given technology *m* the corresponding profit from export sales is

$$(2)\qquad \pi_m^* = A\left(\frac{c_m\tau}{\alpha\varphi}\right)^{1-\varepsilon}(1-\alpha) - f_m^*$$

Following Melitz (2003), we can easily show that the higher is productivity φ the higher are domestic and export profits. We calculate cut-off productivity levels when a zero-profit condition is imposed in (1) and (2). Domestic and foreign cut-offs for dirty-type firms are

$$(3)\qquad DD = \frac{c(1+t)}{\alpha}\left[\frac{f_d}{A(1-\alpha)}\right]^{\frac{1}{\varepsilon-1}}$$

$$(4)\qquad DF = \frac{c(1+t)\tau}{\alpha}\left[\frac{f_d^*}{A(1-\alpha)}\right]^{\frac{1}{\varepsilon-1}} = DD\,\tau\left[\frac{f_d^*}{f_d}\right]^{\frac{1}{\varepsilon-1}}$$

and for clean-type firms are the following

$$(5)\qquad CD = \frac{c_c}{\alpha}\left[\frac{f_c}{A(1-\alpha)}\right]^{\frac{1}{\varepsilon-1}} = DD\,\frac{c_c}{c(1+t)}\left[\frac{f_c}{f_d}\right]^{\frac{1}{\varepsilon-1}}$$

$$(6) \qquad CF = \frac{c_c \tau}{\alpha}\left[\frac{f_c^*}{A(1-\alpha)}\right]^{\frac{1}{\varepsilon-1}} = CD\,\tau\left[\frac{f_c^*}{f_c}\right]^{\frac{1}{\varepsilon-1}} = DD\,\frac{c_c \tau}{c(1+t)}\left[\frac{f_c^*}{f_d}\right]^{\frac{1}{\varepsilon-1}}$$

Then we can identify three groups of non-active firms, non-exporters, and exporters for each technology. The domestic cut-off *DD* (*CD*) identifies the lowest productivity level for successful entry when a dirty (clean) technology is chosen. Analogously, the foreign cut-off *DF* (*CF*) relates to a dirty-type (clean-type) marginal productivity level to get non-negative foreign profits. A dirty-type (clean-type) firm producing for the domestic market will have an ex-ante productivity level φ, which is higher than *DD* (*CD*) but lower than *DF* (*CF*). With $\varphi > DF$ ($\varphi > CF$), firms will sell to domestic and foreign customers. The partitioning of firms will occur whenever $\tau^{\varepsilon-1}\frac{f_m^*}{f_m} > 1$, with $m = d, c$. So that $DF > DD$ ($CF > CD$).

Finally, we compare dirty-type and clean-type firm's profits to evaluate *j* firm's innovation decision. We assume that $\frac{f_c}{f_c^*} > \frac{f_d}{f_d^*}$, thus domestic initial fixed of clean-type technology is higher than dirty-type technology given similar foreign fixed costs. As for non-exporter, we can show that using the clean technology is always dominated by the dirty technology when $CD > DD$, which occurs when the environmental tax is not too high, or $(1+t) < \frac{c_c}{c}\left[\frac{f_c}{f_d}\right]^{\frac{1}{\varepsilon-1}} = T1$. When firms export, some of them will use dirty technology and other ones will use clean technology. In this case, what is labelled by Bustos (2011) an adoption productivity cut-off $\tilde{\varphi}$ - such that $\pi_d^d + \pi_d^* = \pi_c^d + \pi_c^*$ - must be greater than DF. The adoption cut-off is the following

$$(7) \qquad \tilde{\varphi} = DF\left[\frac{f_c + f_c^* - f_d - f_d^*}{(1+\tau^{\varepsilon-1})\left\{\left[\frac{c(1+t)}{c_c}\right]^{\varepsilon-1} - 1\right\}f_d^*}\right]^{\frac{1}{\varepsilon-1}} = DD\left[\frac{f_c + f_c^* - f_d - f_d^*}{(1+\tau^{\varepsilon-1})\left\{\left[\frac{c(1+t)}{c_c}\right]^{\varepsilon-1} - 1\right\}f_d}\right]^{\frac{1}{\varepsilon-1}}$$

The condition for which $\tilde{\varphi} > DF$ is $(1+t) < \frac{c_c}{c}\left[1 + \frac{f_c + f_c^* - f_d - f_d^*}{(1+\tau^{\varepsilon-1})f_d^*}\right]^{\frac{1}{\varepsilon-1}} = T2$. In the opposite case, all exporters will adopt the clean technology. However, the latter case is not empirically supported by CIS data.

When $T1 > T2$, we can obtain three possible scenarios. The first, where the environmental tax could guarantee the coexistence between dirty-type and clean-type exporters, is verified when $(1+t) < T2 < T1$. The second scenario, that underlines the existence of clean-type exporters only, is guaranteed if $T2 < (1+t) < T1$ and the third one, where dirty-type firms disappear and both domestic and foreign markets are supplied by clean-type firms, when $T1 < (1+t)$[34].

Industry equilibrium: two conditions are required to determine the (unique) industry equilibrium. First, the industry average profit can be calculated by exploiting zero profit conditions (3), (4) and (7) to get a negative relationship between the industry average profit $\bar{\pi}$ and the productivity cut-off *DD* as follows

$$(8)\qquad \bar{\pi} = f_d k(DD) + f_d^* k(DF)\frac{1-G(DF)}{1-G(DD)} + (f_c - f_d)k(\tilde{\varphi})\frac{1-G(\tilde{\varphi})}{1-G(DD)}$$

where $k(i) = \frac{i^{1-\varepsilon}}{1-G(i)}\int_i^{+\infty}\varphi^{\varepsilon-1}g(\varphi)d\varphi$, with $k'(i) < 0$ and $i = DD, DF, \tilde{\varphi}$.

Second, a free entry condition for which the net value of entry is equal to zero indicates a positive correlation between the industry average profit and the productivity cut-off *DD*. Given a discounting factor δ and the fixed entry cost f_e we have

$$(9)\qquad \bar{\pi} = \frac{\delta f_e}{1-G(DD)}$$

By combining (8) and (9) we can determine a unique domestic cut-off *DD* and average profit $\bar{\pi}$ such that the industry is in equilibrium. In turn, we can

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[34] If $T1 < T2$, there is only one environmental tax range for which dirty-type and clean-type firms export and it corresponds to $(1+t) < T1 < T2$. If this condition is not satisfied, dirty-type firms disappear and markets are supplied by clean-type firms only.

obtain the equilibrium export cut-off *DF* and the adoption cut-off $\tilde{\varphi}$, from (4) and (7) respectively[35].

The impact of environmental regulation: we study the effect of an increase of the environmental tax t on *DD*, *DF* and $\tilde{\varphi}$. We can show that the domestic and export cut-offs for dirty-type firms increase, so that it is more difficult to keep producing for the least productive firms and some (low productive) exporters will stop selling abroad. Conversely, the adoption cut-off will decrease so it is convenient for some intermediate productive exporters to switch from the dirty technology to the clean one (see the Appendix for formal proofs).

Summary: In the presence of CES consumers' preferences and a probability distribution for firms' ex ante productivity, we have shown that more productive firms invest in the abatement technology and have no emission intensity. Since exporters tend to be more productive and more eco-innovative than non-exporters, we can state the following prediction to be tested in the empirical analysis:

Prediction 1: More productive firms will have a higher propensity to invest in a green technology and a higher propensity of exporting than other firms.

Prediction 2: Eco-innovators have a higher export propensity than non-innovators.

Prediction 3: there is a negative direct effect of environmental tax on export propensity for non-innovators and a positive effect on eco-innovation propensity for exporters. The latter effect implies that environmental taxation will indirectly promote export propensity, by stimulating innovation. However, the net effect is ambiguous since the negative direct effect and the positive indirect one will affect different firm groups.

The direct effect is consistent with the *Pollution Haven Effect*, for which eco-taxes generate higher compliance costs and harm firms' economic performance. By testing the *weak* Porter Hypothesis, we can analyse the positive effect of the environmental tax on the innovation propensity of firms, which is also in line with neoclassical model of environmental policy

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[35] For a deeper mathematical analysis of industry equilibrium see Appendix B.

incentives. By testing the impact of the environmental tax on innovation and, consequently, the effect of innovation on exporting propensity of firms, we can study the indirect effect of a green tax on exports.

In conclusion, this model can improve our understanding of *Pollution Haven* and *Porter* views by admitting firms' productivity heterogeneity. Firm's heterogeneity may be interpreted as a driver of the relationship between environmental regulation, environmental innovation and exporting propensity. The next Section will describe the econometric methodology to empirically test our predictions using micro-level data.

4. Econometric Model

We aim at empirically evaluating the potential direct and indirect effects of environmental taxation on the exporting probability at firm level, when export participation and eco-innovation upgrading are modelled in terms of dichotomous outcome variables. Our analysis is conducted by implementing the endogenous switching model drawn by Miranda and Rabe-Hescketh (2006). This model accounts for the potential endogeneity of an explanatory variable (eco-innovation) and for the non-linear nature of the relationship between dependent and independent variables[36].

The estimated model is expressed as a system of two latent variables of export and environmental innovation intensity, EXP_j^* and $EnvInno_j^*$. The first equation is

$$(10) \quad EXP_j^* = \beta_1 EnvTax_j + \beta_2 dEnvInno_i + \boldsymbol{\alpha} \boldsymbol{X_j'} + u_j$$

$$(11) \quad dEXP_j = \begin{cases} 1\ if\ EXP_j^* > 0 \\ 0\ otherwise \end{cases}$$

where $dEXP_j$ is a binary variable that identifies j's firm's export status, $EnvTax_j$ is a dummy variable when there is environmental taxation, $dEnvInno_j$ is a binary variable that concerns environmental innovation and

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[36] For a complete review of econometric methods for binary regression see Nichols (2007).

$\boldsymbol{X_j'}$ is a set of control variables. u_j is the error term. β_1, β_2 and $\boldsymbol{\alpha}$ are the parameters to be estimated. The second equation relates to innovation variable and is the following

(12) $EnvInno_j^* = \delta_1 EnvTax_j + \boldsymbol{\theta}\, \boldsymbol{Z_j'} + \boldsymbol{\gamma}\, \boldsymbol{X_j'} + v_j$

(13) $dEnvInno_j = \begin{cases} 1\ if\ EnvInno_j^* > 0 \\ 0\ otherwise \end{cases}$

where $dEnvInno_j$ is a binary variable that identifies if firm *j* is an eco-innovator, $\boldsymbol{Z_j'}$ is a set of instrumental variables; $\boldsymbol{X_j'}$ is the same set of control variables of equation (10); v_j is the error term, δ_1, $\boldsymbol{\theta}$ and $\boldsymbol{\gamma}$ are the parameters to be estimated. Probit models are used for both $dEXP_j$ and $dEnvInno_j$.

u_j and v_j are assumed to be bivariate normally distributed. Potential dependence among u_j and v_j has been accounted by using a shared random effect, ε_j. This means that:

(14) $u_j = \lambda\varepsilon_j + \tau_j$

(15) $v_j = \varepsilon_j + \varsigma_j$

where τ_j, ς_j and ε_i are independently normal distributed random variables with 0 mean and variance equal to 1. λ is named *factor loading* and represents a free parameter. The covariance matrix of u_j and v_j is represented as follows:

(16) $Cov\left\{\left(u_j, v_j\right)'\right\} = \begin{pmatrix} \lambda^2 + 1 & \lambda \\ \lambda & 2 \end{pmatrix}$

and correlation ρ is given by

(17) $\rho = \frac{\lambda}{\sqrt{2(\lambda^2+1)}}$

In this framework, if ρ=0, $dEnvInno_i$ will be exogenous; if ρ≠0, $dEnvInno_i$ is endogenous and correlated with the error term u_j via the unobserved heterogeneity term ε_j. If the potential endogeneity of $dEnvInno_j$ is neglected, biased coefficients of equation (10-11) are obtained. A positive value of λ (so that ρ >0) brings to an upward biased coefficient of the endogenous variable; while a negative value of λ, so ρ<0, implies a downward bias. Furthermore, other covariates' coefficients could differ in sign and size too[37].

The model uses a Generalized Linear Latent and Mixed Model by stacking the response variables into one variable, q_{jk}. It is supposed that q_{jk} has a binomial distribution. k equals 1 if q_{jk}. and refers to the main response $dEXP_j$; while k equals 2 if it concerns the switching response $EnvInno_j$. Viewing both response variables as clustered within firms, it could be possible to define two dummies, $d_{1kj} = 1$ if *j=1* and d_{2kj} if *k=2*. The conditional mean of q_{jk} is specified as $E(q_{jk}|\varepsilon_j)$ and the link function for responses q_{jk} are probit and could be defined as:

$$(18) \quad g_k[E(q_{jk}|\varepsilon_j)] = d_{1kj}(\beta_1 EnvTax_j + \beta_2 dEnvInno_j + \boldsymbol{\alpha}\, \boldsymbol{X}_j' + \lambda\, \varepsilon_j) + d_{2kj}(\delta_1 EnvTax_j + \boldsymbol{\theta}\, \boldsymbol{Z}_j' + \boldsymbol{\gamma}\, \boldsymbol{X}_j' + \varepsilon_j)$$

The obtained coefficients are estimated by Maximum Likelihood Estimation and the unobserved heterogeneity, captured by ε_j, is integrated out into the model.

5. Data Description

In this work, the Eurostat Community Innovation Survey 2008 (CIS2008) and Community Innovation Survey 2014 (CIS2014) have been used to get

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[37] Since no free parameters are identified for variances, the endogenous switching model differs from bivariate probit model where variances are set equal to 1. Through a simple re-parametrization, it is possible to convert the adopted model to usual bivariate probit.

German manufacturing firms' data. The first dataset covers the three-year period 2006-2008; the second one refers to 2012-2014 time-period. Both CIS2008 and CIS2014 are based on Oslo Manual of 2005 and consider all *2-digit level* Nace Rev.2 sectors of the economy. In the present study, we study manufacturing firms export and innovation decisions only (see Table 2 for sector description). Net samples include 3060 firms for CIS2008 and 2987 firms for CIS2014. Table 5 and 6 in the Appendix report summary statistics.

5.1 Economic performance and exports

In the literature about the quantitative effects of environmental policies on competitiveness, several measures of trade performance have been used. Some macroeconomic researches largely adopted net trade flows as a measure for competitiveness with reference to aggregate and sectoral data. Tobey (1990), Van Beers and Van Den Berg (2000), Ederington and Minier (2003) and Ederington et al. (2005) have analysed U.S. net imports. In the last two studies net imports have been scaled by shipments in a specific sector at a specific time. Others, such as Mulatu et al. (2003) and Tsurumi et al. (2015), use net exports. Specifically, Mulatu et al. (2003), measures net exports on the total value of production. Few works use imports as international competitiveness measure. For example, Harris et al. (2002) choose the total value of imports while Jug and Mirza (2005) adopt the relative demand for imports in a specific country[38]. Furthermore, Costantini and Mazzanti (2012) consider the volume of trade into a gravity empirical model at industry level. At micro level, Rammer et al. (2017) contributes to the literature by measuring exporting performance through two variables: exports on total sales at the end of a referring period and a dummy variable for export activities in the last period.

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[38] By examining neoclassical studies, other variables could be employed to account for the competitiveness of firms, especially productivity [Gollop and Roberts (1983), Berman and Bui (2001), Gray and Shadbegian (2003), Shadbegian and Gray (2005), Becker (2011) and Greenstone (2012)]. Only Gollop and Roberts (1983) and Shadbegian and Gray (2003) find results that support the negative role of environmental policy on competitiveness.

In this paper, firm's export status is used ($dEXP_j$)[39] as a measure of economic performance. $dEXP_j$ is equal to 1 if a firm j exports to European Union countries and/or to other extra European Union countries, 0 otherwise. A firm's export status has been interpreted as a measure of economic performance in a microeconomic framework, in view of the existing literature on international trade with heterogeneous firms. International trade propensity is strictly related to the heterogeneous productivity at firm level so that only the most productive firms may serve foreign markets, as we have already stated in Section 3.

5.2 Explanatory Variables

Environmental Regulation

A huge number of studies use binary variables to measure environmental policy[40]. For example, at macro level, Aichele and Felbermayr (2012), by studying the effect of Kyoto Protocol on net emissions embodied in net imports, adopt a binary variable for accounting for this specific regulation[41]. Moreover, Costantini and Mazzanti (2012) account for different types of environmental regulations, such as energy tax, environmental tax, private actions and Environmental Management System implementation. At micro level, Rexhäuser and Rammer (2014) implement a dummy variable that measures if a new innovation is implemented due to a new environmental policy. By following the same perspective of these authors, in this work we use as proxy for environmental taxation a dichotomous variable ($EnvTax_j$)

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[39] In order to construct the exporting propensity dummy, answers to the following question of CIS2008 are considered: "*In which geographic markets did your enterprises sell goods and/or services during the three years 2006 to 2008?*". For CIS2014, the referring period is 2012-2014. Exporters relates to firms selling in European Union and extra European Union markets.

[40] Concerning environmental regulation and stringency, the most employed measure is the pollution abatement costs expenditure or the pollution abatement operating cost. [Mulatu et al. (2003), Ederington and Minier (2003), Ederington et al. (2005), Jug and Mirza (2005), Jaffe and Palmer (1997), Brunnermeier and Cohen (2003) and Rubashkina et al. (2015)]. Other studies use energy prices [Popp (2002) and Sato et al. (2015)] or composite indexes [Albrizio et al. (2017)] to proxy this measure. See Brunel and Levinson (2013) for a detailed overview on the measures of environmental policy stringency.

[41] Greenstone et al. (2012) also account for a specific instrument of the Clean Air Act (pollutant-specific country-level attainment/nonattainment designations), but it studies the connection between environmental regulation and productivity.

that captures firm's potential innovation adoption if a pollution tax or charges exists. Specifically, $EnvTax_j$ is equal to 1 if firms introduce eco-innovation because of environmental tax exists; 0 otherwise[42]. It is necessary to give two specifications. First, for CIS2008 this variable is already binary, while for CIS2014 we have construct a new dichotomous variable because this variable is categorical. Firms can choose among four degree of importance of the tax in introducing innovation: 0 not important, 1 low importance, 2 medium importance, 3 high importance. For this dataset $EnvTax_j$ is equal to 1 if firms answer 1, 2 or 3, otherwise it is equal to 0. Second, for CIS2014 the adopted variable directly refers to eco-tax or charges, while for CIS2008 it comprehends all types of regulation, so we cannot separate the effect of the tax from the one of other policies. Since the environmental tax should vary at country or sectoral level but not at firm level, we choose the above-mentioned variables for green tax because we expect that, since firms differ in efficiency, so in productivity, they can perceive tax stringency differently. As theoretically demonstrated in the previous paragraph, firms with a higher productivity have more propensity to implement innovation than least productive firms and the most productive ones adopt more advanced innovation, thus the introduction of a tax that fosters firms to adopt abatement technologies, which are generally advanced innovation, is differently perceived by most efficient firms. These firms probably have a lower perception of new policies[43].

As for the predicted effect of environmental regulation, we expect a negative direct effect of environmental tax on exporting propensity due to the existence of compliance costs, in line with the *Pollution Haven Effect*

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[42] CIS2008 survey identifies the existence of an environmental regulation or taxation by asking firms "*During 2006 to 2008, did your enterprise introduce an environmental innovation in response to existing environmental regulations or taxes on pollution?*". For CIS2014, firms must answer to the following question "*During 2012 to 2014, how important were existing environmental regulation or existing environmental taxes, charges or fees in driving your enterprise's decisions to introduce innovations with environmental benefits?".*

[43] This assertion is confirmed by our data. Despite the boost of environmental regulation in introducing eco-innovation, the share of firms that do not adopt an eco-innovation decreases if productivity increases. In CIS2008, this share is equal to 6.8% when least productive firms (productivity lower than the first percentile) are considered while, it is equal to 5.7% when more productive firms (productivity higher than third percentile) are taken into account. For CIS2014, these shares are respectively equal to 13.35% and 10.36%.

hypothesis. Moreover, in line with the *weak* Porter Hypothesis, which also confirms the theoretical neoclassical position, the effect of eco-tax on innovation is expected to be positive.

Environmental Innovation

The introduction of an environmental innovation should reduce the environmental risk, the amount of emitted pollution and other resources used in the production process. In this study the eco-innovation variable - $dEnvInno_j$ - captures innovation decisions strictly connected to the reduction of the energy use per unit of output and of the total amount of CO_2 produced by the firm. $dEnvInno_j$ is a binary variable which is equal to 1 if firm j will adopt one or both types of innovation, 0 otherwise[44]. We expect a positive effect on export propensity as predicted by the theoretical model developed in Section 3 and supported by Raxhäuser and Rammer (2014), who adopt a similar measure of environmental innovation[45].

Due to the potential endogeneity of environmental innovation, some instruments from the CIS2008 and CIS2014 surveys are required. For our purposes, it is necessary to choose some variables that influence firms' eco-innovation decisions but not their exporting propensity. Chosen instrumental variables are consistent with the already empirically identified drivers of eco-innovation, which are classified into four macro areas by Horbach (2008) and Horbach et al. (2012): demand-pull factors, technology-push factors, environmental regulation, and firms' characteristics. By applying some traditional tests for instrument identification (test for excluded instruments, under-identification test, weak-instruments robust inference test and the Hansen J over-identification test)[46] on possible instruments, we have identified three instrumental variables. The first one is represented by the

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[44] Firms have to answer positively to one or both of the following questions: "*During the three years 2006 to 2008, did your enterprise introduce a product, process, organisational or marketing innovation with one of these environmental benefits?: 1) reduced energy use per unit of output; 2) reduce CO2 footprint (CO2 total production)?".* For CIS2014 the referring period is 2012-2014.

[45] These authors also include in their innovation measure other types of environmental technologies, which aim at reducing material use, soil, water and noise pollution, recycling of waste and other materials.

[46] A detailed overview of test results is given in Table 8.1 and 8.2 in the Appendix.

cooperation arrangements on innovation activities within the enterprise group ($WithinCO_j$). This measure underlines the importance of knowledge sharing and cooperation for the adoption of innovation [Horbach et al. (2012)], especially in multinational firms. The second instrument, which is represented by the current or expected demand from customers for environmental innovation ($DemandPull_j$), economically reflects an increase in general income level and a substantial customer benefit from eco-friendly products [Kammerer (2009)] that consequently increase their environmental awareness, so firms are induced to adopt environmental technologies, that also have an impact on both reputation [Rennings (2000)] and market expansion [Green et al. (1994)]. Finally, the availability of government grants, subsidies or incentives for eco-innovation ($GovIncentives_j$)[47] has been implemented as instrumental variable. As policy push instruments, government incentives represent a crucial driver of eco-innovation, especially in small firms.

By analysing instrumental variables test, $WithinCO_j$ variable is excluded for CIS2014 estimations. This result could refer to a higher presence of intra-group trade which makes $WithinCO_j$ an exogenous variable.

In this view, we expect a positive and highly significant effect of these variables on the adoption of environmental innovation [Frondel et al. (2007), Horbach et al. (2012)]. Among the drivers of eco-innovation, specific attention is also devoted to the environmental regulation, which is a control variable for both export and innovation propensity equations. Its effect on the adoption of an abatement technology is fundamental in order to understand the overall effect of a green policy on the exporting propensity of firms.

Other Control Variables

Some additional control variables account for heterogeneity at firm level. First, size and sector fixed effects are introduced. The empirical literature shows that large firms are more productive than small ones because they take

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[47] For CIS2014 these instrumental variables are categorical and measure the degree of importance of demand for green innovations and of government incentives.

advantage from scale economies. Furthermore, firms' export status is affected by their productivity so that the higher is productivity the higher is export propensity [Melitz and Redding (2014), Bernard and Jensen (1999)]. In this view, a productivity control variable is calculated in terms of firm's relative profitability, as proposed by Aw et al. (2008)[48].

