THE EFFECTIVENESS OF THE MARKET-BASED ENVIRONMENTAL POLICY MIX IN THE EUROPEAN UNION[1][2]

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Abstract

The goal of this paper is to analyze the effectiveness of the environmental taxes and emissions trading in achieving cleaner production, that is, higher production per unit of emissions in the European Union (EU). The hypothesis of the paper is that the combined use of taxes and emission permits yields synergistic benefits in addition to their individual contributions. The paper uses panel analysis on the EU27 data from 2005 to 2012. The analysis does not robustly find positive effects from the interaction of these policy instruments, but it confirms that there are no negative ones. Additional interesting results are that, on average, (i) the effects of both instruments on production cleanliness are more beneficial at the regulated industries than at the national level, (ii) emissions trading is more effective than taxes, (iii) both instruments are more effective in the EU15 than in the EU12, and (iv) crisis did not significantly affect production cleanliness in the EU.

Key words: effectiveness, production cleanliness, policy mix, environmental taxes, EU ETS, panel

JEL classification: E60, H20, Q50

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1. INTRODUCTION

To achieve climate policy targets, the European Union (EU) focuses on environmental taxes and the European Union Emissions Trading Scheme (EU ETS). These market-based instruments, as opposed to direct regulation, allow for internalization of pollution costs, making cost-effectiveness their main advantage. Under theoretical conditions of certainty, both of them yield the same, allocatively efficient and cost-effective result. Under uncertainty, however, the choice between the two becomes more complex. Theoretical and empirical ex ante analyses on the subject are numerous. Under uncertainty, due to imperfect information regarding abatement costs and benefits, they favor environmental taxes over emission permits (EP) and their well-designed combination over their individual use. Economic policy today, thus, looks for the optimal policy mix (PM) to achieve environmental objectives with minimal adverse effects for the economy. However, to answer whether currently implemented policies are effective at achieving both maximum benefits (environmental quality) and minimum costs (adverse effects for the economy), we need ex post econometric studies. This paper bridges the existing literature gap by providing the analysis of the effectiveness of environmental taxes and emissions trading in achieving cleaner production, that is, higher production per unit of emissions in the EU. We hypothesize that, in addition to their individual contributions, their PM yields synergistic benefits. This paper uses static and dynamic panel analysis on the EU27 annual data for the first two EU ETS trading periods (2005–2012).

The paper is organized as follows. In section 2, we present a literature review; in section 3, theoretical and empirical models; in section 4, data and methodology; and in section 5, results and discussion. Section 6 concludes.

2. LITERATURE REVIEW

Climate policy targets can be achieved only by regulation. However, in addition to controlling pollution, it is preferable to keep the adverse effects of regulation on economic systems at their minimum. Consequently, due to their cost-effectiveness, market-based instruments (primarily taxes and tradable EP) are the preferred instruments. In theory, given the ideal market conditions, primarily perfect information, there is no difference between emission (Pigouvian) taxes and tradable EP. They both yield the same, cost-effective and allocatively efficient result.

Under uncertainty, however, these two instruments will not result in the same outcome (Martin L. Weitzman 1974). Uncertainty caused by imperfect information regarding (the present value of) costs and benefits from abatement resulted in most controversial question of the economics of global climate change — that of optimal emissions level and optimal emissions price (William D. Nordhaus 2007). Consequently, there is no consensus regarding optimal design of intervention — policy instrument choice, policy intensity, or policy timing (Robert S. Pindyck 2007). The question of the best market-based instrument for greenhouse gas (GHG) emissions regulation is still debated.

Until recently, the focus of economic policy was solely on individual regulatory instruments and the available research on their individual strengths and weaknesses, similarities, and differences. The empirical research, so far, has also predominantly focused on each of the market-based instruments separately.