6. Results

6.1 Environmental Innovation: Exogeneity VS. Endogeneity

A preliminary analysis to understand if environmental innovation is an endogenous determinant of export propensity is presented to avoid any potential bias issue. The baseline model (Model 1), whose results are reported in Table 9 of Appendix, is estimated by implementing three kinds of econometric models: exogenous probit model, endogenous switching Maximum Simulated Likelihood (MSL) model and, in line with the previous literature, a bivariate probit model. The former model is based on specification (1) reported in Section 4, while the second and the latter ones refer to equations (1) and (2). As a first result, the hypothesis that the environmental innovation is endogenous cannot be rejected for both CIS2008 and CIS2014 data. As we can see from Column 3 and 6 of Table 9, we find a negative and statistically significant value of rho (at 1% significance level); it is equal to -0.313, for CIS2008, and -0.580, for CIS2014. As it is outlined in Section 4, if we do not account for the potential endogeneity of the innovation variable, biased estimates are obtained. By comparing Probit and MSL coefficients, we can confirm that, if the null hypothesis on rho cannot be rejected, the bias issue exists. Specifically, for CIS2008 and CIS2014, the coefficient of $dEnvInno$ is downward biased, thus it is lower (0.099 for

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[48] For any firm j, productivity is constructed as follows:

$$Prod_j = \ln\left(\frac{turnover_j}{sector\ turnover}\right) - \frac{1}{n}\sum_j \ln\left(\frac{turnover_j}{sector\ turnover}\right)$$

where n is the number of firms in a specific sector. Turnover is defined as the market sales of goods and services (Include all taxes except VAT

CIS2008, and 0.015 for CIS2014) than the value obtained with MSL (0.571 for CIS2008 and 0.951 for CIS2014). This result is also confirmed by bivariate probit estimation. Moreover, by using the exogenous probit model, the coefficient of environmental innovation is not significant, while the MSL and bivariate probit coefficients are highly significant (at 1% significant level).

6.2 The role of environmental taxation

As a second step, we aim at studying the effect of environmental tax on both exporting and adopting eco-innovation propensity of firms. Specifically, we test the direct effect of environmental taxation on firms' exporting propensity of the endogenous switching model, and the effect of environmental regulation on firm's probability of being eco-innovative (*weak* Porter Hypothesis).

By comparing the estimated coefficients of eco-tax for both datasets, Column 3 of Table 9 reports a negative but not significant effect of $EnvTax$ on the exporting propensity for CIS2008 (-0.058). Differently, taxation has a significant (at 5% significant level) effect on exporting probability for CIS2014 firms; Column 6 shows a coefficient equal to -0.182. Estimation with the bivariate probit is in line with this result but the coefficient is significant at 10%. From an economic point of view, we can argue that the *Pollution Haven Effect* is confirmed. Firms' competitiveness, measured in terms of trade propensity, is negatively affected by the existence of an environmental tax. By focusing on the impact of the tax on eco-innovation propensity, Table 9 shows that it has a positive and significant (at 1% significance level) effect on the adoption of the abatement innovation for both dataset; Column 3 and 6 corresponding coefficients are equal to 0.526 for CIS2008 and 0.401 for CIS2014. This result supports the *weak* Porter Hypothesis. Moreover, environmental innovation positively increases the probability of exporting. In general, it is possible to assert that this result is in line with Prediction 2, so innovators have a higher probability of exporting than non-innovators.

Concerning control variables, both productivity and size have a significant effect on firms' probability of exporting. Productivity increases the exporting propensity; this means that only the most productive firms decide to export. Focusing on size, different results on small and medium firms confirm the idea that size can be interpreted as an additional measure of efficiency [Bernard and Jensen (1995), Bernard et al. (2007)].

The positive coefficient for productivity partially confirms Prediction 1: more productive firms have a higher propensity to export Furthermore, productivity has a positive and significant impact on innovating propensity of firms while, size, is significant for CIS2008 manufacturing firms only and related coefficients are negative. Some interesting comments on eco-innovation instruments have to be reported. All instruments have a positive and significant effect on the probability of introducing environmental innovation for CIS2008. These results are consistent with the literature on the drivers of environmental innovation [Horbach (2008)]. However $GovIncentives$ variable has no significant effect for CIS2014.

Environmental taxation by emission intensity

A deeper investigation of the effect of environmental regulation on firms' competitiveness is conducted by accounting for a differentiation of environmental tax's coefficient by sector emission intensity. The idea is to capture differences in the stringency of eco policies at sector level. As a preliminary step, we have generated interaction terms that combine $EnvTax$ and the classification of sector by emission intensity. This procedure requires three phases. First, by following Marin et al. (2014), we define three levels of emission intensity (brown, grey and green), which reflect a high, medium and low level of air pollution emissions. Second, three dummies have been consequently generated ($Green$, $Grey$ and $Brown$). Each dummy is equal to 1 if a sector shows an emission intensity level that lies inside one of the above categories, 0 otherwise. Finally, interaction variables are obtained by multiplying emission intensity dummies by environmental tax covariate, so three new variables have been constructed and added to the estimation (Model 2).

The analysis implements both bivariate probit and the endogenous switching model, as in the previous section. Estimates are reported in Table 10 of the Appendix.

A first result shows that $EnvTax$ variable has a statistically significant (at 5%, for CIS2008, and 10%, for CIS2014, significant level) and negative effect for exporting propensity of brown sector firms. This result confirms the $Pollution\ Haven\ Effect$, but it seems to lose significance in 2012-2014 period. Bivariate probit estimated on $EnvTaxBrown$ of CIS2014 are in line with endogenous switching estimates but it is not statistically significant. For firms of green and grey sectors, the existence of a tax or charges does not have a significant impact on their export status. On the contrary, if we analyse the effect of the eco-tax on the probability of introducing an abatement technology, a general positive and significant value is registered for both datasets, whatever is the considered sector. We can affirm that the *weak* Porter Hypothesis is also confirmed if environmental tax's coefficient is differentiated by emission intensity.

Concerning the other explanatory variables, the adoption of eco-innovation has always a positive and significant impact on firms' export status, so eco-innovators have a higher propensity to be also exporters. Finally, results on productivity and size are confirmed and instrumental variables play a relevant role for the adoption of green technologies as before.

7. Robustness analysis by firms' size

In this section, we deeply study the effect of existing environmental taxes on three firms' subsamples: small, medium and large firms. This type of analysis is useful because we aspect that firms could react differently to regulation depending on their size. The analysis is based on the same model specifications used in previous sections, by implementing both endogenous switching and bivariate probit estimations. Results are reported in Table 11.1, 11.2 and 11.3.

Small Firms: Concerning both CIS2008 and CIS2014 small firms, Table 11.1 shows that the environmental tax does not have a significant effect on exporting propensity of firms. Specifically, when we account for environmental tax, it has a positive effect on the exports status, except for brown sector firms when Model 2 is estimated, but it is not statistically significant. Unfortunately, also the adoption of environmental innovation does not significantly affect the exporting propensity of manufacturing firms, so Prediction 2 of the theoretical model is not verified.

Some remarks on the estimates of the relationship between taxation and innovation are necessary. The environmental taxation has a positive and significant influence on eco-innovation adoption for small firms, whichever is the referring sector and the estimated model specification. As we can see from Column 1-2 and 5-6 of Table 11.1, coefficients are positive and highly significant (5% or 1%). Results are also verified if a bivariate probit estimator is implemented. Furthermore, green innovation is substantially driven by demand pull factor, thus the demand for abatement innovation from customers increases the probability of adopting eco-innovation; coefficients are positive and significant (at 1% level of significance). Among other instrumental variables, Column 1 and 5 show that the existence of government incentives has a positive and significant impact (at 10%) on eco-innovation introduction, but only if we estimate Model 1 through the endogenous switching model. Results lose robustness by applying bivariate probit. Finally, collaboration among firms of the same group fosters innovation when tax coefficient is differentiated by emission intensity for CIS2008 firms.

Interesting results refer to productivity. It seems to be the only driver of exporting propensity for this type of firms; its coefficient is the only statistically significant one (1%). This is verified for all specification and estimators. Concerning its effect on the implementation of eco-innovation, it positively and significantly affects this behaviour exclusively in CIS2014 small firms.

Medium Firms: As reported in Table 11.2, some interesting results are obtained for medium firms. First, talking about the existence of an eco-tax, data show that it generally decreases the probability of exporting of firms, except for CIS2008 medium firms. Corresponding coefficients are statistically significant at 1% or 5%. Proceeding with the analysis, when $EnvTax$ coefficient is differentiated by emission intensity, so Model 2 is estimated, different results are obtained. For CIS2008 firms, environmental tax has a negative effect for brown sector firms only. Coefficient is equal to -0.361 with endogenous switching and to -0.479 with bivariate probit. The second estimation gives a higher level of significance, 1%, than the former, 10%. Focusing on CIS2014 medium firms, the negative and significant effect of environmental taxation on export status for brown sector firms is confirmed. Furthermore, taxation negatively and significantly affects also green and grey sector firms when bivariate probit is used. Column 8 of Table 11.2 reports negative coefficients for all $EnvTaxGreen$, $EnvTaxGrey$ and $EnvTaxBrown$. This is partially verified if the endogenous switching model is the implemented estimation model. As shown by Column 6, the existence of a green tax decreases the propensity of being exporters for green and brown sector firms only. In general, we can assert that the *Pollution Haven Effect* is confirmed for medium firms, especially for brown sector ones.

By analysing the effect of the tax in introducing eco-innovation, a second important conclusion can be made: environmental taxation represents a driver for eco-regulation implementation; positive and significant (1%) effect of $EnvTax$ is obtained for all specifications and both datasets. Through a deeper analysis and the estimation of Model 2, we can affirm that this result is essentially driven by green sector firms. For CIS2008 only, the positive relationship is also verified for grey and brown firms.

A third important result concerns $dEnvInno$ variable. Table 11.2 shows that the theoretical Prediction 2 is verified, thus being an environmental innovator increases the probability of exporting; all coefficients are positive and significant at 1% or 5%.

Finally, productivity has always a positive effect on both $dEnvInno$ and $dEXP$, except for CIS2008 data where this variable has not a statistically significant impact on eco-innovation adoption. Referring to instrumental variables, government incentives are statistically significant for CIS2008 firms but not for CIS2014 ones, while demand for eco-innovation from customers is positive and significant. Collaboration within the same firms' group does not drive the introduction of innovation at all.

Large Firms: By examining Table 11.3, we can see that taxation has not a significant effect on firms' probability of being an exporter, except when Model 2 is estimated through a bivariate probit on CIS2014 large firms. Specifically, the environmental tax contributes to an increase of exporting propensity of green sector firms; Column 6 reports a coefficient equal to 0.588. Economically, being a large and green firm means being more efficient and competitive on markets, so the introduction of an eco-tax fosters firms to be even more competitive through exports. Estimates that concern the propensity of introducing an eco-innovation confirm the positive and significant role of taxation. It seems that this result is driven by grey sector firms; coefficients are equal to 1.051 and 1.050 for CIS2008 and 0.831 for CIS2014. An interesting result is related to productivity. It is a relevant driver for the adoption of innovation but not for exporting goods in foreign markets when CIS2008 data is considered and endogenous switching model is applied; indeed, coefficients of productivity are not statistically significant. This result is in line with the literature, which suggests that more productive firms are also the larger ones, so an additional increase of productivity marginally affects the exporting propensity.

As already stated for medium firms, government incentives are fundamental for CIS2008 large firms; coefficients are positive and statistically significant (1% or 5%). Despite medium firms, incentives are also relevant for CIS2014 large firms.

Finally, considering the $DemandPull$ variable, it has a positive and significant effect on eco-innovation propensity except for the estimation of Model 1 of CIS2014 data.

8. Conclusions

In a scenario where trade and innovation play a relevant role for sustainable development and where environmental policies are constantly improved in order to preserve natural resources and to account for climate change, many researchers have studied the links between environmental policy, environmental innovation and trade performance. The existing empirical evidence has underlined a strong relation among all these aspects, especially at macro level. This paper has contributed to the literature by considering the role of firms' productivity heterogeneity on environmental policies, innovation and trade dynamics. Specifically, results confirm that heterogeneity across firms - in terms of productivity, of adopted technology and size - is important in defining the relationship between green policies, green technologies and trade decisions.

Our econometric analysis has provided different insights. First, the hypothesis of the Pollution Haven Effect is generally confirmed for German firms of CIS2014 only, confirming Prediction 2. Furthermore, the *weak* Porter hypothesis, which is also confirmed by previous theoretical researches, is also confirmed and eco innovation positively affects the probability of exporting. Second, when the coefficient of regulation is distinguished by emission intensity of sectors, it has a negative effect only on exporting propensity of brown sector firms, but this result loses some robustness over time from CIS2008 to CIS2014. Generally, we can assert that, being exporters also means being eco-innovator.

We have also tested the relationship among trade, policy and innovation on three subsamples of firms, which refer to their size. For small firms, results do not substantially change over time by comparing CIS2008 and CIS2014. Environmental taxation does not represent an important driver of the exporting propensity of small firms, while it has a significant impact on innovating propensity. Exporting probability of small firms seems to be only driven by productivity. For this subsample, environmental innovation seems to have no impact on trade decision of firms. Moreover, the existence of a demand of eco-innovations is fundamental for the adoption of eco-innovation. Results on medium firms, show that a green tax has a negative effect on the probability of exporting for brown firms. As regard to CIS2014 firms, this is also confirmed for both green and grey sector firms. For medium firms, the adoption of eco-innovation is a significant driver for being an exporter. Finally, results on large firms underline that environmental tax has a positive impact on exporting propensity of green firms. Furthermore, in line with the literature, it positively affects the environmental innovation adoption but for grey sector firms only.

Concerning other variables, we can generally assert that productivity significantly increases firms' probability to export, except for large firms, and to innovate, so the most productive firms export and adopt environmental innovation. This is in line with our theoretical Prediction1. Furthermore, eco-innovation seems to be driven especially by demand for eco-friendly technologies by consumers, and by government incentives too when large firms are analysed.

From a policy point of view, our results suggest that authorities should implement tax, fees or charges by considering firms' heterogeneity, so they should consider productivity and especially emission intensity at sector level and size. Furthermore, public efforts in lowering pollution should be concentrated to more polluting sectors and supported by a system of incentives.

Further research could be done by distinguishing among different types of eco-innovations, such as end-of-pipe and cleaner-production technologies. This kind of analysis could be useful because this innovation requires different levels of fixed and variable costs, so the exporting propensity of firms. Another improvement channel for this work is represented by a cross-country study on European Union firms. It is fundamental because it could give some insight about the adoption of common environmental regulations, which can be adopted at different time and with different methods by countries. Moreover, in each country, firms could introduce, or not, eco-innovation and the drivers can be different.

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Appendix A - Tables

Table 1. Variables Description – CIS2008

Variable	Description
dEXP	Dummy variable that refers to exporting propensity of firms: equal to 1 if firm exports, 0 otherwise
EnvTax	Dummy related to environmental regulation: equal to 1 if firm introduces an eco-innovation due to present environmental regulation or tax, 0 otherwise
dEnvInno	Dummy related to the introduction of eco-innovation: equal to 1 if firm introduces an eco-innovation that reduces the amount of CO2 produced and/or the energy use, 0 otherwise
WithinCO	Dummy equals to 1 if firm has cooperation arrangements on innovation activities within the enterprise group, 0 otherwise
DemandPull	Dummy equals to 1 if firm introduces eco-innovation because of the current or expected demand from customers for environmental innovation, 0 otherwise
GovIncentives	Dummy equals to 1 if firm introduces eco-innovation because of the availability of government grants, subsidies or other financial incentives, 0 otherwise
Prod	Firms' s relative profitability, Aw et al. (2010)
dsmall	Dummy equals to 1 if firm has <50 employees, 0 otherwise
dmedium	Dummy equals to 1 if firm has a number of employees between 50 and 250, 0 otherwise
dlarge	Dummy equals to 1 if firm has >250 employees, 0 otherwise
ds1-ds7	Seven dummies referring to sectors at *2-digit* level Nace Rev. 2 classification
Green	Dummy equals to 1 if a firm operates in a green or low emission intensity sector, 0 otherwise
Grey	Dummy equals to 1 if a firm operates in a grey or medium emission intensity sector, 0 otherwise
Brown	Dummy equals to 1 if a firm operates in a brown or high emission intensity sector, 0 otherwise

Table 2. Variables Description – CIS2014

Variable	Description
dEXP	Dummy variable that refers to exporting propensity of firms: equal to 1 if firm exports, 0 otherwise
EnvTax	Dummy variable equals to 1 if the degree of importance of existing environmental taxes or charges is equal to 1 (low), 2 (medium) or 3 (high), 0 otherwise
dEnvInno	Dummy related to the introduction of eco-innovation: equal to 1 if firm introduces an eco-innovation that reduces the amount of CO2 produced and/or the energy use, 0 otherwise
DemandPull	Dummy equals to 1 if firm introduces eco-innovation because of the current or expected demand from customers for environmental innovation, 0 otherwise
GovIncentives	Dummy equals to 1 if firm introduces eco-innovation because of the availability of government grants, subsidies or other financial incentives, 0 otherwise
Prod	Firms' s relative profitability, Aw et al. (2010)
dsmall	Dummy equals to 1 if firm has <50 employees, 0 otherwise
dmedium	Dummy equals to 1 if firm has a number of employees between 50 and 250, 0 otherwise
dlarge	Dummy equals to 1 if firm has >250 employees, 0 otherwise
ds1-ds18	18 dummies referring to sectors at *2-digit* level Nace Rev. 2 classification
Green	Dummy equals to 1 if a firm operates in a green or low emission intensity sector, 0 otherwise
Grey	Dummy equals to 1 if a firm operates in a grey or medium emission intensity sector, 0 otherwise
Brown	Dummy equals to 1 if a firm operates in a brown or high emission intensity sector, 0 otherwise

Table 3. Manufacturing sector description – CIS2008

Nace Rev. 2	**Description**	**Emission intensity**
C10_C12	Manufacture of goods and products, beverage and tobacco products	Brown
C13_C15	Manufacture of textile, wearing apparel, leather and related products	Grey
C16_C18	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials; manufacture of paper and paper products; printing and reproduction of recorded media	Brown
C19_C23	Manufacture of coke and refined petroleum products, chemicals and chemical products, basic pharmaceutical products and pharmaceutical preparations, rubber and plastic, other non-metallic mineral products	Brown
C24_C25	Manufacture of basic metals and fabricated metal products, except machinery and equipment	Brown
C26_C30	Manufacture of computer, electronic and optical products, electrical equipment, machinery and equipment n.e.c., motor vehicles, trailers and semi-trailers, other transport equipment	Grey
C31_C33	Manufacture of furniture, repair and installation of machinery and equipment, other manufacturing	Green

Table 4. Manufacturing sectors description – CIS2014

Nace Rev. 2	**Description**	**Emission Intensity**
C10_C12	Manufacture of goods, products, beverage, tobacco products	Grey
C13_C15	Manufacture of textile, wearing apparel, leather and related products	Grey
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	Brown
C17	Manufacture of paper and paper products	Brown
C18	Printing and reproduction of recorded media	Grey
C19	Manufacture of coke and refined petroleum products	Brown
C20	Manufacture of chemicals and chemical products	Grey
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations	Grey
C22	Manufacture of rubber and plastic products	Brown
C23	Manufacture of other non-metallic mineral products	Brown
C24	Manufacture of basic metals	Grey
C25	Manufacture of fabricated metal products, except machinery and equipment	Green
C26	Manufacture of computer, electronic and optical products	Green
C27	Manufacture of electrical equipment	Green
C28	Manufacture of machinery and equipment n.e.c.	Green
C29	Manufacture of motor vehicles, trailers and semi-trailers	Grey
C30	Manufacture of other transport equipment	Green
C31_C32	Manufacture of furniture and other manufacture	Green
C33	Repair and installation of machinery and equipment	Green

Table 5. Summary Statistics – CIS2008

Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
dEXP	3,060	0.724	0.447	0	1
dEnvInno	2,709	0.538	0.499	0	1
EnvTax	2,662	0.304	0.460	0	1
EnvRegGreen	2,662	0.148	0.355	0	1
EnvRegGrey	2,662	0.046	0.210	0	1
EnvRegBrown	2,662	0.110	0.314	0	1
Prod	3,060	-0.153	2.117	-5.555	7.368
dsmall	3,060	0.396	0.489	0	1
dmedium	3,060	0.364	0.481	0	1
dlarge	3,060	0.240	0.427	0	1
ds1	3,060	0.094	0.292	0	1
ds2	3,060	0.048	0.213	0	1
ds3	3,060	0.097	0.296	0	1
ds4	3,060	0.180	0.384	0	1
ds5	3,060	0.132	0.339	0	1
ds6	3,060	0.345	0.475	0	1
ds7	3,060	0.104	0.305	0	1
DemandPull	2,662	0.227	0.419	0	1
GovIncentives	2,662	0.059	0.236	0	1
WithinCO	2,773	0.115	0.319	0	1
Green	3,060	0.104	0.305	0	1
Grey	3,060	0.487	0.500	0	1
Brown	3,060	0.409	0.492	0	1

Table 6. Summary statistics – CIS2014

Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
dEXP	2,987	.7291597	.4444682	0	1
dEnvInno	2,485	.5637827	.4960149	0	1
EnvTax	2,252	.3552398	.4786922	0	1
EnvTaxGreen	2,252	.1181172	.3228186	0	1
EnvTaxGrey	2,252	.1056838	.3075008	0	1
EnvTaxBrown	2,252	.0870337	.2819471	0	1
DemandPull	2,249	.3877279	.4873403	0	1
GovIncentives	2,250	.3075556	.461584	0	1
Prod	2,624	-.0984304	212.282	-6.394	6.494
dsmall	2,987	.4405758	.4965393	0	1
dmedium	2,987	.3157014	.4648724	0	1
dlarge	2,987	.2437228	.4293993	0	1
ds1	2,987	.0920656	.289167	0	1
ds2	2,987	.0579176	.2336268	0	1
ds3	2,987	.0284566	.1663013	0	1
ds4	2,987	.0254436	.1574945	0	1
ds5	2,987	.029461	.1691231	0	1
ds6	2,987	.0575829	.2329919	0	1
ds7	2,987	.0210914	.1437131	0	1
ds8	2,987	.0539002	.2258585	0	1
ds9	2,987	.0411784	.198736	0	1
ds10	2,987	.0334784	.1799123	0	1
ds11	2,987	.1121527	.315607	0	1
ds12	2,987	.1014396	.3019604	0	1
ds13	2,987	.0535655	.2251958	0	1
ds14	2,987	.1201875	.3252351	0	1
ds15	2,987	.0398393	.1956143	0	1
ds16	2,987	.0190827	.1368386	0	1
ds17	2,987	0	0	0	0
ds18	2,987	.0498828	.2177393	0	1
Green	2,987	.3649146	.4814868	0	1
Grey	2,987	.2936056	.4554896	0	1
Brown	2,987	.2206227	.4147359	0	1

Table 7.1 Correlation matrix – CIS2008

	dEXP	*EnvTax*	*EnvTaxGreen*	*EnvTaxGrey*	*EnvTaxBrown*	*dEnvInno*	*Prod*	*WithinCO*	*DemandPull*	*GovIncentives*
dEXP	1									
EnvTax	0.106	1								
EnvTaxGreen	0.121	0.557	1							
EnvTaxGrey	0.036	0.291	-0.070	1						
EnvTaxBrown	-0.019	0.460	-0.111	-0.058	1					
dEnvInno	0.104	0.318	0.132	0.114	0.179	1				
Prod	0.345	0.234	0.141	0.069	0.109	0.244	1			
WithinCO	0.155	0.179	0.152	0.009	0.061	0.178	0.386	1		
DemandPull	0.144	0.340	0.233	0.091	0.123	0.300	0.225	0.251	1	
GovIncentives	0.030	0.218	0.086	0.121	0.131	0.154	0.092	0.129	0.251	1

Table 7.2 Correlation matrix – CIS2014

	dEXP	*EnvTax*	*EnvTaxGreen*	*EnvTaxGrey*	*EnvTaxBrown*	*dEnvInno*	*Prod*	*DemandPull*	*GovIncentives*
dEXP	1								
EnvTax	0.102	1							
EnvTaxGreen	0.123	0.517	1						
EnvTaxGrey	0.027	0.440	-0.132	1					
EnvTaxBrown	-0.045	0.440	-0.132	-0.112	1				
dEnvInno	0.112	0.306	0.137	0.124	0.167	1			
Prod	0.285	0.218	0.108	0.110	0.109	0.248	1		
DemandPull	0.144	0.519	0.302	0.203	0.217	0.313	0.215	1	
GovIncentives	0.060	0.589	0.316	0.256	0.267	0.260	0.121	0.556	1

Table 8.1 Test for Environmental Innovation Instruments: GovIncentives, DemandPull and WithinCO – CIS2008

	1	**2**
First stage		
Test for excluded instruments	F (3, 2556)= 55.11***	F(3, 2554) = 55.30***
H_0: the endogenous regressor is unidentified		
Underidentification test		
H_0: matrix of reduced form coefficients has rank=K1-1		
Kleinbergen-Paap rank LM statistic	chi2 (3) = 133.56***	chi2 (3) = 134.24***
Weak-instrument robust inference		
H_0: the endogenous regressor coefficient is equal to 0 and the overidentifying restrictions are valid		
Anderson-Rubin Wald test	F (3, 2556) = 1.88	F (3, 2554) = 1.85
Anderson-Rubin Wald test	Chi2 (3) =5.68	chi2 (3) = 5.57
Stock-Wright LM S statistic	Chi2 (3) = 5.61	chi2 (3) = 5.51
Second stage		
Overidentification test		
H_0: the instruments are valid instruments and are uncorrelated with error term		
Hansen J statistic	Chi2 (3) = 2.31	chi2 (3) = 2.25
N. observations	2570	2570
N. regressors	12	14
N. endogenous regressors	1	1
N. instruments	14	16
N. of excluded instruments	3	3

Specification: The model specifications use different variables for the environmental regulation: 1. EnvTax; 2. EnvTaxGreen, EnvTaxGrey, EnvTaxBrown.

Table 8.2 Test for Environmental Innovation Instruments: GovIncentives and DemandPull – CIS2014

	1	**2**
First stage		
Test for excluded instruments	F (2, 1895) = 32.79***	F (1, 1896) = 60.36***
H_0: the endogenous regressor is unidentified		
Underidentification test		
H_0: matrix of reduced form coefficients has rank=K1-1		
Kleinbergen-Paap rank LM statistic	chi2 (2) = 62.60***	chi2 (1) = 56.28***
Weak-instrument robust inference		
H_0: the endogenous regressor coefficient is equal to 0 and the overidentifying restrictions are valid		
Anderson-Rubin Wald test	F (2, 1895) = 3.97**	F (1, 1896) = 5.43**
Anderson-Rubin Wald test	chi2 (2) =8.02**	chi2 (1) =5.50**
Stock-Wright LM S statistic	chi2 (2) = 8.19**	chi2 (1) = 5.64**
Second stage		
Overidentification test		
H_0: the instruments are valid instruments and are uncorrelated with error term		
Hansen J statistic	chi2 (1) = 2.27	Eq. exactly identified
N. observations	1917	1919
N. regressors	21	23
N. endogenous regressors	1	1
N. instruments	22	23
N. of excluded instruments	2	1

Specification: The model specifications use different variables for environmental regulation: 1. EnvTax; 2. EnvTaxGreen, EnvTaxGrey, EnvTaxBrown (no GovIncentives).

Table 9. Probit Estimation, Bivariate Probit Estimation and Maximum Simulated Likelihood Estimation of Endogenous Switching Model CIS2008-CIS2014

	CIS2008			**CIS2014**		
	Probit	**Bivariate Probit**	**ESM**	**Probit**	**Bivariate Probit**	**ESM**
	Model 1					
	b/se					
dEXP						
dENVINNO	0.099	0.735***	0.573***	0.015	0.963***	0.951***
	(0.061)	(0.176)	(0.206)	(0.075)	(0.324)	(0.190)
EnvTax	0.066	-0.121	-0.058	0.051	-0.194*	-0.182**
	(0.075)	(0.086)	(0.090)	(0.079)	(0.109)	(0.082)
dsmall	0.403**	0.491***	0.468***	0.397**	0.350*	0.354*
	(0.161)	(0.159)	(0.157)	(0.198)	(0.193)	(0.188)
dmedium	0.359***	0.412***	0.388***	0.411***	0.337**	0.342**
	(0.118)	(0.117)	(0.118)	(0.149)	(0.151)	(0.145)
Prod	0.398***	0.367***	0.375***	0.402***	0.314***	0.317***
	(0.035)	(0.037)	(0.035)	(0.049)	(0.066)	(0.046)
dENVINNO						
EnvTax	0.531***	0.530***	0.526***	0.545*	0.404***	0.401***
	(0.069)	(0.069)	(0.069)	(0.322)	(0.083)	(0.086)
DemandPull	0.713***	0.720***	0.724***	0.026	0.509***	0.511***
	(0.072)	(0.071)	(0.072)	(0.282)	(0.078)	(0.079)
GovIncentives	0.472***	0.456***	0.464***	0.461	0.128	0.128
	(0.145)	(0.143)	(0.135)	(0.349)	(0.093)	(0.091)
WithinCO	0.223**	0.228**	0.229**			
	(0.104)	(0.102)	(0.098)			
dsmall	-0.384***	-0.383***	-0.384***	0.525	0.038	0.036
	(0.139)	(0.138)	(0.138)	(0.701)	(0.171)	(0.170)
dmedium	-0.207**	-0.207**	-0.205**	-0.157	0.055	0.054
	(0.101)	(0.100)	(0.099)	(0.469)	(0.127)	(0.125)
Prod	0.061**	0.061**	0.061**	0.321**	0.175***	0.174***
	(0.028)	(0.028)	(0.029)	(0.142)	(0.035)	(0.035)
dEXP						
N. of Observations	2640			1924		
Log PseudoLikelihood	-1242.19			-837.93		
Wald Chi2	500.38***			367.93***		
dEnvInno						
N. of Observations	2570			1927		
Log PseudoLikelihood	-1524.31			-1077.08		
Wald Chi2	377.85***			311.74***		
dEXP						
N. of Observations		2570	3060		1917	2987
Log Likelihood		-2720.64	-2763.93		-1909.86	-1912.17
Rho		-0.407***	-0.313**		-0.586**	-0.580***
Wald chi2		1032.58***	1025.59***		935.43***	1029.44***

*Note: Significance levels: *** 0.01, ** 0.05, * 0.1; sector dummies are considered but not reported*

Table 10. Maximum Simulated Likelihood Estimation of Endogenous Switching Model and Bivariate Probit Model by environmental taxation distinguished by emission intensity – CIS2008 and CIS2014

	CIS2008		**CIS2014**	
	ESM	**Bivariate Probit**	**ESM**	**Bivariate Probit**
	Model 2			
	b/se			
dEXP				
dENVINNO	0.562***	0.731***	0.965***	0.929***
	(0.206)	(0.175)	(0.183)	(0.348)
EnvTaxGreen	0.072	0.024	-0.092	-0.077
	(0.121)	(0.118)	(0.139)	(0.157)
EnvTaxGrey	0.122	0.007	-0.153	-0.171
	(0.191)	(0.189)	(0.127)	(0.154)
EnvTaxBrown	-0.263**	-0.325**	-0.244*	-0.236
	(0.126)	(0.127)	(0.143)	(0.156)
dsmall	0.467***	0.489***	0.368**	0.368*
	(0.157)	(0.160)	(0.187)	(0.194)
dmedium	0.394***	0.418***	0.351**	0.353**
	(0.118)	(0.117)	(0.145)	(0.154)
Prod	0.378***	0.369***	0.316***	0.318***
	(0.035)	(0.037)	(0.045)	(0.068)
dENVINNO				
EnvTaxGreen	0.368***	0.370***	0.408***	0.408***
	(0.094)	(0.096)	(0.116)	(0.116)
EnvTaxGrey	0.659***	0.674***	0.445***	0.455***
	(0.177)	(0.184)	(0.133)	(0.131)
EnvTaxBrown	0.704***	0.706***	0.575***	0.576***
	(0.117)	(0.121)	(0.143)	(0.141)
DemandPull	0.729***	0.725***	0.553***	0.555***
	(0.072)	(0.071)	(0.074)	(0.077)
GovIncentives	0.442***	0.435***		
	(0.136)	(0.143)		
WithinCO	0.229**	0.229**		
	(0.097)	(0.102)		
dsmall	-0.380***	-0.379***	0.368**	0.024
	(0.138)	(0.138)	(0.187)	(0.172)
dmedium	-0.208**	-0.210**	0.351**	0.047
	(0.099)	(0.100)	(0.145)	(0.127)
Prod	0.061**	0.061**	0.316***	0.173***
	(0.028)	(0.028)	(0.045)	(0.036)
dEXP				
N. of Observations	3060	2570	2987	1919
Log Likelihood	-2758.61	-2715.58	-1919.40	-1912.16
Rho	-0.305**	-0.403***	-0.591***	-0.568***
Wald chi2	1026.24***	1027.98***	1048.77***	928.16***

*Note. Significance levels: *** 0.01, ** 0.05, * 0.1; sector dummies are considered but not reported.*

Table 11.1 Maximum Simulated Likelihood Estimation of Endogenous Switching Model and Bivariate Probit by environmental taxation distinguished by emission intensity – CIS2008 and CIS2014 – Small Firms

	CIS2008				**CIS2014**			
	ESM		**Bivariate Probit**		**ESM**		**Bivariate Probit**	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 3
	b/se				b/se			
dEXP								
dENVINNO	0.218	0.229	0.321	0.324	0.083	0.073	0.248	0.320
	(0.335)	(0.335)	(0.405)	(0.414)	(0.547)	(0.556)	(0.740)	(0.638)
EnvTax	0.123		0.077		0.115		0.058	
	(0.158)		(0.175)		(0.204)		(0.260)	
EnvTaxGreen		0.149		0.108		0.132		0.058
		(0.180)		(0.186)		(0.248)		(0.259)
EnvTaxGrey		0.422		0.299		0.212		0.124
		(0.295)		(0.314)		(0.259)		(0.281)
EnvTaxBrown		-0.102		-0.101		0.065		-0.044
		(0.246)		(0.272)		(0.315)		(0.344)
Prod	0.383***	0.383***	0.384***	0.385***	0.413***	0.412***	0.400***	0.394***
	(0.046)	(0.046)	(0.052)	(0.053)	(0.069)	(0.069)	(0.084)	(0.080)
dENVINNO								
EnvTax	0.597***		0.598***		0.435***		0.437***	
	(0.116)		(0.117)		(0.141)		(0.140)	
EnvTaxGreen		0.368**		0.369**		0.436**		0.435**
		(0.156)		(0.160)		(0.185)		(0.186)
EnvTaxGrey		0.608**		0.614**		0.584***		0.584***
		(0.268)		(0.283)		(0.202)		(0.200)
EnvTaxBrown		1.017***		1.015***		1.024***		1.015***
		(0.220)		(0.223)		(0.248)		(0.243)
DemandPull	0.638***	0.653***	0.639***	0.653***	0.426***	0.541***	0.433***	0.542***
	(0.119)	(0.121)	(0.118)	(0.120)	(0.133)	(0.118)	(0.136)	(0.117)
GovIncentives	0.352*	0.270	0.308	0.266	0.288*		0.278	
	(0.206)	(0.205)	(0.223)	(0.227)	(0.156)		(0.169)	
WithinCO	0.313	0.363*	0.344	0.356				
	(0.203)	(0.206)	(0.237)	(0.236)				
Prod	-0.001	-0.003	-0.001	-0.003	0.165***	0.162***	0.165***	0.162***
	(0.044)	(0.045)	(0.045)	(0.044)	(0.054)	(0.054)	(0.054)	(0.054)
N. of Observations	1213	1213	1066	1066	1316	1316	889	891
Log Likelihood	-1326.09	-1321.05	-1306.83	-1303.23	-1032.17	-1030.65	-1030.86	-1029.58
Rho	-0.151	-0.124	-0.214	-0.216	-0.005	-0.001	-0.106	-0.152
Wald chi2	274.80	281.062***	268.90***	268.96***	332.74***	334.38***	345.70***	363.87***

*Note. Significance levels: *** 0.01, ** 0.05, * 0.1; sector dummies are considered but not reported.*

Table 11.2 Maximum Simulated Likelihood Estimation of Endogenous Switching Model and Bivariate Probit by environmental taxation distinguished by emission intensity – CIS2008 and CIS2014 – Medium firms

	CIS2008				CIS2014			
	ESM		**Bivariate Probit**		**ESM**		**Bivariate Probit**	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
	b/se				b/se			
dEXP								
dENVINNO	0.813**	0.819**	1.049***	1.054***	0.875***	0.879***	1.445**	1.678***
	(0.340)	(0.341)	(0.249)	(0.247)	(0.157)	(0.156)	(0.562)	(0.083)
EnvTax	-0.195		-0.293**		-0.333**		-0.455***	
	(0.146)		(0.133)		(0.131)		(0.165)	
EnvTaxGreen		-0.068		-0.141		-0.405*		-0.447**
		(0.210)		(0.200)		(0.229)		(0.209)
EnvTaxGrey		0.016		-0.087		-0.138		-0.503***
		(0.321)		(0.315)		(0.210)		(0.162)
EnvTaxBrown		-0.361*		-0.479***		-0.383*		-0.450**
		(0.186)		(0.185)		(0.220)		(0.191)
Prod	0.471***	0.469***	0.459***	0.457***	0.350***	0.350***	0.338***	0.278***
	(0.065)	(0.066)	(0.068)	(0.068)	(0.074)	(0.076)	(0.128)	(0.064)
dENVINNO								
EnvTax	0.596***		0.605***		0.317**		0.335***	
	(0.110)		(0.110)		(0.143)		(0.125)	
EnvTaxGreen		0.530***		0.534***		0.524**		0.514***
		(0.159)		(0.165)		(0.208)		(0.199)
EnvTaxGrey		0.666**		0.686**		0.221		0.100
		(0.284)		(0.299)		(0.208)		(0.167)
EnvTaxBrown		0.646***		0.657***		0.249		0.338
		(0.176)		(0.174)		(0.228)		(0.207)
DemandPull	0.901***	0.903***	0.889***	0.890***	0.584***	0.641***	0.529***	0.536***
	(0.117)	(0.118)	(0.118)	(0.119)	(0.130)	(0.125)	(0.129)	(0.094)
GovIncentives	0.415*	0.403*	0.412*	0.399	0.141		0.089	
	(0.218)	(0.220)	(0.240)	(0.243)	(0.145)		(0.182)	
WithinCO	0.127	0.127	0.133	0.135				
	(0.175)	(0.175)	(0.179)	(0.178)				
Prod	0.068	0.068	0.068	0.067	0.350***	0.143**	0.112*	0.095
	(0.048)	(0.048)	(0.048)	(0.048)	(0.074)	(0.063)	(0.063)	(0.059)
N. of Observations	1114	1114	978	978	943	943	652	652
Log Likelihood	-1021.47	-1020.36	-998.41	-997.08	-620.82	-621.65	-610.65	-608.96
Rho	-0.394*	-0.401*	-0.526***	-0.532***	-0.617***	-0.619***	-0.908	-1***
Wald chi2	328.47***	331.68***	356.94***	356.66***	248.62***	245.67***	1687.69***	-

*Note. Significance levels: *** 0.01, ** 0.05, * 0.1; sector dummies are considered but not reported*

Table 31.3 Maximum Simulated Likelihood Estimation of Endogenous Switching Model and Bivariate Probit by environmental taxation distinguished by emission – CIS2008 and CIS2014 – Large Firms

	CIS2008				**CIS2014**	
	ESM		**Bivariate Probit**		**Bivariate Probit**	
	Model 1	Model 2	Model 1	Model 2	Model 1	Model 2
	b/se				b/se	
dEXP						
dENVINNO	1.033*	0.998**	1.110***	1.109***	1.504***	1.420***
	(0.556)	(0.476)	(0.342)	(0.362)	(0.426)	(0.396)
EnvTax	-0.055		-0.074		0.108	
	(0.179)		(0.173)		(0.222)	
EnvTaxGreen		0.193		0.178		0.588*
		(0.296)		(0.292)		(0.341)
EnvTaxGrey		-0.404		-0.409		-0.396
		(0.416)		(0.398)		(0.567)
EnvTaxBrown		-0.131		-0.165		-0.034
		(0.261)		(0.256)		(0.371)
Prod	0.133	0.128	0.123*	0.115*	0.231**	0.246**
	(0.083)	(0.083)	(0.066)	(0.067)	(0.112)	(0.116)
dENVINNO						
EnvTax	0.289**		0.290**		0.424**	
	(0.142)		(0.139)		(0.178)	
EnvTaxGreen		0.125		0.126		0.248
		(0.188)		(0.186)		(0.259)
EnvTaxGrey		1.051*		1.050*		0.831**
		(0.546)		(0.553)		(0.368)
EnvTaxBrown		0.358		0.356		0.505
		(0.247)		(0.248)		(0.352)
DemandPull	0.573***	0.593**	0.575***	0.595***	-0.053	0.608***
	(0.153)	(0.155)	(0.147)	(0.148)	(0.218)	(0.165)
GovIncentives	1.224**	1.241**	1.224***	1.242***	0.638***	
	(0.497)	(0.505)	(0.462)	(0.453)	(0.182)	
WithinCO	0.228	0.234	0.230	0.238		
	(0.152)	(0.153)	(0.152)	(0.153)		
Prod	0.179***	0.189**	0.178***	0.187***	0.273***	0.267***
	(0.066)	(0.065)	(0.060)	(0.060)	(0.077)	(0.077)
N. of Observations	733	733	526	526	376	376
Log Likelihood	-387.02	-384.94	-385.35	-383.27	-207.18	-204.66
Rho	-0.511*	-0.488*	-0.548***	-0.545**	-0.823***	-0.768***
Wald chi2	166.70***	117.16***	162.96***	160.58***	9557.26***	8096.53***

*Note. Significance levels: *** 0.01, ** 0.05, * 0.1; sector dummies are considered but not reported. For CIS2014, estimates through ESM cannot be reported due to convergence issues.*

Appendix B – Mathematical derivation of industry equilibrium

We look for the value of domestic cut-off for dirty-type firms such that the industry is in equilibrium, so the zero profit condition (8) and the free entry condition (9) have to be satisfied. We can write δf_e as follows

(B1) $$\delta f_e = f_d k(DD)[1-G(DD)] + f_d^* k(DF)[1-G(DF)] + \Delta f k(\tilde{\varphi})[1-G(\tilde{\varphi})]$$

where

(B2) $$k(i) = \left[\frac{\bar{\varphi}(i)}{i}\right]^{\varepsilon-1} - 1 \qquad i = DD, DF, \tilde{\varphi}$$

(B3) $$\bar{\varphi}(i) = \left[\frac{1}{1-G(i)}\int_i^{\infty} \varphi^{\varepsilon-1} g(\varphi) d\varphi\right]^{\frac{1}{\varepsilon-1}}$$

(B4) $$\Delta f = f_c + f_c^* - f_d - f_d^*$$

Let define $J(i) \equiv k(i)[1-G(i)]$. Following Melitz (2003), we can demonstrate that $J(i) > 0$ and $J'(i) < 0$.
By substituting $J(i)$ into Equation (B1), we obtain

(B5) $$\delta f_e = f_d\, J(DD) + f_d^*\, J(DF) + \Delta f\, J(\tilde{\varphi}\,)$$

By differentiating Equation (B5) with respect to t, we can study the effect of a change of the environmental tax on DD

(B6) $$\frac{d\delta f_e}{dt} = f_d\, J'(DD)\frac{dDD}{dt} + f_d^*\, J'(DF)\frac{dDF}{dt} + \Delta f\, J'(\tilde{\varphi}\,)\frac{d\tilde{\varphi}}{dt} = 0$$

Firstly, we calculate $\frac{dDF}{dt}$ and $\frac{d\tilde{\varphi}}{dt}$, that represent the derivative of (4) and (7) with respect to t.

(B7) $$\frac{dDF}{dt} = \tau \left(\frac{f_d^*}{f_d}\right)^{\frac{1}{\varepsilon-1}} \frac{dDD}{dt}$$

(B8) $$\frac{d\tilde{\varphi}}{dt} = \frac{dDD}{dt}\,\frac{\tilde{\varphi}}{DD} - \frac{\tilde{\varphi}}{1+t}\, a$$

where $a = \frac{1}{1 - \left[\frac{c(1+t)}{c_C}\right]^{\varepsilon}}$. The obtained values are substituted in equation (B6) and we get

$$\text{(B9)} \qquad \frac{dDD}{dt} = \frac{DD}{1+t}\, a\, b$$

where $b = \frac{\Delta f\, J'(\tilde{\varphi})\, \tilde{\varphi}}{f_d\, J'(DD)\, DD + f_d^{*}\, J'(DF)\, DF + \Delta f\, J'(\tilde{\varphi})\, \tilde{\varphi}}$.

It is easy to show that Equation (B9) is positive. Since $a > 0$ and $0 < b < 1$, then the derivative $\frac{dDF}{dt} > 0$ too.

As regards to the effect of t on the adoption cut-off $\tilde{\varphi}$, we have to calculate the derivative of $\tilde{\varphi}$ with respect to t.

$$\text{(B10)} \qquad \frac{d\tilde{\varphi}}{dt} = \frac{\tilde{\varphi}}{1+t}\, a\, [b - 1]$$

Since $0 < b < 1$, this derivative is negative.

Scale, composition and technique effects: a decomposition and empirical analysis of greenhouse gases and acidifying gases in European Union countries

1. Introduction

In the last four decades, the environmental issues have become a worldwide problem and countries have started to implement green policies in order to preserve resources, vegetation and ecosystems through a sustainable development. In this scenario, two important aspects have been underlined. On one hand, air pollution has always represented a priority for countries because of their negative effects on human health. These effects are extremely harmful in some areas where a huge quantity of greenhouse gases (GHG) and, especially, acidifying gases (AG) is emitted. For this reason, many environmental policies aim at reducing the emissions of these air pollutants. On the other hand, a crucial role in reinforcing the importance of global emissions has been played by the European Union (EU), which represents one of the most important geographical and political regions in terms of size and economic position. Since 1973, with the first European Environment Action Programme, EU has been developing its own environmental policy structure with the implementation of many directives, gaining a global influence in the sustainability process worldwide. In view of these highly relevant aspects, this paper aims at investigating the role of different economic aspects - such as income, trade openness, capital-labour endowments and investment in green technologies and renewable energy - on the well-known *scale*, *composition* and *technique* effects for 23 EU countries in 2008-2015 period.