The EP system has so far been empirically analyzed mostly using ex ante simulation computable general equilibrium (CGE) methodology, focusing on different aspects of its design and the related outcomes in terms of emissions, welfare, production, unemployment, and so on. Ex post studies that analyze the effects of already implemented EP, however, are scarcer. Ralf Martin, Mirabelle Muûls, and Ulrich J. Wagner (2015) provide a thorough literature review of the ex post analyses of the impacts tradable permits (EU ETS) have so far had on emissions, economic performance and innovation. Although these ex post studies are still relatively few, mostly due to the lack of suitable data, Martin, Muûls, and Wagner (2015) stress that this represents the fast growing branch of literature. In general, available research suggests that, so far, an emission trading has proved to decrease GHG emissions and not to have a negative impact on the economic performance (Martin, Muûls, and Wagner 2015). Irena Raguž Krištić (2017) supports these studies' conclusions by finding that EU ETS had, on average, a positive impact on production cleanliness, that is, production per unit of emissions, but that those effects were limited to regulated industries.

The effects of environmentally related taxes have also been examined separately in many studies. Benoît Bosquet (2000) reviews the vast literature on ex ante simulations of environmental tax effects, concluding that when environmental tax revenues are used to reduce payroll taxes (so-called environmental tax reform [ETR]), and if wage-price inflation is prevented, significant reductions in pollution, small gains in employment, drop in investments, increase in prices, and marginal gains or losses in production are likely in the short to medium run. However, the results are, as they state, less certain in the long run. The precise effects vary depending on the design of the environmental taxes, but more specifically on the design of the revenue recycling mechanism (Roberto Patuelli, Peter Nijkamp, and Eric Pels 2005). If there is no environmental tax revenue recycling, ex ante studies tend to show that it takes much more time for the positive effects on pollution reduction to set in and the negative effects on the economy are more pronounced (e.g., Grant Allan et al. (2014), Sam Meng, Mahinda Siriwardana, and Judith McNeill (2013) and others).

Compared with the extensive literature based on simulating different policy scenarios, ex post studies on environmental taxes are very scarce, despite their policy relevance. Those that exist tend to find a positive impact of environmental taxes on emission reductions (for example, Boqiang Lin and Xuehui Li (2011), Mikael Skou Andersen (2010), and Brian Murray and Nicholas Rivers (2015)) and a decrease in energy intensity and electricity use (Ralf Martin, Laure B. De Preux, and Ulrich J. Wagner 2014) which suggests that taxes are an effective policy for mitigating global warming. They have also proven to be costly (Nikolaos Floros and Andriana Vlachou 2005). However, Skou Andersen (2010) and Murray and Rivers (2015) show only modest negative impacts for emissions-intensive industries and, on average, no negative impacts of carbon-energy taxation on aggregate production levels. Likewise, Martin, De Preux, and Wagner (2014) found no statistically significant impacts for employment, revenue, or plant exit in their micro-econometric study on UK manufacturing plants. Skou Andersen (2010) suggests that these modest negative impacts on production were due to many tax exemptions and occasional revenue recycling schemes. Lin and Li (2011) also stress the role of exemption policies in certain energy intensive industries in the modest results of carbon tax in the domain of emission reductions.

As an alternative, instead of focusing on just one environmental policy instrument, a combination of tradable EP and environmental taxes has been favored in theory by numerous researchers for a long time (Neil Gunningham and Darren Sinclair 1999), specifically in the climate change context (for example, William A. Pizer (2002), Lori Snyder Bennear and Robert N. Stavins (2007), and others). Economic policy has adopted these views as well. However, theoretical views on the optimal combination of policy instruments differ and depend on the shape of the (unknown) benefit and cost functions and the nature and size of uncertainty (Pindyck 2007). Empirical studies can shed more light on this question.