The existing literature has underlined that the environmental degradation and the increasing air pollution have been affected by different causes. Since

1991, when Grossman and Krueger pointed out the inverted-U relationship between income and environmental emissions (Environmental Kuznets Curve - EKC)[49], economists have conducted many theoretical and empirical studies on the possible drivers of this relation. They have found that changes in emissions seem to depend on different economic factors related to a country level of development, such as trade openness, innovation and environmental regulation, [Shafik and Bandyopadhyay (1992), Selden and Song (1995), Andreoni and Levinson (2001)][50]. Specifically, Grossman and Krueger (1991) have identified three effects: scale, composition and technique effect. The *scale* effect is connected to the economic activity at country level. If countries increase their output over time, they subsequently generate a higher level of emissions, holding all other factors constant. This result is enlarged if international trade is free. The *composition* effect is related to changes in countries' sectoral composition. In other words, an increase of the economic activity brings countries to specialize in more advanced, and cleaner, sectors. The effect on emissions will be either positive or negative depending on the sources of comparative advantage driving international flows of goods and services. Grossman and Krueger (1991) state that the net impact of this trade effect on emissions depends on the prevailing comparative advantage factor. If comparative advantage comes from an environmental regulation, countries invest in cleaner sectors and transfer the production related to more polluting ones in countries with less stringent regulation. This reduces the level of emissions in the referring country. Otherwise, if comparative advantage is related to factor endowments, the overall impact of free trade on pollution cannot be exactly recorded: capital abundant countries specialize in sectors that are capital-intensive, which are generally more polluting; labour abundant countries specialize in labour-intensive sectors, that are less polluting than capital intensive ones. Finally,

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[49] For deep reviews on EKC see Dasgupta et al. (2002), Stern (2004), Dinda (2004) and Carson (2010). For a meta-analysis refer to Sarkodie and Strezov (2019).

[50] As underlined by several reviews on this topic, more recent researches have not confirmed the validity of EKC hypothesis, so that the relation between environmental pollution and economic activity level could not be represented by an inverted U-shaped curve. Other types of relations can be obtained, such as monotone, N-shaped or U-shaped curves. Results relate to many aspects, such as the measure of environmental degradation, the implemented empirical strategy, the used dataset and the analysed period.

the *technique* effect is connected with technological progress. Specifically, with sustained economic growth countries will more likely invest resources in green technologies, which are generally less polluting than older ones. This improvement will lower the overall level of air pollution. This positive impact is amplified by income levels and trade liberalization, as in the composition effect. The higher is income level, interpreted as a measure of life quality, the larger is demand for environmental-friendly products. This demand driven effect is fostered by free trade. In turn, the increasing demand for green goods is usually combined with a stronger awareness of pollution issues entailing growing political pressure for the introduction of new and more stringent environmental policies. As a consequence, firm propensity of adopting emission abatement technologies will increase. Moreover, a direct effect of openness on the technique effect may come from a further source of comparative advantage connected to technological differences across countries.

Another relevant strand of the literature has studied scale, composition and technique effects. By using the Logarithmic Mean Divisia method, a decomposition analysis of the emission levels has been done for several countries. De Bruyn (1997) has analyzed Dutch and West Germany data; Viguier (1999) has considered some East European countries (Hungary, Poland and Russia), France and United Kingdom; Bruvoll and Medin (2003) have used Norwegian data. These works, by using statistical or empirical analysis, commonly agree on the crucial role played by the interaction among technology adoption and economic growth on the level of air pollutants emissions.

The fundamental contribution of this paper is to analyse the effect of different economic factors on scale, composition and technique effects. The existing literature has estimated the effect of economic factors, such as income, trade openness, capital-labour endowments and investment in green technologies and renewable energy, on the overall amount of emissions by using the EKC relationship. By allowing heterogeneous coefficients by components, we can better understand how and to what extent each economic factor has driven air emissions. Thus, some precise policy insights toward a more sustainable growth will be formulated. Furthermore, since our data refer to 2008-2015 years, we can study how the 2008 international crisis has influenced emissions and economic factors dynamics.

The paper is organized as follows. Section 2 reports the decomposition methodology, respectively. In Section 3, a detailed analysis of air emission decomposition results is conducted. Section 4 describes the econometric framework for the analysis of scale, composition and technique effects and data description. In Section 5, results are reported. In Section 6, a brief discussion of results is presented and Section 7 concludes with some policy implications.

2. Decomposition Methodology

Considering the increasing importance of air pollution and the high number of environmental policies that aim at reducing air pollution, this work analyses the different impact of scale, composition and technique effects on GHG and AG emissions. In order to conduct our research, emissions have been decomposed through an index decomposition analysis (IDA)[51]. By correctly approaching to the analysis, as a first step we have chosen the type of indicator to be decomposed. Since it can be easy to understand, we opt for the volume of aggregate country emissions as the measured indicator. Subsequently, as a second step, we have opted for Log Mean Divisia Index (LMDI) Method II, proposed by Ang et al. (1998), as decomposition method[52]. The basic idea of this approach is to decompose the differential change of the volume of emissions into three different influencing factors: economies of scale, sector's composition and technological differences. LMDI is a refined version of Arithmetic Mean Divisia Index and it has three important properties that make this index a suitable decomposition method. First, it satisfies factor reversal test, which means that the index gives a

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[51] For a detailed overview of decomposition methods see Hoeskstra et al (2003) and Ang and Zhang (2000).

[52] For a detailed guide on the implementation of LMDI decomposition analysis see Ang (2015).

decomposition without residuals, thus the interpretation of results is not defected. Second, time reversal test is also satisfied; this means that, given two periods, the result does not change if the index is measured forwards, from the first to the second period, or backwards, from the second to the first period. Third, LMDI allows for the accommodation of zero-values of the dataset. As Ang and Choi (1997) suggest, zeros are replaced by a small positive number[53].

Due to the nature of our data and the aim of the research, we implement, as suggested by Ang (2015), specification II with the multiplicative decomposition.

In order to analyse scale, composition and technique effects for GHG and AG emissions in a specific time period, the LMDI is constructed by considering the following set of variables

Y_{it}	Real Gross Value Added (GVA) in country *i* in year *t*
Y_{ijt}	Real GVA in country *i* in sector *j* in year *t*
E_{it}	Total volume of emissions in country *i* in year *t*
E_{ijt}	Volume of emissions in country *i* in sector *j* in year *t*
$S_{ijt} = \frac{Y_{ijt}}{Y_{it}}$	Share of sector *j* real GVA on total real GVA in country *i* in year *t*
$I_{it} = \frac{E_{it}}{Y_{it}} = \sum_j \frac{E_{ijt}}{Y_{it}}$	Total emissions intensity in country *i* in year *t*
$I_{ijt} = \frac{E_{ijt}}{Y_{ijt}}$	Emissions intensity in country *i* in sector *j* in year *t*

Changes of aggregate emissions between base period $t = 0$ and any period t in country *i* is calculated by the following multiplicative form

$$\frac{E_{it}}{E_{i0}} = Scale_{it} * Composition_{it} * Technique_{it} \tag{1}$$

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[53] In our dataset, zero-values on some sectoral-level emissions are replaced by 0.01, if the observation is equal to 0 every year, by the mean of previous and following year values and by the mean of the last three year if the 0 value refers to the last year of the analysis.

where $Scale_{it}$ represents the scale effect, which describes a *ceteris paribus* variation of economic activity, holding all the other factors constant. $Composition_{it}$ identifies the composition effect. This variable isolates the effect of changes in sector economic weight on environmental emissions when all other factors are fixed at their initial values. Finally, $Technique_{it}$ measures the technique effect as a change of emissions volume when the real GVA and sector economic weight are held constant to their initial values [Kisielewicz et al. (2016)].

By implementing the LMDI Method II, the three terms of Equation 1 can be expressed as

$$(2) \qquad Scale_i = \exp\left\{\sum_j \alpha_{ijt}\, ln\frac{Y_T}{Y_0}\right\}$$

$$(3) \qquad Composition_i = exp\left\{\sum_j \alpha_{ijt}\, ln\frac{S_{ijT}}{S_{ij0}}\right\}$$

$$(4) \qquad Technique_i = exp\left\{\sum_j \alpha_{ijt}\, ln\frac{I_{ijT}}{I_{ij0}}\right\}$$

where $\alpha_{ijt} = \frac{(E_{ijt}-E_{ij0})/(lnE_{ijt}-lnE_{ij0})}{(E_{it}-E_{i0})/(lnE_{it}-lnE_{i0})}$ represents the sector emissions logarithmic average change rate.

We use Eurostat data for EU countries from 2008 to 2015 to investigate the contribution of scale, composition and technique effects to total emission variation [54]. We focus on manufacturing sector only. Specifically, data include 19 NACE Rev. 2 manufacturing sectors at 2-digit level[55].

Focusing on air pollutants emissions, the decomposition analysis is conducted for two pollutants: the aggregate volume of GHG [carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)] and AG [sulfur oxide (SO_x), nitrogen oxide (NO_x) and ammonia (NH_3)] in thousand tonnes[56]. Emissions for GHG are expressed in CO_2 equivalent units, while emissions for AG in SO_2 equivalent units.

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[54] Excluded countries are Cyprus, Czech Republic, Ireland, Luxembourg and Malta, because of several missing observations in the time interval considered.

[55] See Table A1 in Appendix for a detailed description of sectors.

[56] Data on emissions are from Eurostat “Air emissions accounts by NACE Rev. 2 activity”.

Concerning the real GVA variable, it has been obtained as a ratio between the nominal GVA at current prices and the implicit price deflator by Nace Rev.2 sectors in 2010[57].

3. Decomposition of air pollutants

We use Eurostat data for EU countries from 2008 to 2015 to investigate the contribution of scale, composition and technique effects to total emission variation [58]. We focus on manufacturing sector only. Specifically, data include 19 NACE Rev. 2 manufacturing sectors at 2-digit level[59].

Focusing on air pollutants emissions, the decomposition analysis described in Section 2 is conducted for two pollutants: the aggregate volume of GHG [carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)] and AG [sulfur oxide (SO_x), nitrogen oxide (NO_x) and ammonia (NH_3)] in thousand tonnes[60]. Emissions for GHG are expressed in CO_2 equivalent units, while emissions for AG in SO_2 equivalent units. Concerning the real GVA variable, it has been obtained as a ratio between the nominal GVA at current prices and the implicit price deflator by Nace Rev.2 sectors in 2010[61].

We first describe the overall variation in GHG and AG in the after crisis period (2008-2015). We can see from Graphs 1 and 2 that the level of EU28 emissions, represented by the yellow line, has been decreasing, especially if we refer to GHG. The most drastic decline of emissions concentrated in 2009 for all countries, which can be highly correlated with the decrease of GVA in 2008. A limited increase of air pollution occurred in 2010, but then data have

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[57] Data on nominal GVA and prices come from Eurostat "National accounts aggregates by industry (up to NACE A*64)". Eurostat defines GVA as the "*output (at basic prices) minus intermediate consumption (at purchaser prices); it is the balancing item of the national accounts' production account. The sum of GVA over all industries or sectors plus taxes on products minus subsidies on products gives Gross Domestic Product*".

[58] Excluded countries are Cyprus, Czech Republic, Ireland, Luxembourg and Malta, because of several missing observations in the time interval considered.

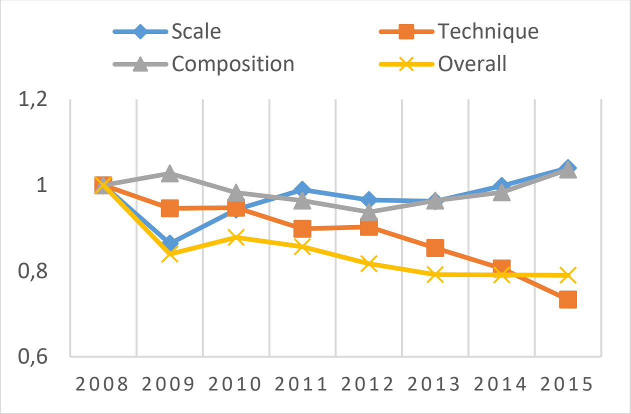
[59] See Table A1 in Appendix for a detailed description of sectors.

[60] Data on emissions are from Eurostat "Air emissions accounts by NACE Rev. 2 activity".

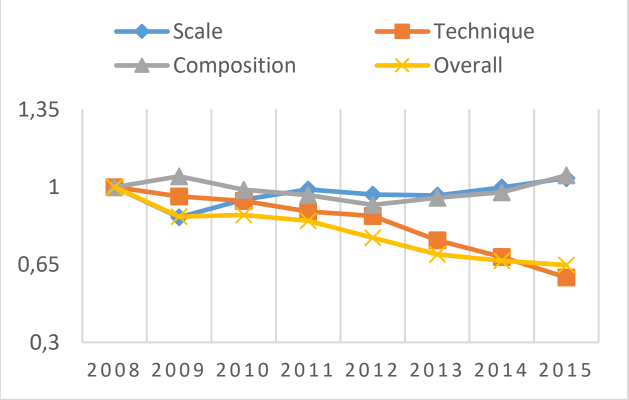
[61] Data on nominal GVA and prices come from Eurostat "National accounts aggregates by industry (up to NACE A*64)". Eurostat defines GVA as the "*output (at basic prices) minus intermediate consumption (at purchaser prices); it is the balancing item of the national accounts' production account. The sum of GVA over all industries or sectors plus taxes on products minus subsidies on products gives Gross Domestic Product*".

shown a decreasing trend since 2011. This result is in line with Kisielewicz et al. (2016), which have conducted a similar analysis for a shorter period (2008-2012). By looking at the three components obtained through the LMDI Method II decomposition described in Section 2, we can see that the scale effect has increased the overall volume of air emissions, while the composition effect has caused a decrease between 2008 and 2012 and an increase afterwards on emissions. Furthermore, the technique effect contributed to reducing the level of both GHG and AG as suggested by the literature.

Graph 1. GHG emissions decomposition 2008-2015 for EU28



Graph 2. AG emissions decomposition 2008-2015 for EU28



Since decomposition results are represented by indexes, we cannot make a direct comparison among countries, but we can only describe the contribute of each country on emissions in terms of variation. Specifically, by studying ranking results, differences on the overall emissions of GHG and AG between countries exist. Tables A2 shows that, for GHG, the smallest variation of overall effect refers to Estonia in 2010, which is equal to 0.525; while the highest is reported for Latvia (1.142) in the same period. As we can see from Table A3, concerning AG emissions, the lower value of the overall effect is the Croatian one (0.505) in 2014, while the highest has been registered in 2015 in Lithuania (1.083). In general, by studying time trends, we can classify EU countries into three groups[62]. As we can see from Table 1 ranking, a first group, which comprehends United Kingdom, Italy, France and Croatia, has reported a decrease of their level of emissions. This is verified for both GHG and AG. Denmark and Spain have recorded a decrease in AG emissions since 2013, while, concerning GHG, this positive trend is confirmed for Slovakia and Bulgaria. The second group, substantially formed by East European Union countries, such as Estonia, Hungary and Lithuania, refers to countries that recorded a worsen situation. These nations show a huge increase in air pollution. Finally, the last group is related to countries that have a constant level of GHG and AG emissions, such as Austria and Germany.

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[62] Detailed graphs by country are reported in Appendix B and C.

Table 1. Ranking of countries by overall effect, GHG and AG emissions in 2009-2015

	GHG							**AG**						
	2009	2010	2011	2012	2013	2014	2015	2009	2010	2011	2012	2013	2014	2015
Austria	20	21	22	22	22	19	22	21	22	20	21	20	19	20
Belgium	5	12	9	11	10	9	12	2	1	4	2	2	5	5
Bulgaria	2	3	1	1	1	.	1	22	18	23	22	22	.	21
Croatia	10	7	7	5	4	2	4	9	6	3	3	1	1	4
Denmark	14	8	16	17	16	13	.	4	7	5	5	3	3	.
Estonia	3	1	4	4	12	20	20	3	3	13	18	18	15	19
Finland	7	10	13	7	7	5	7	6	12	12	12	12	10	13
France	19	16	15	14	11	8	8	13	9	10	7	6	4	3
Germany	21	19	17	19	19	16	17	15	19	17	17	15	14	16
Greece	13	6	2	3	13	12	13	18	15	6	1	9	9	11
Hungary	11	9	14	13	15	15	19	10	14	16	16	14	13	15
Italy	12	13	12	6	2	.	3	12	13	11	6	4	.	1
Latvia	9	23	23	23	23	.	15	20	8	1	4	.	.	7
Lithuania	1	2	5	9	5	3	6	14	17	22	23	21	20	22
Netherland	23	22	21	20	21	17	21	5	5	8	10	8	6	6
Poland	15	17	20	21	20	18	18	17	16	19	19	17	18	18
Portugal	16	15	10	10	18	14	16	11	10	9	9	10	8	10
Romania	4	4	6	8	3	1	2	1	2	2	8	7	7	9
Slovakia	22	18	19	16	8	6	10	8	4	7	11	11	11	12
Slovenia	8	5	3	2	6	4	5	7	11	15	13	16	16	14
Spain	18	14	11	15	9	7	11	23	23	21	15	5	2	2
Sweden	6	20	18	18	17	11	14	19	21	18	20	19	17	17
United Kingdom	17	11	8	12	14	10	9	16	20	14	14	13	12	8

Note. Countries are ranked from the lowest to the highest overall effect. Year 2008 has been dropped from the table; it is the referring period

By analysing the three sub-indices, we can formulate some important conclusions[63]. First, concerning the impact of scale effect on GHG emissions, all countries have registered a decrease between 2008 and 2009 due to the economic crisis, which has reduced the level of GVA, but from 2010 to 2015, countries have behaved differently. A group of them (Austria, Croatia, France, Hungary, Italy, Netherland, Portugal, Slovenia, Sweden and United Kingdom) does not show evident changes in emissions related to scale effect. On the contrary, many Northern and Eastern EU countries (Belgium, Bulgaria, Denmark. Estonia, Germany, Latvia, Lithuania, Poland and Slovakia) have registered an increasing scale effect. This result is in line with empirical evidence on scale effect, which have demonstrated that an increase in country economic activity has been reflected by a growth of air emissions, holding all other factors constant. Moreover, Finland, Greece and Spain only have reported a decreasing scale effect. Among the other countries, Romania shows a peculiar situation; its scale effect has not a steady trend over the considered period. Results on scale effect are also confirmed for AG emissions. A second important result refers to composition effect. Most of the countries (Bulgaria, Croatia, France, Germany, Greece, Italy, Poland, Spain, Sweden and United Kingdom) have not registered substantial changes of their composition effect, but other countries have behaved differently. For example, considering GHG pollution, for Latvia, Belgium, Finland and Netherland we can observe an increasing composition effect. In Belgium, this negative effect on emissions is driven by an increase of specific sectors economic weight; specifically, manufacture of basic metal, coke and refined petroleum sectors, which are capital intensive, have contributed to an augmentation of total air emissions because their relative GVA has been grown. Considering the other countries (Austria, Denmark, Estonia, Hungary, Lithuania, Portugal, Slovenia and Slovakia), they have registered a decreasing composition effect. Specifically, if we study the structure of this effect, we can assert that the decline in GHG emissions especially depends

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[63] Specific scores on each sub-indexes are reported in Table A2.1-A2.3 and Table A3.1-A3-3 in Appendix A. Graphs related to each countries GHG and AG emissions decomposition are reported in Appendix B and C.

on a reduction of some sector economic weight. With reference to AG emissions, some countries, such as Germany and Italy, have shown a decreasing composition effect, so differences on sector composition among GHG and AG emissions exist. By analysing results as a whole, we can assert that standard factors of comparative advantage, such as factor endowments, play an important role on changes of air emissions over the time.

Finally, some conclusions have to be reported regarding the technique effect. Talking about GHG emissions, a huge number of countries show a decreasing trend of technique effects. This result could be correlated with the introduction of new or improved technologies that aim at reducing pollution. Nevertheless, the highest number of countries have a positive effect on emissions through technological progress, other countries, such as Greece, Hungary and Portugal, have reported a negative trend of technique effect. By analysing our data, we can affirm that this increase in emissions due to innovation depends on higher emissions intensity of some sectors. Furthermore, some particular situations have been underlined. From 2012 to 2014, Austria has registered a radical increase of technique effect for GHG emissions then suddenly declines. This behaviour seems to be related to the economic activity of some sectors; indeed, some polluting industries (manufacture of basic metals, motor vehicles, trailers and machinery) have increased their GVA level. Considering AG emissions, Bulgaria, Estonia, Germany and Greece have all an irregular trend of the technique effect from 2008 to 2015.

A specific description of the real drivers of these three effects cannot be done with a qualitative decomposition analysis only, so in the next section we give some insights by conducting an econometric analysis to quantitatively identify the economic factors that could affect scale, composition and technique effects.

4. Econometric Methodology

As shown by a large strand of the literature, the relationship between economic growth and environmental degradation is generally represented by an inverted U-shaped curve, which is defined Environmental Kuznets Curve (EKC). The increasing part of the curve is connected to the scale effect, which describes a growth of emissions due to the increasing level of output, while the decreasing part of EKC mainly refers to composition and technique effects, which bring to a reduction of environmental emissions thanks to cleaner technologies [Sarkodie and Strezov (2019)].

Since many studies have underlined that the shape of EKC can be affected by many factors, the analysis of the determinants of scale, composition and technique effects can by admitting heterogeneous coefficients can improve our knowledge of the forces behind GHG and AG emissions over time.

The econometric analysis has been conducted along three steps. As a first step, we estimate the classical EKC by adopting an Ordinary Least Squared (OLS) estimator with country specific effects for both air pollutants. Through the analysis conducted in Section 2, we have decomposed the emissions into scale, composition and technique effects. Given the decomposition equation (1), we can write emissions in country *i* in year *t* as

$$(5) \qquad E_{it} = E_{i0} * Scale_{it} * Composition_{it} * Technique_{it}$$

where E_{i0} captures the level of emission in year $t = 0$, given that $i = 1, \dots, 23$ is the number of panels and $t = 1, \dots, 6$ is the number of years. The estimated equation for EKC can be formulated as follows

$$(6) \qquad lnE_{it} = \boldsymbol{X_{it}\beta} + \alpha_i + v_t + \varepsilon_{it}$$

$\boldsymbol{X}_{it}$ is a vector of panel type independent variables, $\boldsymbol{\beta}$ is the vector of estimated coefficients; α_i is the country specific effect and v_t is the time fixed effect to capture both deterministic and stochastic time trends. ε_{it} are i.i.d. disturbances.

As a second step, since all effects (overall, scale, composition and technique) are expressed in terms of indexes, a direct comparison of them across countries cannot be done. Thus, taking natural logs and time-differences of (5), we get the air pollution emission identity expressed in terms of change rates:

$$(7) \qquad g_{it}^{tot} = g_{it}^{s} + g_{it}^{c} + g_{it}^{T}$$

where $g_{it}^{y} = \ln y_{it} - \ln y_{it-1}$ is the time difference between period t-1 and t for any component, with $y_{it} = \{E_{it}, Scale_{it}, Composition_{it}, Technique_{it}\}$. In addition, we need to transform equation (2) in first differences to get

$$(8) \qquad g_{it}^{E} = \Delta \boldsymbol{X_{it}\beta} + v_t + \varepsilon_{it}$$

Equation (8) is estimated through a Generalized Linear Model with a logit as the link function. This estimator is called non-linear Fractional Logit Model and is usually applied when the value of the dependent variable ranges between 0 and 1. Moreover, it allows us to overcome estimation issues related to OLS in the presence of non-normal distribution of residuals.

Finally, by implementing a Seemingly Unrelated Regression (SUR) estimation, we have estimated all components' change rates as follows:

$$(9) \qquad g_{it}^{s} = \alpha_1 + \Delta \boldsymbol{X_{it}\beta_1} + v_{1t} + \varepsilon_{1it}$$

$$(10) \qquad g_{it}^{c} = \alpha_2 + \Delta \boldsymbol{X_{it}\beta_2} + v_{2t} + \varepsilon_{2it}$$

$$(11) \qquad g_{it}^{T} = \alpha_3 + \Delta \boldsymbol{X_{it}\beta_3} + v_{3t} + \varepsilon_{3it}$$

$\Delta \boldsymbol{X}_{it}$ is the vector of time difference regressors corresponding to the set of panel type independent variables included in (2). $\boldsymbol{\beta_1}, \boldsymbol{\beta_2}$ and $\boldsymbol{\beta_3}$ are the vectors of estimated coefficients which are component-specific; v_{1t}, v_{2t} and v_{3t} are time fixed-effects; $\varepsilon_{1it}, \varepsilon_{2it}$ and ε_{3it} are serial correlated disturbances. We expect that both fixed (or random) effects disappear when estimating model specifications with time differences.