Again, there is a noticeable difference in the amount of ex ante and ex post studies. Ex post studies are very scarce because climate policies are in an infant stage of providing significant results (Vlasis Oikonomou and Catrinus J. Jepma 2008). Most of the existing empirical literature analyzing different instruments are, hence, ex ante, mostly CGE analyses that generally agree with the theoretical conclusions, mostly giving priority to hybrid environmental policy as opposed to taxes, subsidies, and tradable EP (for example, Harrison G. Fell and Richard D. Morgenstern (2010) and Nils Axel Braathen (2011)), and taxes versus tradable EP (e.g., Ian WH Parry, Roberton C. Williams, and Lawrence H. Goulder (1999), Harrison G. Fell, Ian A. MacKenzie and William A. Pizer (2008), Fell and Morgenstern (2010), and others). Ranking of these instruments proves to be dependent on the distinctive features of their design. However, it seems that the use of multiple policy instruments can be justified as optimal in a second-best world (Bennear and Stavins 2007). Combining different policy instruments to address climate change issues has, depending on their exact design, been supported by many studies (Oikonomou and Jepma 2008). However, although theory and ex ante studies are a valuable starting point for understanding the potential consequences of future economic policy, they do not show whether the implemented combination of policy instruments is in fact economically justified in practice, that is, effective at reaching the two goals — helping the environment without hurting the economy (the so-called double dividend). This requires the ex post studies (Kenneth Gillingham, Richard G. Newell, and Karen Palmer 2009).

However, ex post studies that use econometrics to analyze the impacts of multiple instruments on benefits (in the form of higher environmental quality) and costs of regulation (in the form of an adverse effect on economic activity) are almost non-existent. Those that exist are of limited scope. One example are Daniel C. Esty and Michael E. Porter (2005), who analyze the effects that cross-country variations of policy choices have on the environment on a large sample of both developed and developing countries. They conclude that the choice of instrument and the design of the entire regulatory system most likely play a role in the consequences for the environment. However, they do not discuss the relative effectiveness of the specific alternative regulatory instruments nor their impact on economic performance of the country. To the best of our knowledge, there is no ex post comparative analysis of the effects of both environmentally related taxes and EP, on both emissions and production in the existing literature. There is no ex post study on the effectiveness of the currently implemented market-based environmental policy instruments in the EU. This study fills that gap.

It should be noted, however, that the uncertainty over the quantity and price of pollution relative to the optimal production are just one source of constraint for an efficient allocation of pollution through regulation, and this source appears to be systematic. On the other hand, there is another source of constraint which appears to be idiosyncratic on a country-by-country basis and/or regional basis (e.g., EU12 versus EU15 countries). This entails imperfections and specifics of the regulatory design, with respect to both sets of instruments. In this paper, these individual imperfections of the environmental regulatory design are not addressed, and the results are interpreted with that in mind.

3. MODEL

The environmental PM that each country has at its disposal consists of several options. The first one is the status quo (SQ) option, that is, not to intervene with any type of policy in case of environmental degradation. If there is a regulatory intervention, it can be of two broad types: the so-called command and control (CC) regulation and market-based regulation. The CC is the direct regulation of the polluting industry or activity by legislation that states what is and is not permitted, and sanctions the non-compliance to the regulation. Market-based regulation, on the other hand, uses taxes, EP trading, or other instruments as economic incentives to attain the desired level of pollution (McMannus 2009). In general, we can state that the PM is a function of SQ, CC, and market-based instruments — specifically, emissions taxes (ET), and tradable EP, hence:

$$PM = aSQ + bCC + cET + dEP \qquad (1)$$

where the sum of the parameters a, b, c, and d equals to 1. In this paper, however, we focus solely on the selected market-based instruments, and exclusively compare their effectiveness in the environmental PM.

The empirical analysis of the alternative market-based instruments for GHG emissions abatement in the EU is based on profit maximization model where emissions enter production function $Y = f(Z)$ as a production factor. Here, Y represents production as a function of inputs $Z = (K, L, E)$, with K being capital, L labor, and E greenhouse gas emissions. Although emissions are the output of the manufacturing process rather than an input, if they are regulated, they represent a cost to producers, just like labor and capital, either through taxes, tradable permits price, or simply opportunity cost as pointed out by A. Denny Ellerman (2000) and Michael Grubb and Karsten Neuhoff (2006) in the case of free allocation of EP. Therefore, although GHG emissions are a by-product of the production process, they are for the purpose of the analysis alternatively treated as an input to production (William J. Baumol and Wallace E. Oates 1988).

Profit maximization model is then defined as follows:

$$\max_{y,z} pY - \sum wZ \tag{2}$$

$$\text{s.t. } Y = f(Z) \tag{3}$$

$$\max_{z} pf(Z) - \sum wZ \tag{4}$$

where p is the product price, Y is production, Z is production factors' vector, and w is a vector of their prices. Solution of this maximization problem is a vector of the optimal factor demand functions and optimal output level, respectively:

$$Z^*(p, w) \tag{5}$$

$$Y^*\big(Z^*(p, w)\big) \tag{6}$$

Assuming that GHG emissions enter the production function as a production factor and that the production is characterized by constant returns to scale, production, physical capital, and labor can be expressed per unit of GHG emissions (denoted by y, k, and l, respectively). Production per GHG emissions is an inverse of emission intensity of production and called "production cleanliness" following a terminology of Raguž Krištić (2017), where an increase of the production cleanliness is manifested as an increase in production per unit of emissions. However, contrary to Raguž Krištić (2017), in this paper's model, the measure of production cleanliness is theoretically more consistently related to the other factors of production. So equation 6 can be rewritten as

$$y^*\big(z^*(p, w)\big) \tag{7}$$

where y measures production cleanliness, and z is a vector of capital and labor per unit of emissions.

The empirical model is based on theoretical model in equation 7 and includes additional explanatory variables. More specifically, the econometric model is formulated as follows:

$$y_{i,t} = \beta' \cdot z_{i,t} + \gamma \cdot r_{i,t} + \delta \cdot x_{i,t} + \alpha_i + u_{i,t} \tag{8}$$

where $y_{i,t}$ represents production cleanliness of country i at time t, $z_{i,t}$ is the vector of production factors per unit of emissions, $r_{i,t}$ represents the vector of emission regulation variables, $x_{i,t}$ vector of control variables, α_i are either country specific fixed constants or random variables, depending on the methodology of estimation. Finally, $u_{i,t}$ is the error term.

Vector of regulatory variables r includes not only variables of environmental taxes and emissions permits but also an interactive term used to test the synergy effect of simultaneous use of these two market-based instruments. As a form of robustness check, not only alternative measures of production cleanliness but also EP and tax variables are included in the analysis. Robustness analysis also includes models which use production prices as explanatory variables instead of production factors' quantities (based on equation 7). In addition, the difference of the regulation impacts on EU12 and EU15 is analyzed. And finally, the results of the entire period of observation are compared with the results of the second trading period as an additional robustness check.

4. DATA AND METHODOLOGY

4.1. Data

The variables in the model are selected based on empirical model presented in the previous section. Series of spatial and temporal data that are used in the analysis had to, as the first condition, comply with the described economic theory. The temporal range of data covers the period from 2005 to 2012, starting with the first year of the first EU ETS trading period and ending with the last year of the second EU ETS trading period. Data cover EU member states for the last observed period, namely, EU27. EU27 consists of so-called “old” member states of EU15 (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and the United Kingdom) and the “new” member states or EU12 (Bulgaria, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia, and Slovenia). The data were collected from the AMECO database of the European Commission[5], Eurostat, European Environment Agency (EEA), and World Development Indicators (WDI). Table 1 summarizes all the variables, their descriptions, and sources in alphabetical order.

Dependent variables in the model, so-called measures of production cleanliness, are represented by the variables *GDPGHG* and *GDPCO2* at the national level and *GVAindGHGenergy*, *GVAindGHGenind*, and *GVAindGHGets* at the regulated industry level. Explanatory variables of the model are labor per unit of emissions (*LGHG*, *LCO2*, *LGHGenergy*, *LGHGenind*, *LGHGets*) and physical capital per unit of emissions (*KGHG*, *KCO2*, *KGHGenergy*, *KGHGenind*, and *KGHGets*). For a robustness analysis, model with factor (*w, w_ind, r,*) and product prices (*INFcpi*) as explanatory variables is also examined. Total factor productivity variable (*TFP)* is also included as an explanatory variable.