4.1 Data Description

Our dataset includes 23 panels, which refer to 23 EU countries and 8 years from 2008 to 2015. One observation is lost when calculating change rates. Data on GHG and AG emission change rates in terms of overall, scale, composition and technique effects have been obtained following the methodology presented in section 2 trough LMDI Method II technique, and by merging them with Penn World Table[64], Eurostat and OECD data. The vector of explanatory variables includes: $Income$, $PopDens$, KL, $Open$, $EcoInno$ and $Renew$.

First, we use one year lagged real GDP per capita as a measure of income per capita ($Income$). By accounting for a non-linear relationship between income and emissions, the squared term of this variable is also included ($Income^2$). Second, we introduce the capital-to-labour ratio to assess its endowment effect (KL). It is calculated by using data on capital stocks and number of workers engaged[65].

Another important driver of the EKC is represented by technological progress. Concerning this aspect, we consider the number of environmental-related developed inventions expressed in millions of residents ($EcoInno$) to measure eco-innovation[66]. This variable, which is a measure of green patents, have been chosen as measure of technological progress in line with some empirical studies, such as Chichilnisky (1994), that suggest this variable as a fundamental driver of economic progress. Thus, we expect an environmental emission decline by introducing new green technologies. Furthermore, following Choi et al. (2010), a variable related to renewable energy use is considered ($Renew$). This is calculated as a share of total final energy consumption in industry sector[67]. Since an increase in income can foster sectors towards a more efficient use of resources, it is expected that an increase of renewable energy use could reduce environmental degradation.

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[64] For a detailed description of Penn World Table dataset see Feenstra et al. (2015).

[65] Data on GDP, trade, capital and labour refer to Penn World Table.

[66] Data on eco-innovation refer to OECD dataset "Patent Indicators". The indicator is constructed by measuring inventive activity using OECD patent data.

[67] Data on renewable energy refer to Eurostat dataset "Simplified energy balances - annual data".

To account for some non-linear effects, squared terms of eco-innovation and renewables use variables have also been considered.

Among other relevant factors, there is international trade. Antweiler et al. (2001) has pointed out that, the impact of trade on EKC is twofold. On one hand, it increases emissions through the scale effect because it expands the economic activity of a country, which consequently increases pollution. On the other hand, trade positively affects environment through the technique effect; when income increases, consumers are more willing to pay more attention to environmental issues, thus governments have a higher incentive to introduce more stringent regulation, that in turn foster producers to adopt cleaner technology. The introduction of environmental policies could positively affect the EKC also through the composition effect. This effect captures the reduction of emissions related to a transfer of more polluting sectors production towards countries with lax policies. This mechanism usually decreases emissions, but the net effect of trade on pollution also depends on other factors of comparative advantage, which could negatively contribute to environmental pollution [Grossman and Krueger (1993), Copeland and Taylor (1994), Cole et al. (2003)].

The direct effect of trade on air pollution is measured by country trade intensity and squared country trade intensity [$Open$ and ($Open^2$)]. This covariate is constructed by summing up the share of exports and imports of merchandise on real GDP at current purchase power parity. Since trade could have an indirect impact on pollution through scale, composition and technique components (trade-induced effects), some interaction terms have been taken into account. These terms are obtained by multiplying trade intensity and relative values of each covariate[68]: $Open * RInc, Open * RKL, Open * REcoInno, Open * RRenew$. Finally, $PopDens$ measures the population density of country, so country's size effect is captured.

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[68] Relative values are shares of country values and EU average by year.

Table 2. Data Description

Variable	Description
Dependent Variables	
E_{it}	Total emission of air pollutant (in logs)
g_{it}^{tot}	Total emission change rate (see equations 5 and 6)
g_{it}^{s}	Emission change rate due to the scale effect (see equations 5 and 6)
g_{it}^{c}	Emission change rate due to the composition effect (see equations 5 and 6)
g_{it}^{T}	Emission change rate due to the technique effect (see equations 5 and 6)
Independent Variables (in logs)	
Income	Expenditure-side one year lagged real GDP per capita
KL	Capital to labour ratio. Ratio of capital stocks and number of engaged workers
EcoInno	Number of environmental-related developed inventions by millions of residents
Renew	Share of total final energy consumption in industry sector
Open	Country merchandise trade intensity [(EXP+IMP)/GDP at PPP]
Rvariable	Relative variable is a share of country *i* variable and EU average by year ($\ln y_{it} - \ln y_{EUt}$). Variable refers to income, capital-labour ratio, environmental-related inventions and final energy consumption.
PopDens	Density of country population

5. Results

We firstly tested the impact of all factors on total air emissions, as a benchmark of the well-established EKC relationship, using the econometric model (6). We have estimated two model specifications. As a first model [Model (1)], a basic model is constructed by including per capita income, population density, trade intensity, relative factor endowments, per capita eco-innovation and renewable energy use and the corresponding squared variables. A second model [Model (2)] is subsequently estimated by adding trade interaction variables. Then, by transforming the overall emissions into change rates, we estimate equation (8) using the same covariate sets, with explanatory variables expressed in first differences. Finally, the same model specifications are separately estimated for emissions change rates related to scale, composition and technique effects.

EKC and Overall Effect: By considering the EKC analysis, random and fixed effects estimations are reported into Table A4, for both GHG and AG level of emissions. It is necessary to specify that estimates of Model (1) and (2) on GHG are more robust and consistent by implementing a panel data random effects model, while, focusing on AG emissions, Model (1) requires fixed effects and Model (2) random effects[69].

As a first step, we analyse Model (1) results. As we can see from Column 1 and 7 of Table A4, the EKC hypothesis is not confirmed for both GHG and AG emissions. We cannot accept the null hypothesis for coefficients of income and squared income. However, air pollutants are driven by trade intensity. On one hand, GHG pollution increases if country openness rises; they are tied by a linear relationship and the corresponding coefficient (0.304) is positive and statistically significant (10%). On the other hand, AG emissions decrease when trade intensity increases. Furthermore, fixed effect estimation of AG gives some additional information. Emissions are affected by capital-to-labour ratio, which is highly significant (1%). As we can see from Column 7 of Table A4, the capital-labour effect is characterized by an inverted U-shaped relationship. KL has a positive coefficient, while squared KL is negative, thus an increase of capital-to-labour ratio increases emissions until a threshold point and then it oppositely contributes to a pollution decrease[70]. This variable may be connected to a change in sectoral composition of country economy, but you can confirm this prediction in next section. The increase of emissions for low levels of capital to labour endowments could depend on a specialization in more polluting sectors that increases the overall level of air pollution. The following positive effect underlines that, after a specific turning point, for each additional unit of KL, emissions start to decline.

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[69] Hausman Test results are available on request.

[70] This result is also confirmed if random effects estimation is conducted.

As a second step, we account for other variables and estimate Model (2). For both GHG and AG, fixed and random effects estimates give similar results. Concerning GHG emissions level, they are substantially driven by trade-induced interaction terms, except $Open * RInc$. The trade-induced effect of relative factors endowments is negative, so a unit increase in capital-to-labour ratio, relatively to the sample average, tends to reduce air pollution in response to trade. This result confirms the position of the literature, which suggests that a wealthier economy invests more on green sectors, for example because of the introduction of new legislation. Conversely, more polluting sectors have the incentive to move their activity towards countries with less stringent environmental regulation. This is also verified for AG emissions. Moreover, GHG are negatively and significantly affected by $Open * REcoInno$. The corresponding coefficient is equal to -0.102. An opposite interpretation can be made for $Open * RRenew$; its coefficient is positive and statistically significant. When AG emissions results are studied, it is possible to assert that the relationship with relative factors endowments underlined with the estimation of Model (1) is confirmed. Moreover, AG emissions are also driven by income levels; Columns 6 and 8 of Table A4 report a U-shape relation, which is statistically significant at 5%. This means that an expansion of incomes firstly reduces AG emissions, but, after a turning point level, emissions start rising.

By analysing the estimates on overall emissions change rate, obtained by a Generalized Linear Model (Table A5) estimation, none variable seems to have a significant effect. We comment estimated results for the three decomposed effects below.

Scale Effect: By examining Model (1), Column 1 and 7 of Table A6 shows that results for GHG and AG emissions are qualitatively similar. Concerning income change rates, the hypothesis of a U-shaped relationship is confirmed by data. Specifically, income coefficients are negative (-45.675 and -42.879), while squared income coefficients are positive (2.493 and 2.372). All values are statistically significant at 5%. This means that, for low levels of income variation, the more a country grows, the lower is the emission change due to the scale effect. After a specific value of income change rate (turning point), more growing economies will exhibit increasing emission change rates. By conducting a deeper analysis of other economic factors, Model (1) estimates show that changes in country trade openness plays a relevant role on scale component; both first differences of $Open$ and $Open^2$ have positive and statically significant at 1% coefficients, thus a non-linear relationship is underlined. Specifically, the larger is a country trade variation, the larger is the variation of emissions. This positive effect is more than proportional. This is in line with the literature, which underlines that the higher is the trade intensity, the higher are emissions connected with the scale effect: open markets expand the production, which consequently increases pollution. The only other variable that affects the scale component is the adoption of eco-innovation. $EcoInno$ has a positive and significant at 1%, while $EcoInno^2$ shows a negative and robust at 5% coefficient, thus an inverted U-shaped relation exists between the change in country's abatement technology adoption and air pollution variation. Until a specific turning point, the higher is the increase in eco-innovation adoption, the higher is the emission change connected with the scale effect. After the threshold value, the variation of emissions decreases. This effect of eco-innovation is also confirmed when Model (2) is estimated, for both GHG and AG. Furthermore, the relative value of this variable positively affects emissions changes when it is interacted with trade openness change rate. Columns 4 and 10 of Table A6 report the corresponding and significant (at 10%) coefficient of *Open*REcoInno*, equal to 0.153 for GHG and 0.166 for AG. A similar result is obtained for the interaction term that considers changes in relative use of renewable energy and trade intensity. The positive value of these interactions economically means that through a higher increase of openness, a greater adoption of eco-innovation or renewables generates a growth of emissions.

Composition Effect: Focusing on the emission changes related to the composition effect, Model (1) suggests that no relationship between income change rate and air emission variation exists for AG; while an inverted U-shaped one is obtained for GHG. Until the threshold value, the higher is the growth rate, the greater is the GHG emission variation; after the turning point value, emission change rate diminishes. Considering the estimates of GHG composition effect, no other variable has a significant effect. By focusing on AG, Column 8 of Table A6 shows that only changes in factors endowments affect emission variation connected to the composition effect. As we can see, ΔKL coefficient is equal to 15.835, while KL^2 is negative and equal to -0.976, so an inverted U-shaped relation characterizes the capital-labour ratio change rate and AG emission rate. This result is confirmed if we estimate Model (2) and it also gains robustness. Proceeding with the analysis of Model (2), $Open{*}RKL$ variable is negative and statistically significant at 5% for both GHG and AG. An increase of the capital-labour change rate produces a higher emission variation when trade intensity rate increases too.

Technique Effect: Finally, by analysing Model (1) results on emission changes related to the technique effect, we can see, from Table A6 Columns 3 and 9, that none variable has a significant effect. Differently, when Model (2) estimates are studied, differences among GHG and AG arise. Concerning GHG, a non-linear relationship exists among KL and emission change rates connected with technique effect. ΔKL and squared KL coefficients are statistically significant at 5%; the first one is negative (-9.892) and the second one is positive (0.657). These results are consistent with a U-shaped curve, thus an increase in the variation of relative factor endowments generates an initial decrease of GHG emission change rate related to the technique effect, but after a specific turning point, it starts to grow. Moreover, for this air pollutant, KL also operates by trade. Specifically, the impact of the interaction $Open * KL$ is positive and statistically significant (5%). This is also verified for AG.

6. Discussion

In general, results on the EKC underline that GHG emissions are driven by trade intensity and its interaction with other variables, such as relative factor endowments, eco-innovation and the use of renewable energy. Focusing on AG emissions, the more important role is played by capital-to-labor ratio and eco-innovation adoption.

By combining results on the three effects, we can derive some important conclusions on the scenario as a whole. First, estimates have shown that the economic factors have different impacts on each effect change rate and results depend on which air pollutant is considered. Concerning scale component, it seems substantially driven by per capita income, through a U-shaped relationship, but also trade intensity and eco-innovation non-linearly affect emission variation. The only inverted U-shaped relation between economic growth rate and emission variation comes from the composition effect component of GHG when Model (1) is estimated, but it loses robustness when the overall emission change rate is estimated. AG emissions that are connected with the composition effect are driven by changes in relative factor endowments and a U-shaped relation is obtained. This variable also affects the technique component of emission variation when GHG emission changes are estimated by Model (2). Until a turning point, emission variation due to the technique effect falls in response to a larger increase of factor supply, then it begins to increase

7. Conclusions

In the last thirty years, given the increasing importance of environmental issues and their impact on human health and natural degradation, researchers have studied the main economic factors driving pollution emissions to look for possible solutions for a sustainable development. Since emissions are differently affected by these factors, which generate three specific effects (scale, composition and technique) on emissions, in this work we have analysed their impact on scale, composition and technique effects separately. By conducting a first analysis, we have decomposed, through the LMDI method, the overall effect of GHG and AG emissions into scale, composition and technique components for each EU countries. This analysis has shown that the general level of emissions in EU remained constant over the 2008-2015 period, but countries behaved differently. Some of them reported a decrease in air pollution and others, oppositely, showed an increase of GHG and AG concentrations. Despite this scenario, a huge number of countries had no radical changes in their level of air pollution. It is interesting that all countries show a common decline between 2008 and 2010. This result is particularly connected with the economic crisis of 2008, which caused a decrease in countries Gross Value Added. Concerning the three effects, emissions generally decrease by the scale effect and increase by the technique effect. The composition effect behaves differently by country; emissions can rise or fall in terms of this specific effect, indicating that sectoral composition has been changing in the reference period.

From a policy point of view, institutions should manage air pollutants differently, because, as we have seen, economic and policy factors have different impact on their components. Concerning AG, they will promote a rethinking of sectoral composition at country level by an implementation of policies that foster investment in green capital. Focusing on GHG, more attention could be given to eco-innovation and technical progress, which help in lowering emissions.

Future researches could be done. First, it should be considered a wider period because the implementation of an environmental regulation and the adoption of new green technologies require a longer term perspective to allow for a complete structural change of the economy. Second, a robustness analysis of results could be made by accounting for the existence of zero emission values at sectoral level [Wood and Lenzen (2006)]. Third, since we have seen that many differences among pollutants exist, further studies could be done by applying the same analysis to other types of pollutants, such as water pollutants. Finally, it could be useful to find a suitable variable that measures environmental regulation in order to capture the direct impact of specific policies on emissions.

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Appendix A - Tables

Table A1. Manufacturing sectors by Nace Rev. 2 classification

Nace Rev. 2 Code	**Description**
C10_C12	Manufacture of goods, products, beverage, tobacco products
C13_C15	Manufacture of textile, wearing apparel, leather and related products
C16	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
C17	Manufacture of paper and paper products
C18	Printing and reproduction of recorded media
C19	Manufacture of coke and refined petroleum products
C20	Manufacture of chemicals and chemical products
C21	Manufacture of basic pharmaceutical products and pharmaceutical preparations
C22	Manufacture of rubber and plastic products
C23	Manufacture of other non-metallic mineral products
C24	Manufacture of basic metals
C25	Manufacture of fabricated metal products, except machinery and equipment
C26	Manufacture of computer, electronic and optical products
C27	Manufacture of electrical equipment
C28	Manufacture of machinery and equipment n.e.c.
C29	Manufacture of motor vehicles, trailers and semi-trailers
C30	Manufacture of other transport equipment
C31_C32	Manufacture of furniture and other manufacture
C33	Repair and installation of machinery and equipment

Table A2.1 Decomposition of greenhouse gases emissions by country

	Austria				**Belgium**				**Bulgaria**				**Croatia**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.825	1.200	0.889	0.880	0.892	0.945	0.896	0.755	0.885	0.717	0.953	0.604	0.868	0.927	1.014	0.816
2010	0.885	1.318	0.827	0.964	0.948	0.904	1.006	0.862	0.870	0.809	0.906	0.638	0.849	1.032	0.958	0.840
2011	0.949	1.213	0.841	0.967	0.965	0.811	1.049	0.821	0.955	0.737	0.921	0.648	0.852	0.992	0.944	0.798
2012	0.968	1.170	0.836	0.946	0.969	0.745	1.071	0.774	0.979	0.630	0.953	0.588	0.814	0.940	0.950	0.726
2013	0.965	1.763	0.562	0.956	0.990	0.678	1.158	0.777	0.954	0.628	0.925	0.554	0.789	0.894	0.948	0.668
2014	0.987	2.061	0.456	0.928	1.040	0.625	1.194	0.776	0.995	.	.	.	0.821	0.912	0.927	0.694
2015	0.998	1.288	0.742	0.953	1.102	0.531	1.317	0.771	1.046	0.617	1.013	0.654	0.858	0.878	0.918	0.692

	Denmark				Estonia				**Finland**				**France**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.887	0.955	0.977	0.827	0.771	0.913	0.871	0.614	0.766	0.982	1.049	0.789	0.931	0.903	1.041	0.875
2010	0.906	1.451	0.641	0.843	0.914	0.683	0.841	0.525	0.825	0.873	1.192	0.858	0.950	0.957	0.986	0.897
2011	0.963	1.111	0.814	0.871	1.043	0.868	0.809	0.732	0.824	0.831	1.234	0.845	0.989	0.885	0.979	0.857
2012	1.004	1.062	0.791	0.844	1.057	0.849	0.796	0.715	0.728	0.838	1.235	0.754	0.986	0.849	0.947	0.793
2013	1.031	1.044	0.760	0.819	1.089	0.933	0.776	0.789	0.733	0.736	1.376	0.743	0.985	0.805	0.983	0.780
2014	1.035	1.438	0.554	0.825	1.136	1.034	0.817	0.961	0.727	0.788	1.285	0.737	0.997	0.705	1.088	0.765
2015	1.040	.	.	.	1.158	0.918	0.867	0.922	0.718	0.886	1.153	0.734	1.004	0.662	1.124	0.747

Table A2.2. Decomposition of greenhouse gases emissions by country - continued

	Germany				Greece				Hungary				Italy			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.805	1.096	1.002	0.884	0.920	0.788	1.134	0.823	0.794	1.385	0.745	0.818	0.824	1.003	0.991	0.819
2010	0.953	1.007	0.960	0.922	0.765	1.176	0.904	0.813	0.868	1.408	0.695	0.850	0.895	1.017	0.950	0.864
2011	1.034	1.041	0.849	0.914	0.717	1.001	0.930	0.667	0.877	1.671	0.585	0.857	0.913	0.947	0.963	0.833
2012	1.012	1.073	0.820	0.890	0.666	1.124	0.941	0.705	0.862	1.620	0.567	0.792	0.881	0.887	0.956	0.748
2013	1.009	1.003	0.879	0.890	0.670	1.349	0.881	0.796	0.860	1.690	0.552	0.802	0.868	0.818	0.906	0.644
2014	1.064	0.935	0.884	0.880	0.657	1.455	0.861	0.823	0.915	1.718	0.553	0.869	0.873	.	.	.
2015	1.091	0.898	0.899	0.881	0.671	1.119	1.046	0.785	1.009	1.636	0.552	0.912	0.895	0.935	0.806	0.675

	Latvia				Lithuania				Netherland				Poland			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.768	0.980	1.081	0.813	0.836	0.644	1.045	0.563	0.896	0.981	1.044	0.917	1.034	0.731	1.099	0.831
2010	0.881	1.116	1.161	1.142	0.913	0.601	1.046	0.574	0.935	0.989	1.054	0.974	1.037	0.904	0.961	0.901
2011	0.928	0.969	1.150	1.033	1.009	0.743	1.028	0.770	0.977	0.889	1.111	0.964	1.119	0.888	0.959	0.952
2012	0.969	1.049	1.106	1.124	1.073	0.723	0.993	0.771	0.967	0.849	1.134	0.931	1.153	0.855	0.951	0.938
2013	0.953	.	.	.	1.126	0.671	0.922	0.697	0.959	0.844	1.126	0.912	1.157	0.850	0.927	0.912
2014	0.957	.	.	.	1.188	0.634	0.932	0.703	0.984	0.783	1.170	0.901	1.247	0.799	0.915	0.913
2015	0.965	0.887	0.984	0.843	1.222	0.651	0.907	0.722	0.990	0.824	1.137	0.928	1.347	0.696	0.961	0.901

Table A2.3. Decomposition of greenhouse gases emissions by country - continued

	Portugal				**Romania**				**Slovakia**				**Slovenia**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.893	0.994	0.936	0.831	0.939	0.872	0.892	0.730	0.830	1.093	0.995	0.902	0.840	0.981	0.960	0.791
2010	0.952	0.892	1.052	0.893	1.007	1.091	0.698	0.767	1.015	1.121	0.807	0.919	0.902	0.905	0.963	0.786
2011	0.963	0.909	0.942	0.823	1.083	0.791	0.930	0.796	1.056	1.247	0.701	0.923	0.927	0.834	0.933	0.722
2012	0.932	1.038	0.797	0.771	0.948	0.817	0.988	0.765	1.049	0.986	0.786	0.813	0.900	0.831	0.929	0.696
2013	0.939	1.147	0.776	0.836	1.021	0.646	0.989	0.653	1.044	0.957	0.764	0.763	0.897	0.882	0.913	0.723
2014	0.965	1.201	0.717	0.831	1.050	0.579	1.130	0.686	1.206	0.858	0.730	0.756	0.945	0.863	0.902	0.735
2015	0.993	1.226	0.704	0.857	1.120	0.537	1.117	0.672	1.389	0.613	0.890	0.758	0.964	0.844	0.859	0.699
	Spain				**Sweden**				**United Kingdom**				**EU28**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.892	1.004	0.952	0.851	0.754	1.175	0.889	0.787	0.905	0.962	0.956	0.832	0.864	0.946	1.027	0.839
2010	0.892	1.032	0.943	0.869	0.948	1.097	0.920	0.957	0.944	0.945	0.963	0.860	0.943	0.948	0.983	0.878
2011	0.880	0.987	0.952	0.827	0.987	0.944	0.982	0.915	0.965	0.860	0.979	0.812	0.989	0.899	0.964	0.857
2012	0.836	1.091	0.888	0.810	0.904	1.172	0.822	0.871	0.950	0.872	0.952	0.789	0.966	0.903	0.937	0.817
2013	0.842	1.052	0.865	0.765	0.897	1.060	0.863	0.821	0.942	0.894	0.949	0.799	0.962	0.853	0.964	0.792
2014	0.875	1.002	0.866	0.759	0.909	1.045	0.864	0.821	0.967	0.870	0.938	0.789	0.998	0.806	0.984	0.791
2015	0.953	0.723	1.117	0.770	0.845	1.248	0.789	0.832	0.968	0.850	0.921	0.758	1.040	0.733	1.036	0.790

Table A3.1 Decomposition of acidifying gases emissions by country

	Austria				**Belgium**				**Bulgaria**				**Croatia**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.825	1.202	0.919	0.911	0.891	0.993	0.833	0.737	0.886	0.957	1.079	0.914	0.869	0.914	1.020	0.810
2010	0.885	1.222	0.907	0.981	0.948	0.753	0.968	0.691	0.870	0.963	1.059	0.888	0.850	0.904	0.982	0.754
2011	0.949	1.139	0.900	0.973	0.965	0.681	1.027	0.675	0.955	1.086	1.041	1.079	0.851	0.816	0.965	0.670
2012	0.968	1.114	0.880	0.949	0.969	0.604	1.052	0.616	0.979	0.937	1.059	0.972	0.813	0.817	0.967	0.642
2013	0.965	1.306	0.763	0.962	0.990	0.497	1.152	0.567	0.955	1.138	0.988	1.073	0.788	0.717	0.959	0.542
2014	0.987	1.357	0.688	0.922	1.040	0.479	1.164	0.579	0.995	.	.	.	0.821	0.652	0.945	0.505
2015	0.998	1.072	0.863	0.923	1.102	0.418	1.254	0.578	1.047	0.885	1.089	1.009	0.858	0.698	0.944	0.565

	Denmark				Estonia				**Finland**				**France**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.886	0.859	1.004	0.764	0.770	1.145	0.851	0.750	0.766	1.023	1.017	0.797	0.931	0.928	0.982	0.849
2010	0.906	1.228	0.690	0.768	0.912	0.945	0.833	0.718	0.825	0.867	1.165	0.834	0.950	0.922	0.921	0.807
2011	0.963	0.894	0.834	0.717	1.045	1.059	0.767	0.849	0.824	0.814	1.221	0.819	0.989	0.869	0.908	0.780
2012	1.004	0.808	0.818	0.664	1.059	1.107	0.771	0.904	0.728	0.808	1.222	0.719	0.986	0.786	0.865	0.671
2013	1.031	0.697	0.791	0.568	1.091	1.042	0.776	0.881	0.733	0.728	1.333	0.711	0.985	0.680	0.885	0.593
2014	1.035	0.902	0.610	0.570	1.149	0.915	0.811	0.852	0.727	0.756	1.249	0.687	0.997	0.536	1.067	0.571
2015	1.040	.	.	.	1.180	0.848	0.908	0.910	0.718	0.865	1.092	0.678	1.004	0.495	1.109	0.552

Table A3.2 Decomposition of acidifying gases emissions by country - continued

	Germany				**Greece**				**Hungary**				**Italy**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.805	1.099	0.986	0.872	0.920	0.659	1.470	0.892	0.793	1.242	0.829	0.817	0.824	1.015	0.987	0.826
2010	0.953	0.984	0.972	0.912	0.764	1.115	1.016	0.865	0.868	1.297	0.758	0.853	0.895	1.033	0.910	0.841
2011	1.034	1.075	0.814	0.905	0.715	0.932	1.106	0.737	0.877	1.542	0.655	0.885	0.913	0.925	0.930	0.785
2012	1.012	1.112	0.767	0.863	0.664	0.922	0.964	0.590	0.862	1.552	0.630	0.843	0.881	0.846	0.897	0.669
2013	1.009	0.998	0.845	0.851	0.663	1.149	0.865	0.658	0.860	1.459	0.616	0.773	0.868	0.838	0.794	0.578
2014	1.064	0.899	0.858	0.820	0.650	1.230	0.823	0.657	0.915	1.396	0.618	0.789	0.873	.	.	.
2015	1.091	0.827	0.889	0.802	0.664	0.865	1.150	0.661	1.009	1.275	0.614	0.790	0.895	0.847	0.681	0.516
	Latvia				**Lithuania**				**Netherland**				**Poland**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.769	1.040	1.127	0.901	0.835	1.050	0.981	0.860	0.896	0.825	1.051	0.777	1.034	0.753	1.140	0.888
2010	0.885	0.687	1.300	0.791	0.912	0.984	0.986	0.885	0.935	0.762	1.044	0.744	1.037	0.923	0.920	0.882
2011	0.932	0.479	1.231	0.550	1.009	1.007	0.978	0.994	0.977	0.668	1.147	0.748	1.119	0.933	0.914	0.954
2012	0.970	0.566	1.182	0.649	1.073	0.988	0.963	1.021	0.967	0.636	1.150	0.708	1.153	0.860	0.929	0.920
2013	0.956	.	.	.	1.126	0.993	0.940	1.052	0.960	0.547	1.155	0.606	1.156	0.824	0.921	0.877
2014	0.960	.	.	.	1.189	0.925	0.946	1.040	0.984	0.493	1.229	0.596	1.245	0.807	0.899	0.903
2015	0.968	0.582	1.075	0.606	1.223	0.958	0.924	1.083	0.990	0.509	1.199	0.604	1.346	0.686	0.937	0.865

Table A3.3 Decomposition of acidifying gases emissions by country - continued

	Portugal				**Romania**				**Slovakia**				**Slovenia**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.893	1.016	0.900	0.817	0.939	0.896	0.837	0.704	0.830	1.052	0.916	0.800	0.840	1.001	0.951	0.799
2010	0.952	0.780	1.095	0.813	1.007	1.012	0.680	0.693	1.015	0.991	0.727	0.732	0.903	0.947	0.967	0.826
2011	0.963	0.847	0.932	0.760	1.083	0.698	0.875	0.661	1.055	1.207	0.587	0.747	0.928	0.989	0.947	0.870
2012	0.932	1.010	0.747	0.703	0.948	0.743	0.956	0.674	1.049	0.987	0.693	0.717	0.902	0.949	0.941	0.806
2013	0.939	0.933	0.762	0.668	1.021	0.642	0.921	0.604	1.043	0.959	0.702	0.703	0.899	1.038	0.930	0.868
2014	0.965	0.927	0.707	0.632	1.050	0.526	1.098	0.606	1.204	0.821	0.703	0.695	0.946	0.995	0.925	0.871
2015	0.993	0.937	0.689	0.641	1.120	0.520	1.069	0.623	1.383	0.482	1.010	0.674	0.965	0.908	0.875	0.766
	Spain				**Sweden**				**United Kingdom**				**EU28**			
Year	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall	Scale	Technique	Composition	Overall
2008	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
2009	0.892	1.135	0.980	0.991	0.753	1.212	0.983	0.898	0.905	1.004	0.966	0.878	0.864	0.957	1.048	0.867
2010	0.892	1.188	0.982	1.041	0.948	0.987	1.002	0.938	0.944	1.017	0.966	0.928	0.943	0.938	0.987	0.873
2011	0.881	1.112	0.994	0.973	0.987	0.957	0.993	0.938	0.965	0.915	0.978	0.862	0.989	0.890	0.963	0.848
2012	0.836	1.073	0.925	0.830	0.904	1.030	1.007	0.938	0.950	0.905	0.941	0.810	0.966	0.870	0.920	0.772
2013	0.841	0.776	0.895	0.584	0.897	0.974	1.018	0.889	0.942	0.877	0.934	0.772	0.962	0.759	0.952	0.696
2014	0.875	0.661	0.897	0.519	0.909	0.965	1.001	0.879	0.967	0.799	0.915	0.708	0.998	0.686	0.976	0.668
2015	0.953	0.467	1.204	0.535	0.844	0.990	1.017	0.850	0.968	0.699	0.904	0.612	1.040	0.592	1.052	0.648

Table A4. Panel-data OLS estimation with fixed and random effects of EKC in levels

	GHG				AG			
	Random Effects		**Fixed Effects**		**Random Effects**		**Fixed Effects**	
	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)	Model (1)	Model (2)
	b/se		b/se		b/se		b/se	
Income	0.130	-10.855	-0.792	-11.119	-13.564*	-20.541**	-4.857	-15.922*
	(6.96)	(7.78)	(6.81)	(7.45)	(7.42)	(8.74)	(7.39)	(8.47)
Income^2	0.030	0.571	0.060	0.572	0.698*	1.040**	0.259	0.803*
	(0.34)	(0.38)	(0.34)	(0.37)	(0.37)	(0.43)	(0.37)	(0.42)
PopDens	0.157	0.228	0.150	0.286	0.526	0.657	-0.017	0.041
	(0.50)	(0.49)	(0.19)	(0.21)	(0.53)	(0.55)	(0.21)	(0.23)
KL	-1.151	-0.701	0.155	0.284	4.139***	3.841***	2.721***	2.796***
	(0.74)	(0.71)	(0.59)	(0.58)	(0.79)	(0.80)	(0.64)	(0.66)
Open	0.304*	-1.285	0.218	-0.543	-0.099	1.041	-0.286*	3.140
	(0.17)	(2.60)	(0.15)	(2.55)	(0.18)	(2.92)	(0.16)	(2.91)
EcoInno	-0.036	-0.042*	-0.042*	-0.049**	0.001	-0.000	0.007	0.001
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.02)
Renew	0.118	0.083	0.068	0.060	-0.084	-0.063	-0.063	-0.057
	(0.13)	(0.13)	(0.14)	(0.12)	(0.14)	(0.14)	(0.15)	(0.14)
KL^2	0.058	0.042	0.036	0.019	-0.236***	-0.214***	-0.150***	-0.157***
	(0.05)	(0.05)	(0.04)	(0.04)	(0.06)	(0.06)	(0.05)	(0.05)
Open^2	0.061	0.001	0.112	0.036	0.070	-0.086	0.148	-0.009
	(0.10)	(0.14)	(0.10)	(0.13)	(0.10)	(0.15)	(0.11)	(0.15)
EcoInno^2	-0.001	0.013	0.001	0.013	0.028**	0.021	0.014	0.009
	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Renew^2	0.032	0.029	0.026	0.026	-0.013	-0.006	-0.013	-0.008
	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
*Open*RInc*		0.300		0.237		-0.013		-0.241
		(0.28)		(0.27)		(0.31)		(0.31)
*Open*RKL*		-0.170*		-0.177*		-0.227**		-0.223**
		(0.10)		(0.09)		(0.11)		(0.11)
*Open*REcoInno*		-0.102**		-0.088*		0.068		0.094*
		(0.05)		(0.05)		(0.06)		(0.05)
*Open*Renew*		0.123*		0.178***		-0.097		-0.103
		(0.07)		(0.06)		(0.07)		(0.07)
constant	9.799	62.663	8.163	59.374	49.980	85.913*	14.995	70.739*
	(35.28)	(39.61)	(34.48)	(37.78)	(37.60)	(44.52)	(37.40)	(42.97)

*Note. Significance level: *** 0.01, ** 0.05, * 0.1*

Table A5. Generalized Linear Model estimation of overall emissions expressed in change rate – GHG and AG

	GHG		AG	
	Model (1)	Model (2)	Model (1)	Model (2)
	b/se		b/se	
Income	52.601	12.532	0.453	5.089
	(188.56)	(251.336)	(196.59)	(256.781)
Income^2	-2.408	-0.455	0.147	-0.091
	(9.375)	(12.436)	(9.779)	(12.717)
PopDens	-2.479	-1.767	-0.153	-0.055
	(20.871)	(21.406)	(21.205)	(21.620)
KL	-9.703	-5.286	9.219	9.201
	(30.390)	(32.535)	(30.684)	(32.806)
Open	1.254	1.606	-0.117	6.596
	(4.650)	(77.272)	(4.769)	(80.307)
EcoInno	0.064	0.024	0.071	0.103
	(0.441)	(0.461)	(0.441)	(0.457)
Renew	0.166	0.278	0.038	0.053
	(4.039)	(4.105)	(4.187)	(4.241)
KL^2	0.599	0.319	-0.565	-0.522
	(2.144)	(2.265)	(2.174)	(2.292)
Open^2	0.189	-0.164	0.670	0.400
	(2.005)	(3.257)	(2.127)	(3.482)
EcoInno^2	0.027	0.050	0.037	-0.003
	(0.262)	(0.289)	(0.265)	(0.293)
Renew^2	0.033	0.064	0.035	0.035
	(0.536)	(0.575)	(0.590)	(0.597)
*Open*RInc*		0.429		-0.622
		(8.309)		(8.700)
*Open*RKL*		-0.679		-0.277
		(2.472)		(2.597)
*Open*REcoInno*		-0.073		0.354
		(1.079)		(1.098)
*Open*Renew*		0.203		-0.303
		(1.606)		(1.647)
N. Observations	128	128	128	128
AIC	1.154	1.215	1.123	1.185
BIC	-534.57	-515.34	-535.21	-515.949

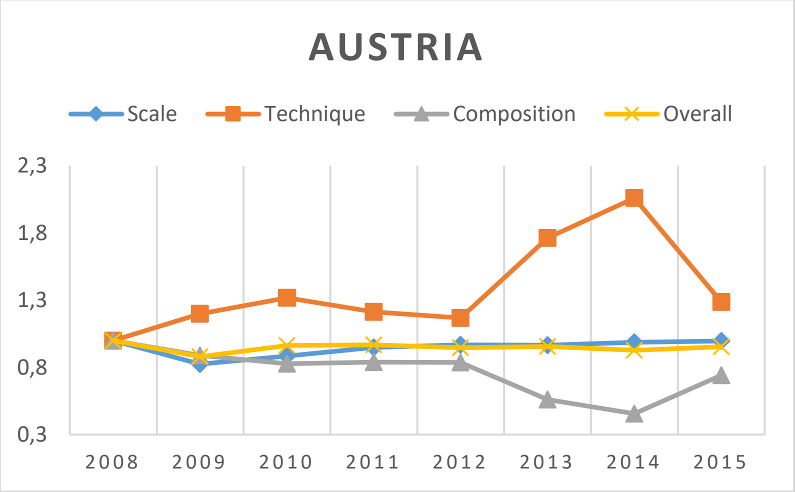
*Note. Significance level: *** 0.01, ** 0.05, * 0.1*

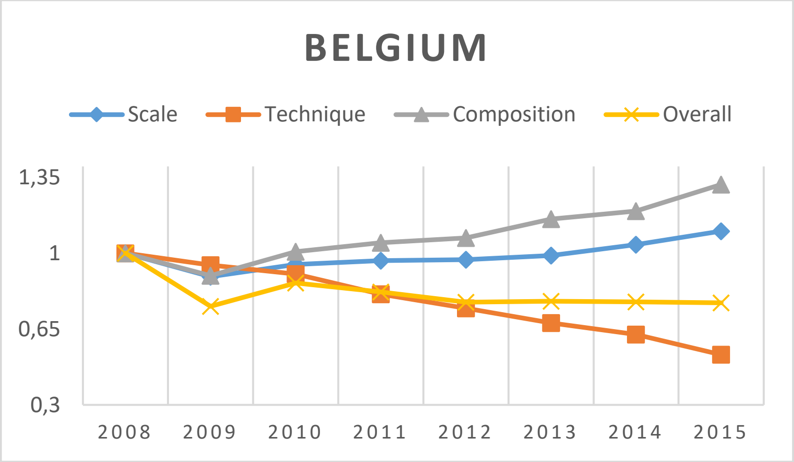
Table A6. SUR estimation with Fractional Logit – GHG and AG

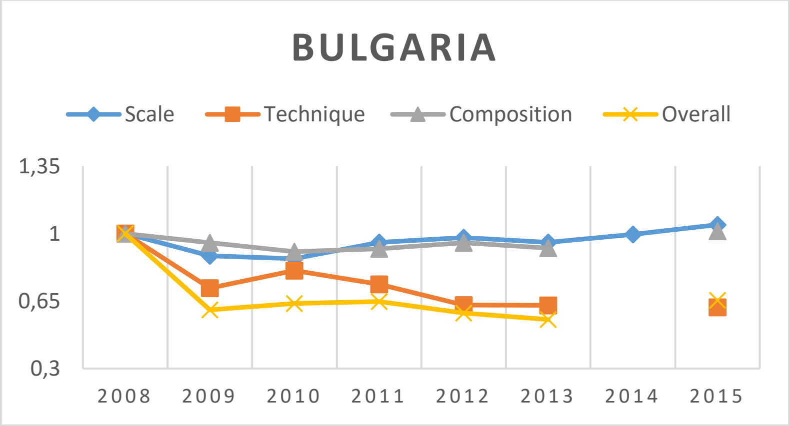
	GHG						AG					
	Model 1			Model 2			Model 1			Model 2		
	Scale	Composition	Technique	Scale	Composition	Technique	Scale	Composition	Technique	Scale	Composition	Technique
	b/se			b/se			b/se			b/se		
Income	-45.675**	122.783**	-34.548	-33.100	32.374	4.027	-42.879**	70.241	-26.456	-29.014	11.487	25.455
	(19.468)	(52.024)	(31.819)	(21.958)	(50.827)	(34.886)	(21.393)	(51.803)	(35.595)	(22.515)	(74.296)	(49.746)
Income^2	2.493**	-6.156**	1.736	1.849*	-1.709	-0.158	2.372**	-3.605	1.362	1.667	-0.703	-1.187
	(0.982)	(2.579)	(1.584)	(1.096)	(2.517)	(1.721)	(1.075)	(2.599)	(1.778)	(1.122)	(3.669)	(2.455)
PopDens	1.413	-0.361	-3.496	2.293	0.028	-4.005	1.915	-0.564	-1.239	3.066	-0.314	-2.175
	(2.283)	(4.687)	(3.309)	(2.288)	(4.758)	(3.575)	(2.339)	(4.930)	(4.111)	(2.263)	(5.545)	(4.421)
KL	-1.691	0.210	-6.364	0.397	6.168	-9.892**	-2.791	15.835**	-5.416	-0.414	19.794**	-10.877
	(1.956)	(6.647)	(3.980)	(2.077)	(6.769)	(4.513)	(2.198)	(7.591)	(5.842)	(2.217)	(8.339)	(6.611)
Open	1.395***	-1.574	1.510	5.002	-13.360	11.219	1.365***	-2.534	1.139	1.253	-19.542	20.054
	(0.458)	(1.349)	(0.964)	(8.191)	(24.262)	(13.534)	(0.476)	(1.555)	(1.136)	(8.868)	(28.698)	(21.170)
EcoInno	0.083***	-0.008	-0.019	0.084***	-0.080	0.018	0.099***	-0.009	-0.015	0.101***	-0.042	0.045
	(0.030)	(0.126)	(0.072)	(0.030)	(0.128)	(0.078)	(0.030)	(0.194)	(0.112)	(0.032)	(0.187)	(0.117)
Renew	-0.370	0.600	-0.171	-0.149	0.466	-0.110	-0.382	-0.249	0.514	-0.177	-0.546	0.586
	(0.321)	(0.955)	(0.671)	(0.295)	(1.009)	(0.715)	(0.332)	(1.023)	(0.697)	(0.296)	(1.086)	(0.760)
KL^2	0.088	-0.034	0.430	-0.040	-0.419	0.657**	0.168	-0.976*	0.346	0.022	-1.226**	0.702
	(0.135)	(0.443)	(0.281)	(0.138)	(0.471)	(0.316)	(0.153)	(0.545)	(0.422)	(0.148)	(0.611)	(0.475)
Open^2	0.373**	-0.442	0.256	0.330	-1.300	0.845	0.423**	-0.408	0.589	0.230	-1.617	1.496*
	(0.179)	(0.618)	(0.403)	(0.312)	(1.002)	(0.582)	(0.197)	(0.611)	(0.562)	(0.340)	(1.056)	(0.801)
EcoInno^2	-0.035**	-0.018	0.083	-0.043**	0.036	0.056	-0.047**	0.040	0.035	-0.058**	0.058	-0.008
	(0.018)	(0.078)	(0.053)	(0.021)	(0.081)	(0.053)	(0.018)	(0.095)	(0.063)	(0.023)	(0.097)	(0.067)
Renew^2	-0.020	0.064	-0.024	0.005	0.086	-0.038	-0.024	-0.031	0.067	0.001	-0.035	0.044
	(0.044)	(0.122)	(0.088)	(0.040)	(0.125)	(0.092)	(0.047)	(0.138)	(0.092)	(0.041)	(0.144)	(0.098)
*Open*RInc*				-0.260	1.943	-1.410				0.169	2.364	-2.560
				(0.890)	(2.630)	(1.495)				(0.973)	(3.058)	(2.2751)
*Open*RKL*				-0.062	-1.387**	0.808**				-0.159	-1.483**	1.185**
				(0.221)	(0.652)	(0.391)				(0.244)	(0.721)	(0.504)
*Open*REcoInno*				0.153*	-0.348	0.135				0.166*	-0.057	0.261
				(0.088)	(0.297)	(0.176)				(0.095)	(0.381)	(0.280)
*Open*Renew*				0.351*	-0.248	0.121				0.366***	-0.729*	0.091
				(0.114)	(0.361)	(0.214)				(0.119)	(0.412)	(0.295)

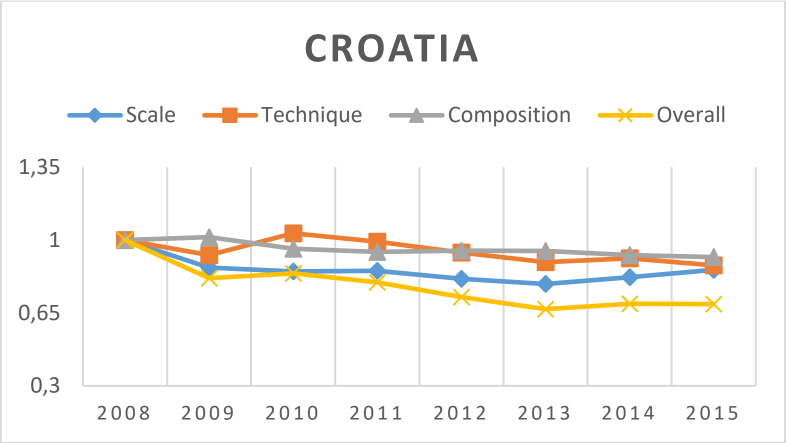
*Note. Significance level: *** 0.01, ** 0.05, * 0.1*