Regulation variables used in the model are taxes and EP. Energy taxes (*EnergTgdp*) and environmental taxes (*EnvTgdp*) represent taxation policy that impacts the production cleanliness. The EP variables are represented by *EUAgvaind*, *FEUAgvaind*, and *EUApc*. Energy tax variable is included in the main analysis and environmental taxes in the robustness analysis because energy taxes are the taxes that affect the air pollution the most. Environmental taxes, on the other hand, contain, in addition to energy taxes, some other environmental taxes, which do not address air pollution but other forms of pollution and biodiversity preservation.

Finally, there is a set of control variables used in the analysis: *HCpc, TFR, RD, RENEW,* and *Crisis*.

Table 1. Variables and data

Variable Name	**Description/Calculation**	**Source**
CO2	Total CO_2 emissions in million tons	EEA
Crisis	Dummy variable: 1 for the recession (at least two consecutive quarters of negative economic growth) in the observed country, 0 for no recession	—
EnergTgdp	Energy tax revenues as a share of GDP	Eurostat

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[5] The annual macro-economic database of the European Commission's Directorate General for Economic and Financial Affairs.

EnvTgdp	Total environmental tax revenues as a share of GDP	Eurostat
EUAgvaind	The share of total emission unit allowances (EUAs) in the industrial gross value added (GVA)	Eurostat
EUApc	EUAs per capita	Eurostat
FEUAgvaind	The share of total freely allocated emission unit allowances (EUAs) in the industrial GVA	Eurostat
GDP	Real GDP in millions of euro, chain-linked volumes, reference year 2005, at 2005 exchange rates	Eurostat
GDPCO2	GDP/CO_2	—
GDPGHG	GDP/GHG	—
GHG	Total GHG emissions in million tons	EEA
GHGenergy	GHG emissions from energy sector in thousand tons of CO_2 equivalent (EEA code: CRF_1)	EEA
GHGenind	GHG emissions from energy sector, industrial processes and product use in thousand tons of CO_2 equivalent (EEA code: CRF_1 and CRF_2)	EEA
GHGets	GHG emissions from energy industries, manufacturing industries and construction, industrial processes and product use in thousand tons of CO_2 equivalent (EEA code: CRF_1A1, CRF_1A2 and CRF_2)	EEA
GVAind	Constant GVA, NACE Rev2 Industry B-E in millions of euro, chain-linked volumes, reference year 2005, at 2005 exchange rates	Eurostat
GVAindGHGenergy	*GVAind/GHGenergy*	—
GVAindGHGenind	*GVAind/GHGenind*	—
GVAindGHGets	*GVAind/GHGets*	—
HCpc	Enrolment in secondary education per capita	WDI
INFcpi	Inflation in percentages based on consumer price index	WDI
K	Net capital stock at 2010 prices in billions of euro	AMECO
KCO2	*K/CO2*	—
KGHG	*K/GHG*	—
KGHGenergy	*K/GHGenergy*	—
KGHGenind	*K/GHGenind*	—
KGHGets	*K/GHGets*	—
L	Employment	Eurostat
LCO2	*L/CO2*	—
LGHG	*L/GHG*	—
LGHGenergy	*L/GHGenergy*	—
LGHGenind	*L/GHGenind*	—
LGHGets	*L/GHGets*	—
r	Net returns on net capital stock expressed as index with a base year 2010	
RD	Research and development (R&D) as a share of GDP	Eurostat
RENEW	The share of renewable energy in gross final energy consumption	Eurostat

TFP	Total factor productivity , an index with a base in 2010	AMECO
TFR	Total fertility rate	Eurostat
w	Total wages and salaries as a percentage of GDP	Eurostat
w_ind	Wages and salaries in industry (except construction) as a percentage of GDP	Eurostat

4.2. Methodology

In accordance with the collected data for which there is spatial and temporal dimension, static panel data analysis is used. Before testing the empirical models, we test the series for unit roots, and we tested for the violation of assumptions in the linear regression model. Fisher-type unit root test (In Choi 2001) and Im-Pesaran-Shin (Kyung So Im, M. Hashem Pesaran, and Yongcheol Shin 2003) unit root test for panel data are used (the results are available from the authors upon request). The variables are then transformed where necessary to obtain stationary series for the empirical analysis. Logarithms and first differences of logarithms are taken of stationary variables, that is, of the non-stationary variables, respectively.