Appendix B – Greenhouse Gases Emissions Decomposition Graphs





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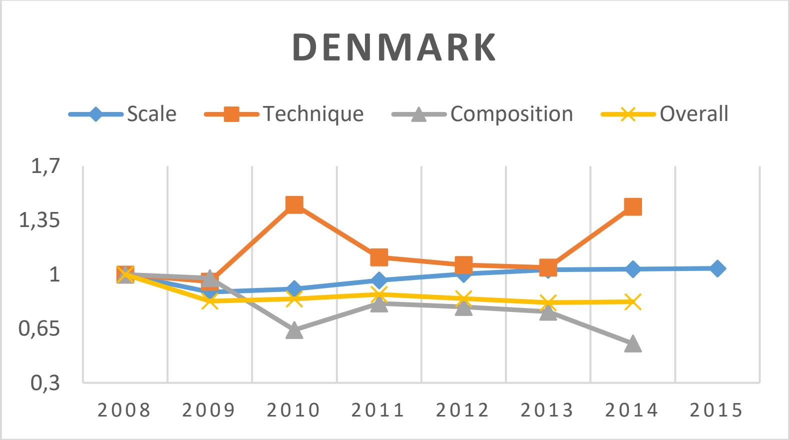
2013
2014
2015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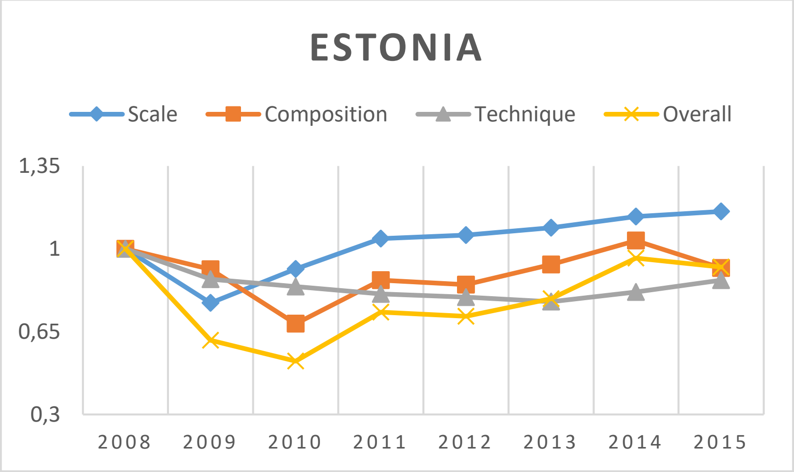
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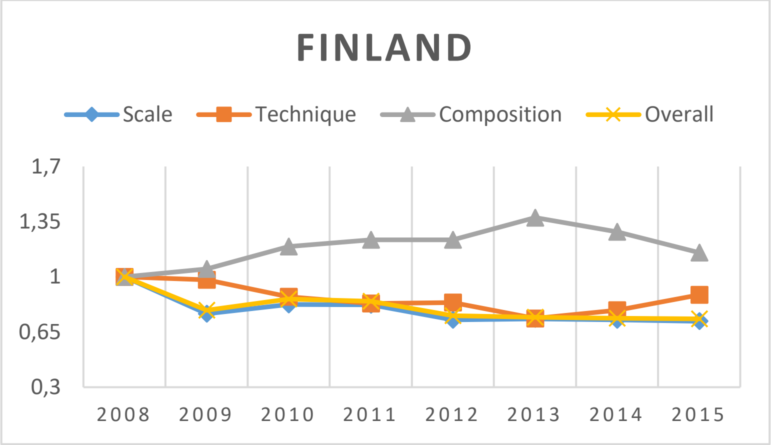
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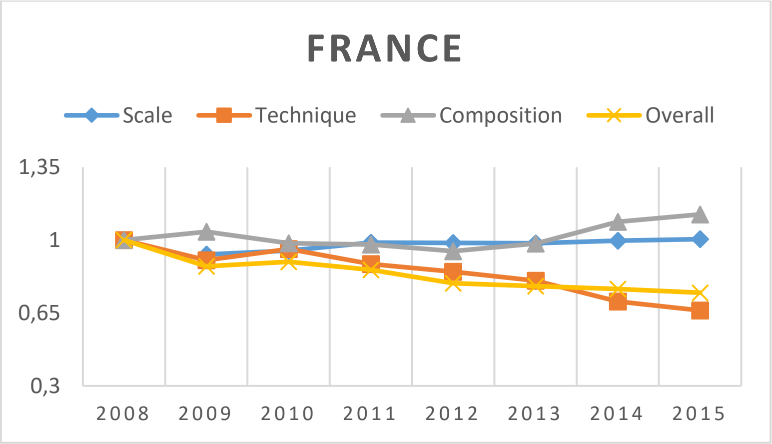
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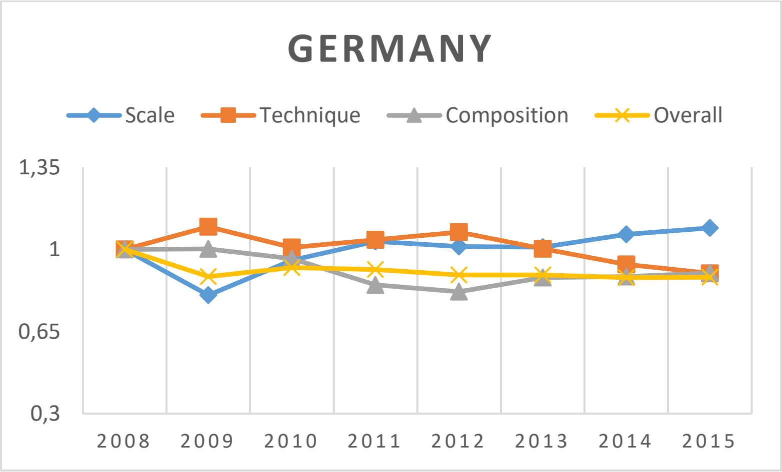
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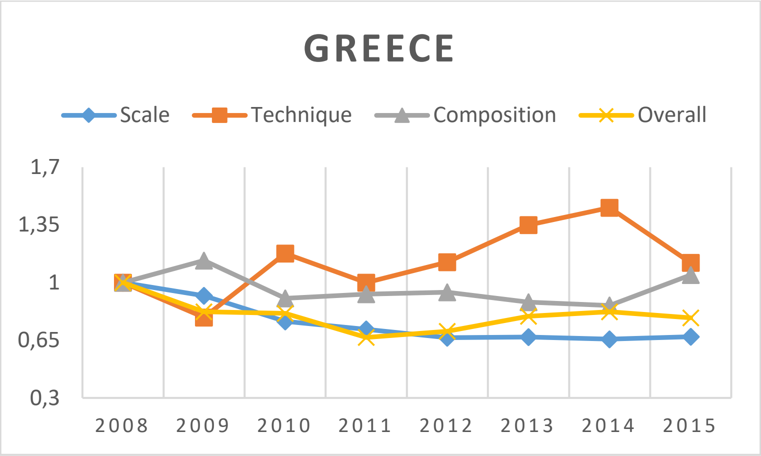
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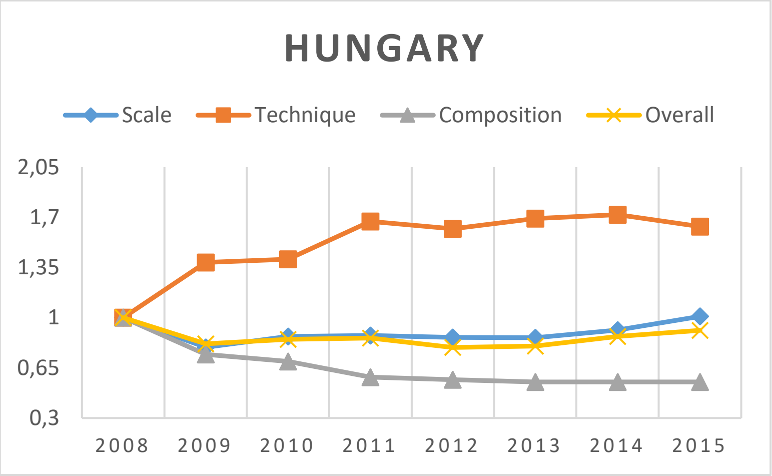
2014
2015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Technique
Composition
Overall
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2008
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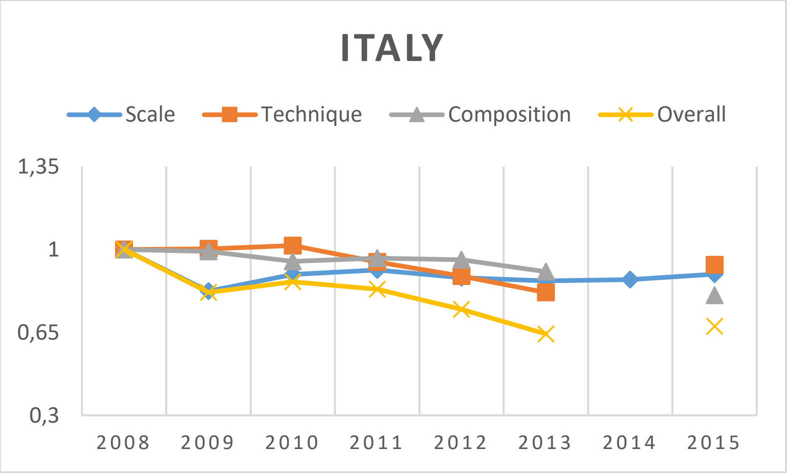
2011
2012
2013
2014
2015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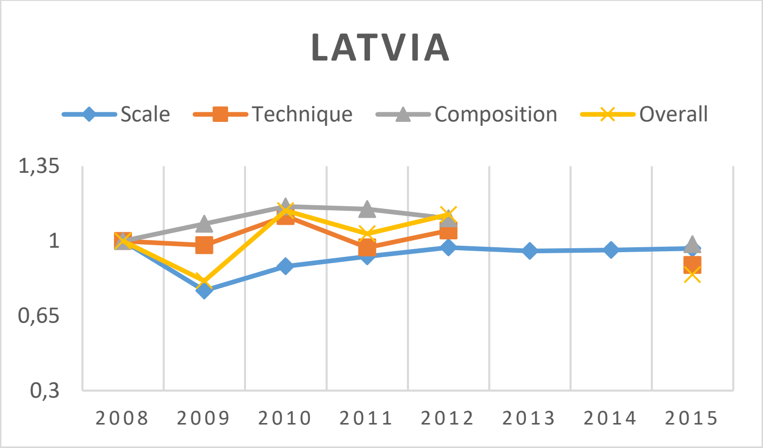
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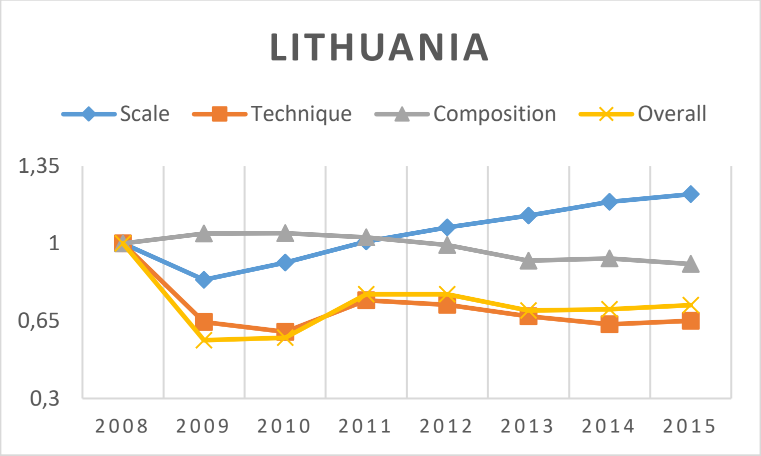
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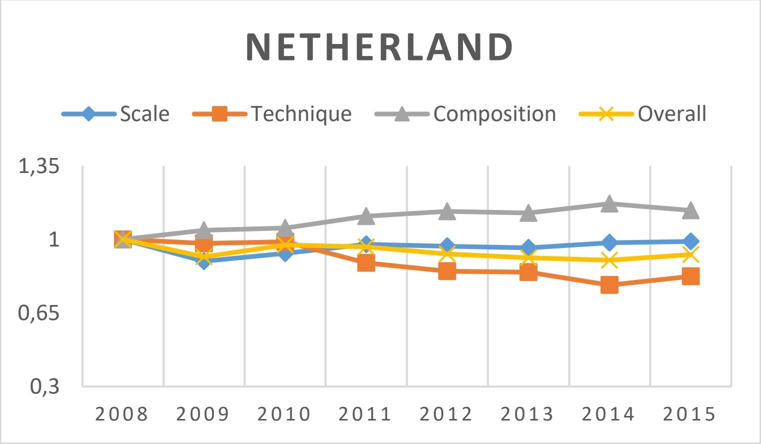
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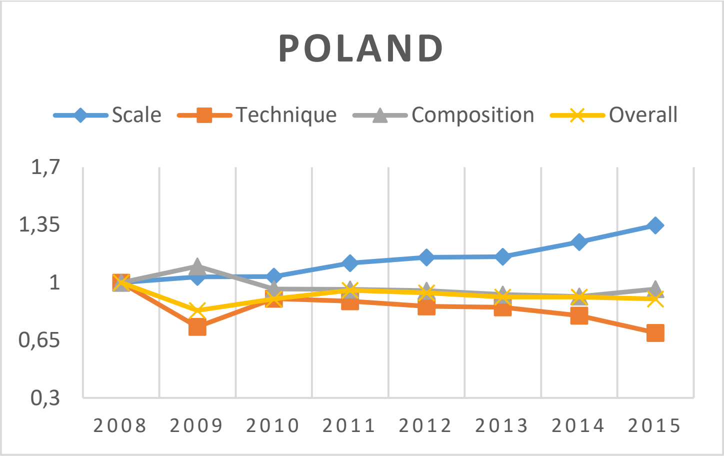
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Technique
Composition
Overall
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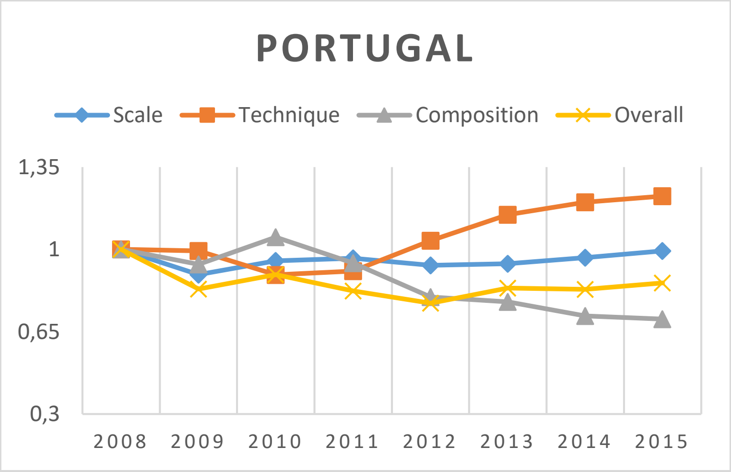
2014
2015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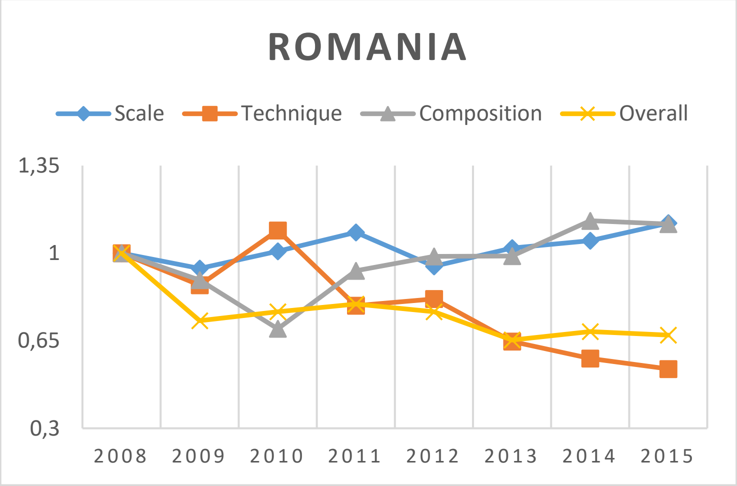
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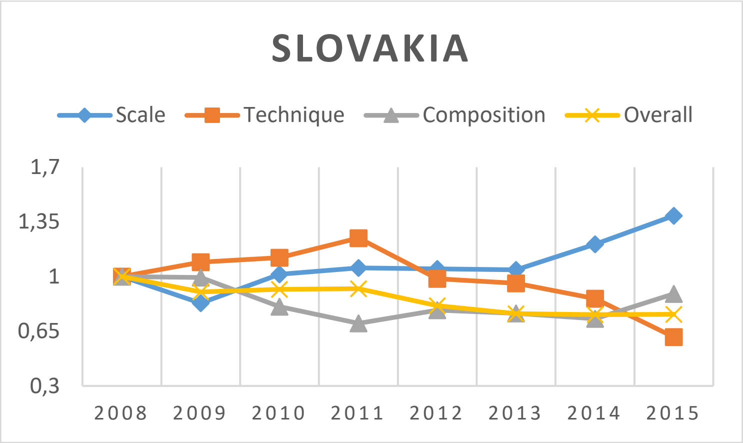
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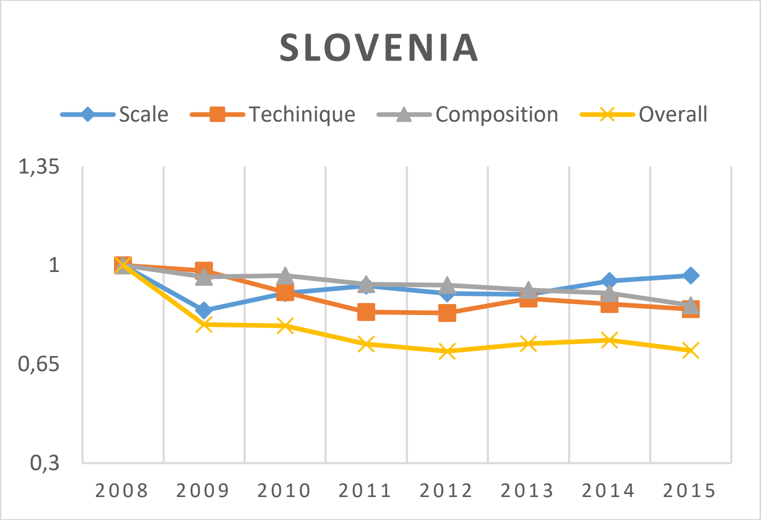
2015


SLOVENIA
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Techinique
Composition
Overall
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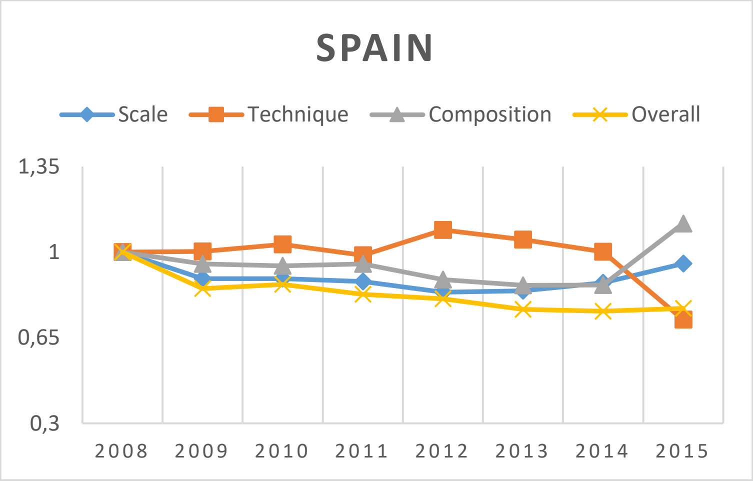
2014
2015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Composition
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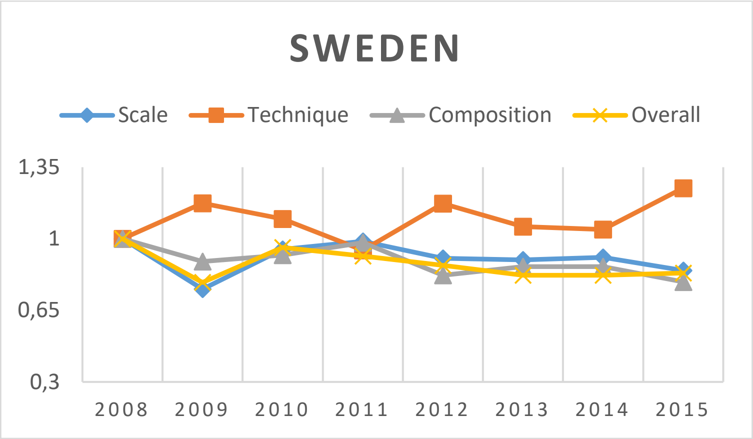
2014
2015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Technique
Composition
Overall
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2008
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2014
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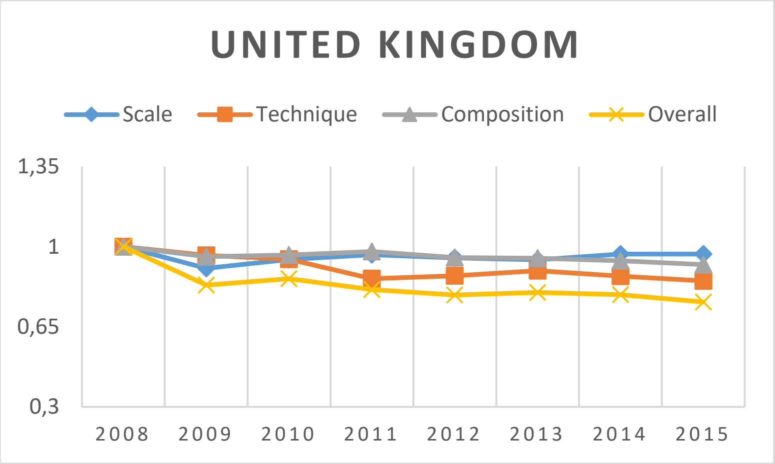
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Technique
Composition
Overall
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2008
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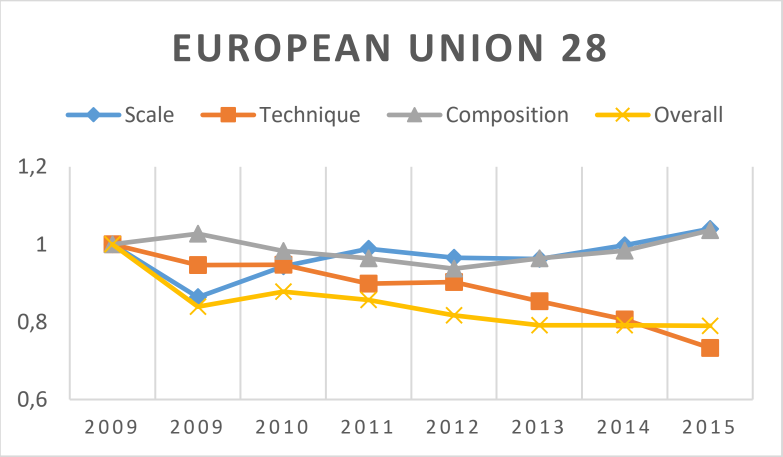
EUROPEAN UNION 28
Scale
Technique
Composition
Overall
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2009
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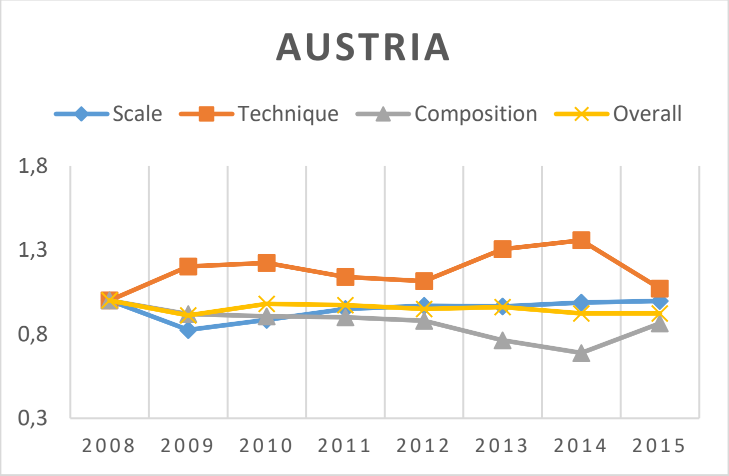
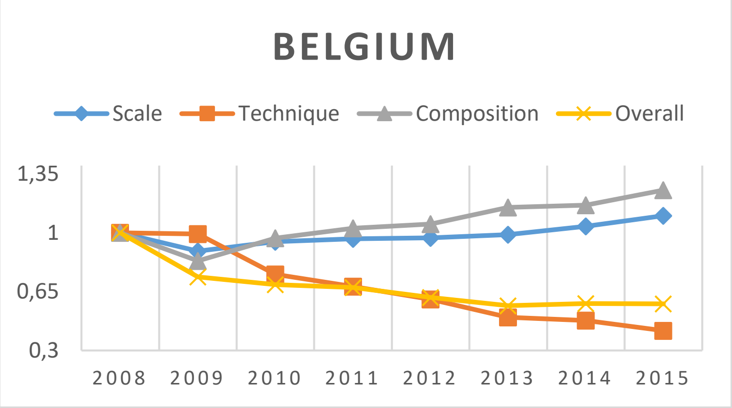
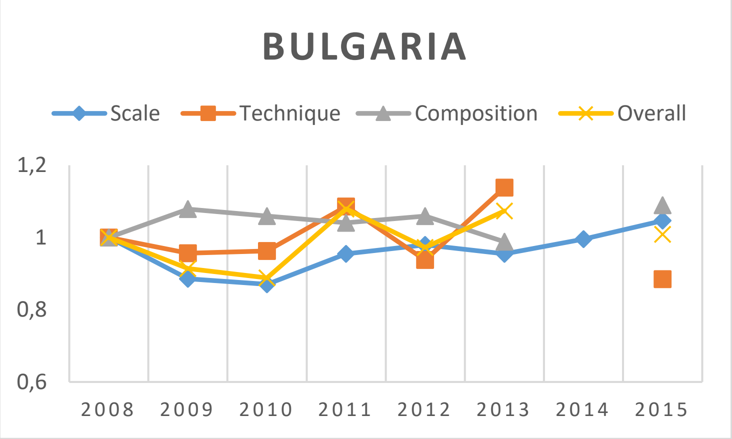
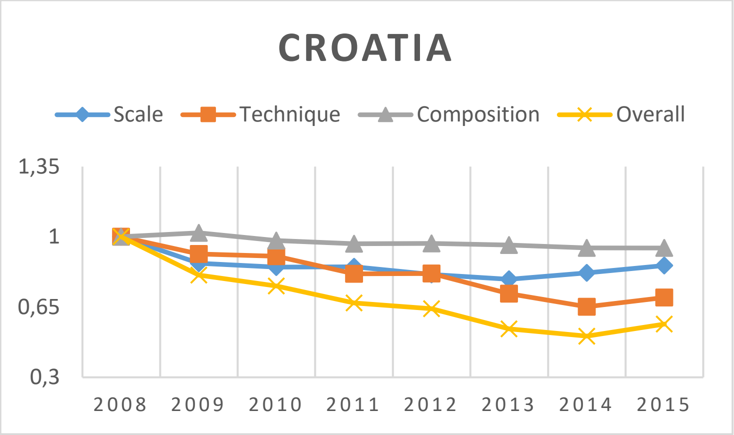
2011
2012
2013
2014
2015