The test of multicollinearity is based on correlation matrix (available from authors upon request) and highly correlated explanatory variables are omitted from further analysis. Homoscedasticity assumption is tested using the modified Wald test for groupwise heteroscedasticity following William Greene (2000). Wooldridge test is used for autocorrelation (Jeffrey M. Wooldridge 2002) and Pesaran test for cross-sectional dependence (M. Hashem Pesaran 2004). The analysis shows that all of the models violate the assumptions of no autocorrelation and homoscedasticity (Table A7). Pesaran test for cross-sectional dependence could not be performed due to insufficient common observations. However, if any one of the explanatory variables is excluded from the analysis, the test shows very high average absolute correlation, suggesting the presence of cross-sectional dependence in the errors. More specifically, although the Pesaran test in our case fails to reject the null hypothesis that the residuals are spatially independent, the main disadvantage of this test is a high probability of erroneous acceptance of the null in the case of alternating signs of the coefficients of correlation between the residuals, which is the case in this analysis. Rafael E. De Hoyos and Vasilis Sarafidis (2006), hence, propose the calculation of the average absolute correlation and the construction of correlation matrix of residuals. High enough average absolute correlation, 0.4 or higher according to De Hoyos and Sarafidis (2006), is in itself sufficient evidence that suggests the existence of spatial dependence. All of the correlation matrices and related results are available from the authors upon request.

Given the obtained results of autocorrelation, heteroscedasticity, and cross-sectional dependence, we base our empirical analysis on robust errors, that is, errors corrected for cross-sectional dependence, heteroscedasticity, and autocorrelation with the Driscoll-Kraay estimators (John C. Driscoll and Aart C. Kraay 1998) adjusted for unbalanced panels by Daniel Hoechle (2007).

The choice of the fixed effects models was based on the Modified Hausman test (Hoechle 2007), used instead of the standard Hausman (1978) test due to the suspected presence of cross-sectional dependence in all of the estimated models.

To test the presence of endogeneity in the model, Sargan test of overidentifying conditions is used after the Arellano-Bond estimation (Manuel Arellano and Stephen Bond 1991). The test rejects the null hypothesis of valid overidentifying restrictions, supporting the use of the static panel data analysis (Table A7). However, because the Sargan test has a tendency to overreject the null hypothesis in the presence of heteroscedasticity (Arellano and Bond, 1991), dynamic panel estimation results are presented for the main models as an additional robustness check.

5. RESULTS AND DISCUSSION

The empirical analysis focuses on the marginal effects of the taxes and EP on the production cleanliness in the EU. Because the interactive effect of these two instruments is also considered, marginal effects of each instrument are calculated as the first derivative of the estimated function with respect to that instrument, given some constant value of all other variables. We use the mean values of policy variables for the calculation of these marginal effects. The mean values of logarithms of regulation variables are shown in Table 2 for the full sample, for the sample period of the second EU ETS trading period (namely, from 2008 to 2012), and for the EU15 and the EU12 countries.

Table 2. Mean values of logarithms of environmental regulation variables

Variables	**Full Sample**	**2nd Trading Period**	**EU15**	**EU12**
lnEnergTgdp	0.6025	0.6240	0.5584	0.6611
lnEnvTgdp	0.9131	0.9022	0.9189	0.9053
lnEUAgvaind	0.3844	0.4030	−0.0806	1.0044
lnFEUAgvaind	0.3727	0.3845	−0.0944	0.9955
lnEUApc	−5.4086	−5.4363	−5.4591	−5.3414

First, the analysis focuses on the impacts that the two instruments have at a national level to find the effects of regulation on the aggregate production cleanliness of EU Member Countries. This analysis is then followed by the industry-level analysis, focusing more specifically on the effects regulation has on the regulated industries in the EU.

5.1. National-level Analysis

The results of the main empirical model estimated at the national level (model 1) are shown in Table 3. Before discussing the regulation variables in more detail, it can be noted that, as expected, there is, on average, a positive impact of both share of labor and share of physical capital in the emissions on the production cleanliness at the national level. Crisis and the share of renewables in the energy consumption do not have a significant effect at the 10% significance level. TFP and R&D, on the other hand, have a positive impact on the production cleanliness at the aggregate level.