Appendix C – Acidifying Gases Emissions Decomposition Graph





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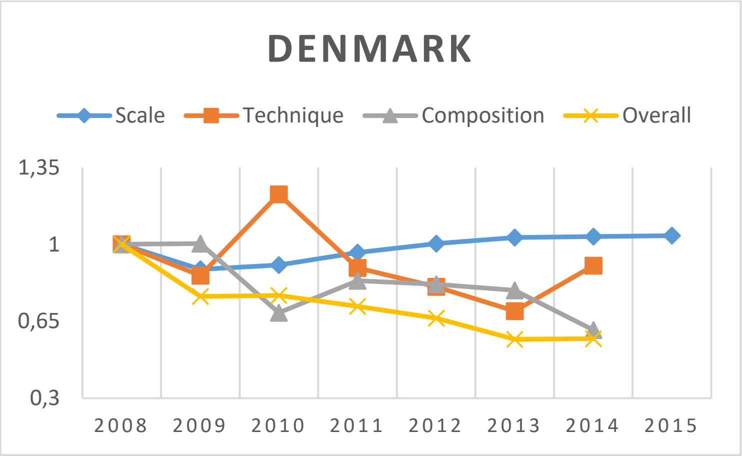
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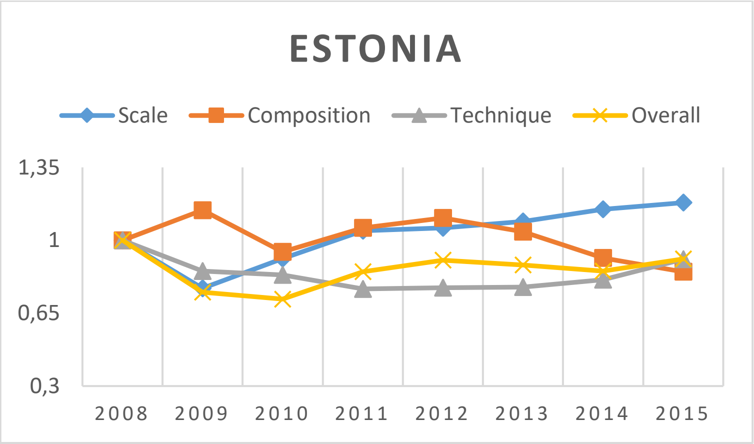
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Technique
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2013
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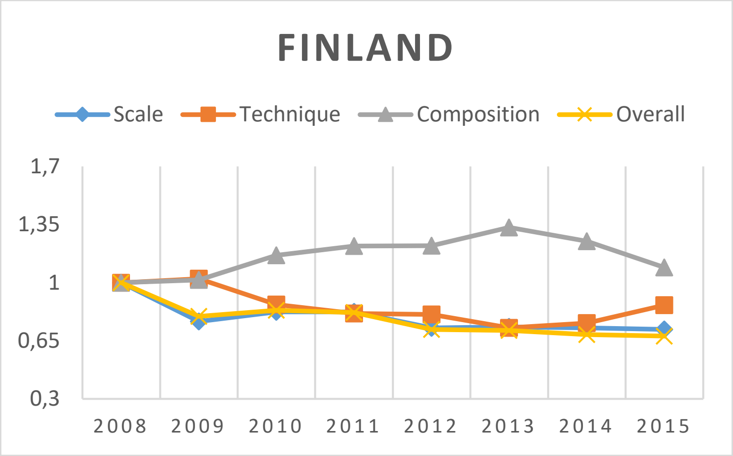
2015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Scale
Technique
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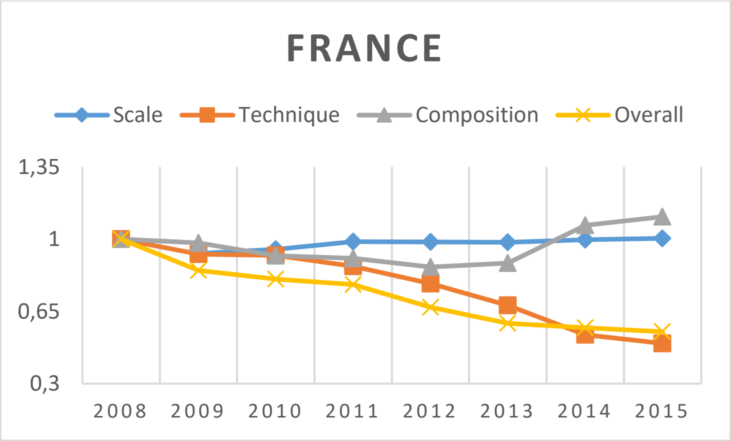
2014
2015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Scale
Technique
Composition
Overall
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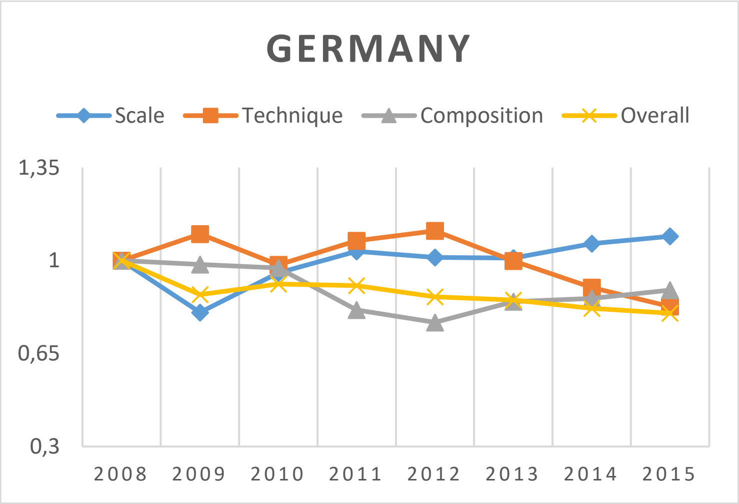
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Scale
Technique
Composition
Overall
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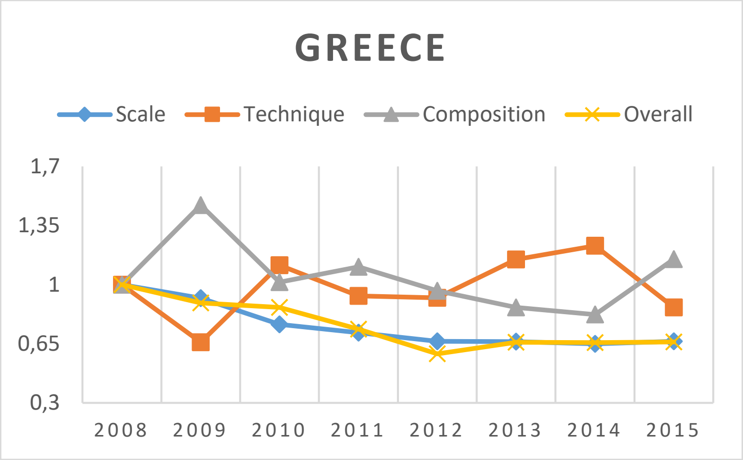
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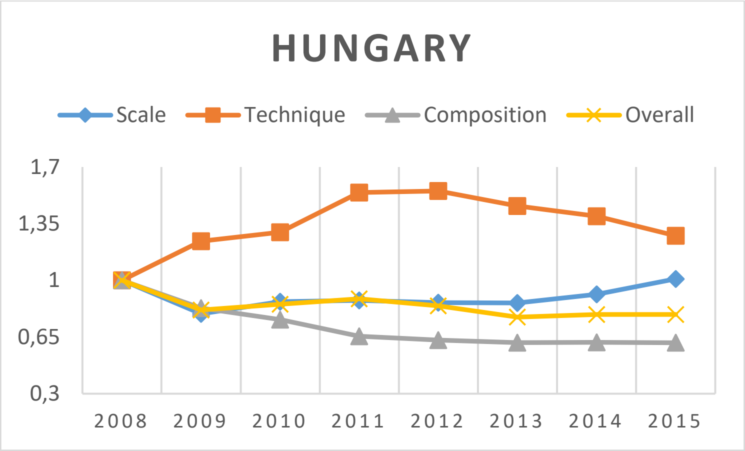
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Technique
Composition
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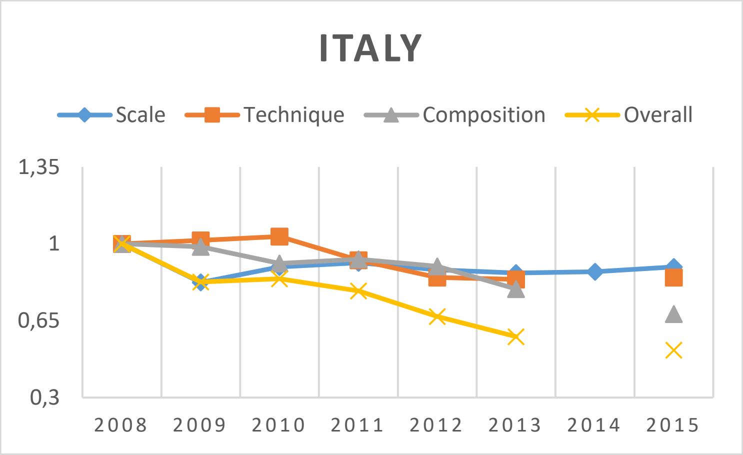
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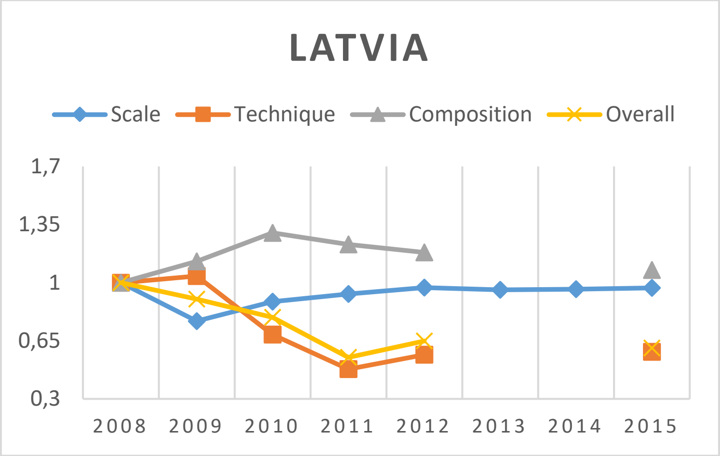
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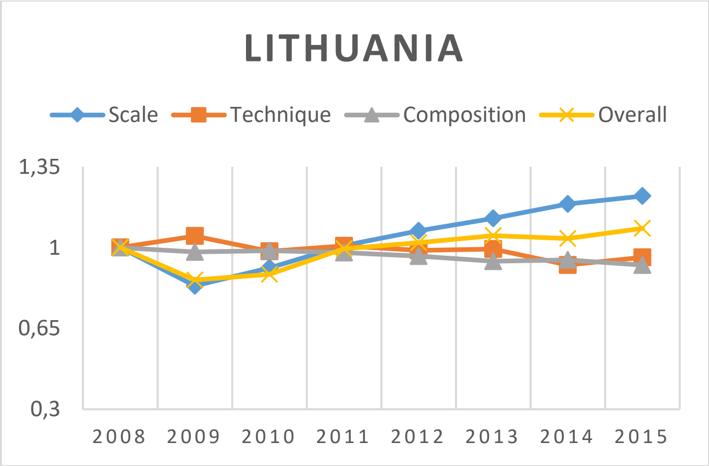
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Scale
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Composition
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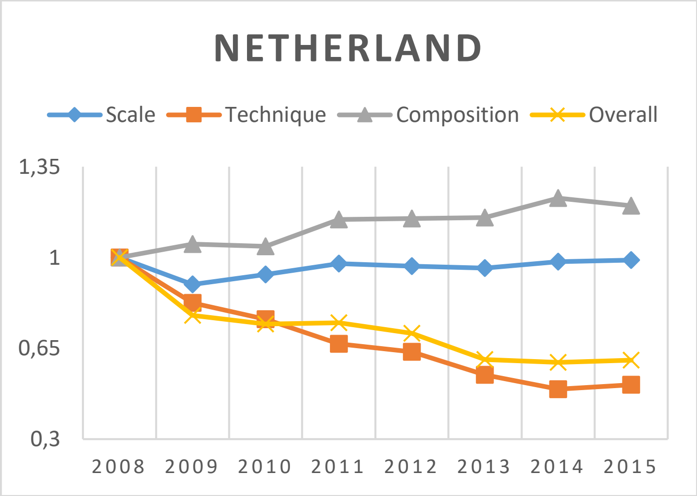
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Technique
Composition
Overall
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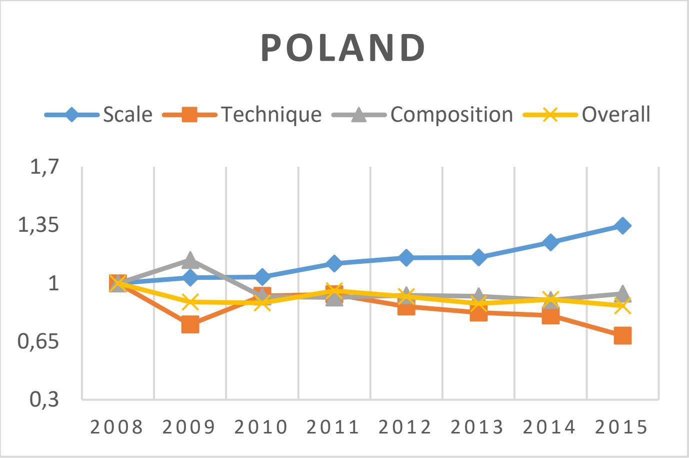
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Technique
Composition
Overall
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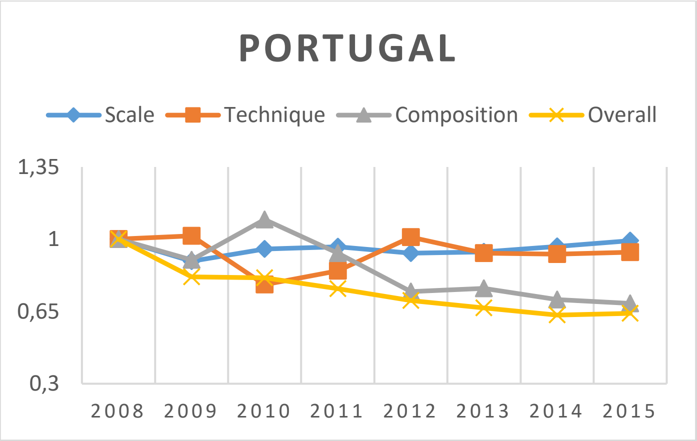
2014
2015


PORTUGAL
Scale
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Composition
Overall
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2008
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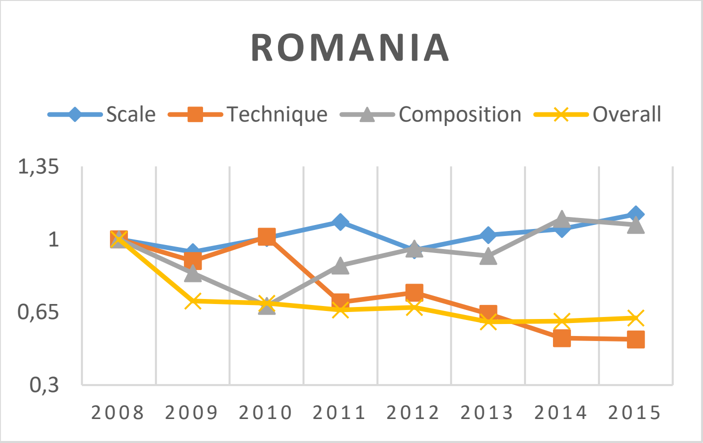
2014
2015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Composition
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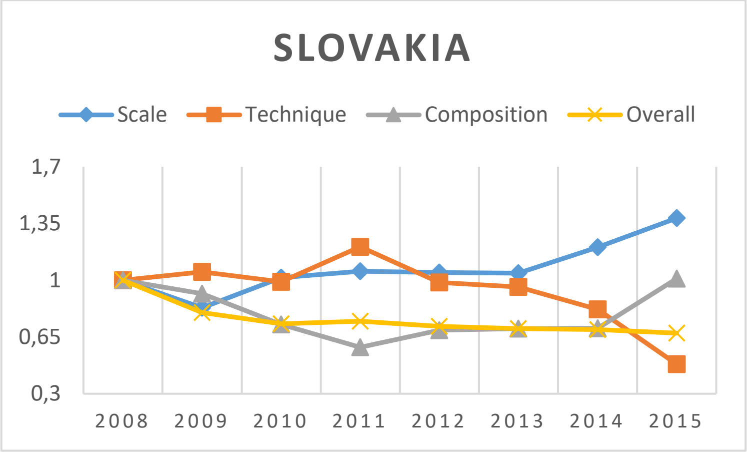
2015


SLOVAKIA
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Technique
Composition
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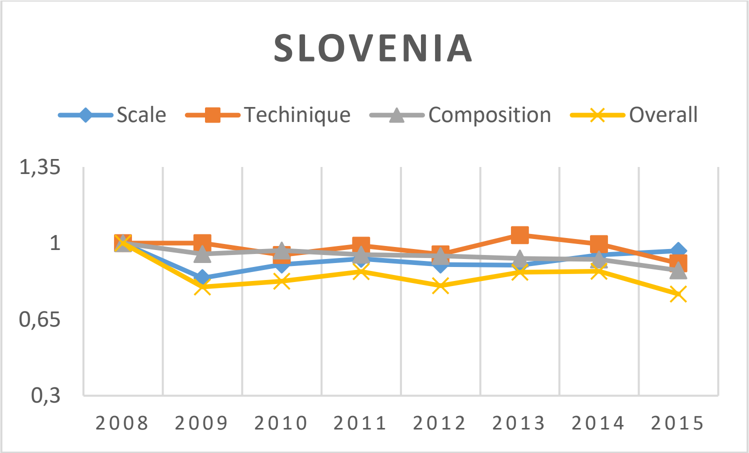
2015


SLOVENIA
Scale
Techinique
Composition
Overall
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2008
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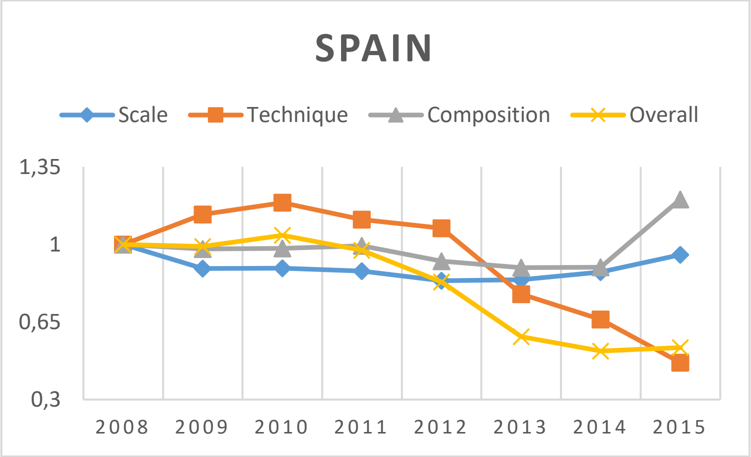
2015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Technique
Composition
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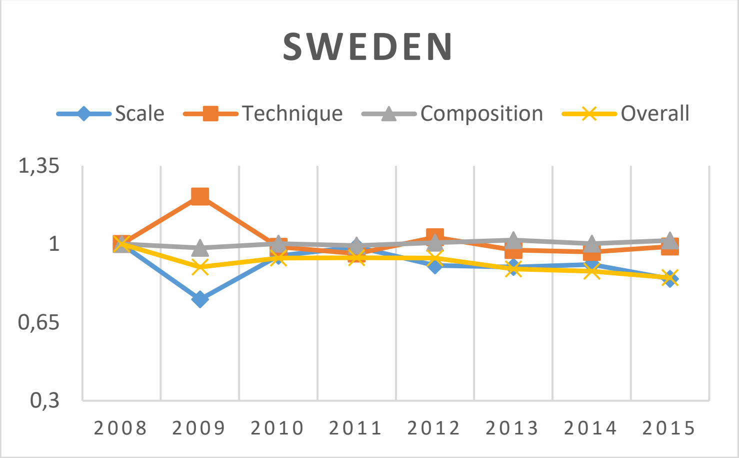
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Technique
Composition
Overall
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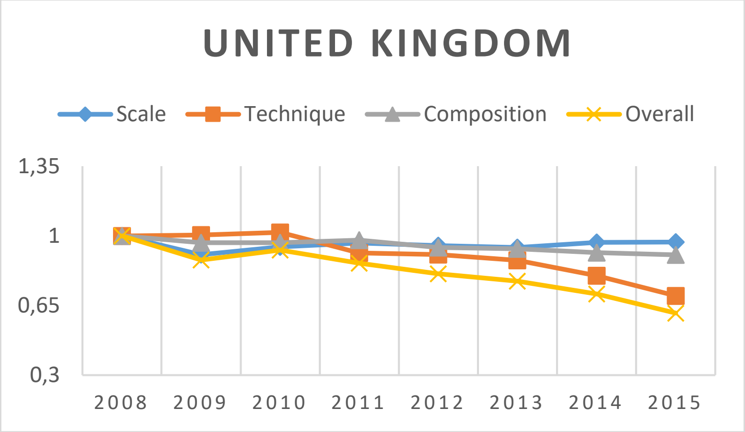
UNITED KINGDOM
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Composition
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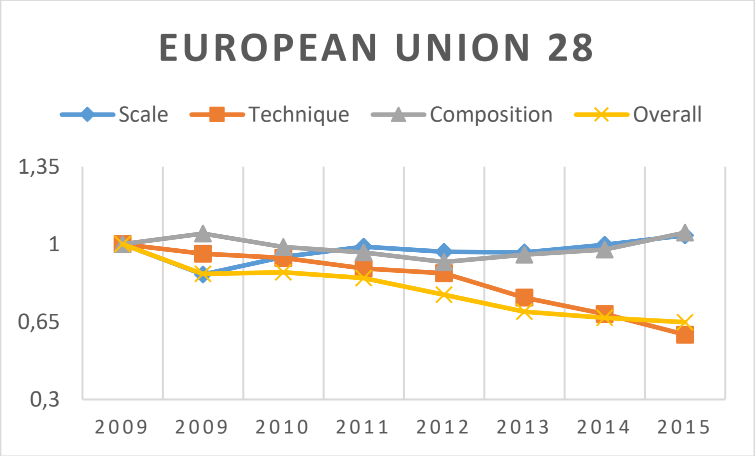
EUROPEAN UNION 28
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Composition
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2015