The analysis of the regulatory variables' impact shows that energy taxes per se, on average, negatively impact production cleanliness in the EU. Stricter EU ETS regulation (i.e., decreasing a number of permits available in the market), on the other hand, is expected to have a positive impact on the cleanliness of the European production. Additionally, on average, there is a positive impact on production cleanliness coming from the interaction between these two regulatory instruments in the market. Overall, at 5% significance level, increase in the share of energy taxes in GDP by 1% is expected to decrease production cleanliness by 0.012%. On the other hand, decrease in the share of EP in the industrial gross value added (GVA) will, on average, increase production cleanliness in the EU by 0.007% (Table 4). However, although these marginal effects are statistically significant, they are nonetheless very small.

Table 3. Estimation output for production cleanliness at the national level (model 1)

Model	**(1)**
Variables	**lnGDPGHG**
lnLGHG	0.448***
	(0.023)
lnKGHG	0.490***
	(0.016)
lnEnergTgdp	−0.030***
	(0.008)
lnEUAgvaind	−0.035***
	(0.006)
lnEnergTgdp_lnEUAgvaind	0.046**
	(0.014)
dHCpc	0.008
	(0.053)
lnTFR	0.046***
	(0.012)
lnTFP	1.032***
	(0.042)
dRD	0.035**
	(0.012)
lnRENEW	−0.013*
	(0.006)

T	0.001
	(0.001)
Crisis	0.003*
	(0.001)
Constant	−20.78***
	(0.983)
Observations	178
Number of groups	27

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Robustness analysis is conducted considering alternative variables (models 1a to 1e), alternative methodology, namely, dynamic panel (models 1_dyn to 1e_dyn), and different subsamples (models 1f to 1k). Models 1a, 1b, and 1c replace the regulation variables from model 1, model 1d uses CO_2 emissions instead of GHG emissions from model 1, and model 1e uses factor and product prices instead of factor quantities as independent variables, following equation (7). Models 1_dyn to 1e_dyn are estimated using Arellano and Bond (1991) methodology. Models 1f to 1k are estimated on the EU15 and EU12 subsamples independently, as well as for all of the countries but just for the 2nd trading period.

Estimation output of these 17 models is provided in Tables A1 to A3 of the Appendix and Table 4 below shows the marginal effects derived from these estimation results.

The result that proves to be robust at the national level is that an increase in the share of taxes is expected to have a negative effect on the production cleanliness. The only exceptions are the two models: 1c_dyn and 1e_dyn which show, on average, no significant impact of environmental, that is, energy taxes on production cleanliness. This relatively robust negative impact seems to be more pronounced in EU12 countries compared with EU15 and during the second EU ETS trading period (model 1j), then in the entire observed sample (model 1).

Marginal effects of the EU ETS on the production cleanliness at the national level are also very robust. All of the analyzed models show an inverse relation between cleaner production and number of permits available. That suggests that a decrease in the share of available number of permits for “dirty” production in industrial GVA, on average, has a positive impact on the cleanliness of GDP. The only exceptions are model 1b, which suggests that a decrease in permits per capita on average decreases production cleanliness, and model 1e_dyn, which shows no statistically significant impact of EU ETS on production cleanliness at the national level.

Regarding the effects of the PM, the results are not robust. As mentioned earlier, model 1 shows a positive effect from the combined use of EU ETS and taxes at the aggregate level in the EU. Almost all of the static models also support this finding (Tables A1 and A3). However, with the exception of the model 1b_dyn, the dynamic models find no statistically significant effect that comes from the simultaneous use of these two policy instruments (Table A2). However, although we cannot conclude with absolute certainty whether the current PM yields positive effects for the production cleanliness, we do have a relatively robust proof that they do not affect it adversely. This is visible in Figure 1 where we see most of the models resulting with positive coefficients (represented by tickers), and for most of them, zero value is outside of their confidence interval implying the rejection of the null hypothesis.

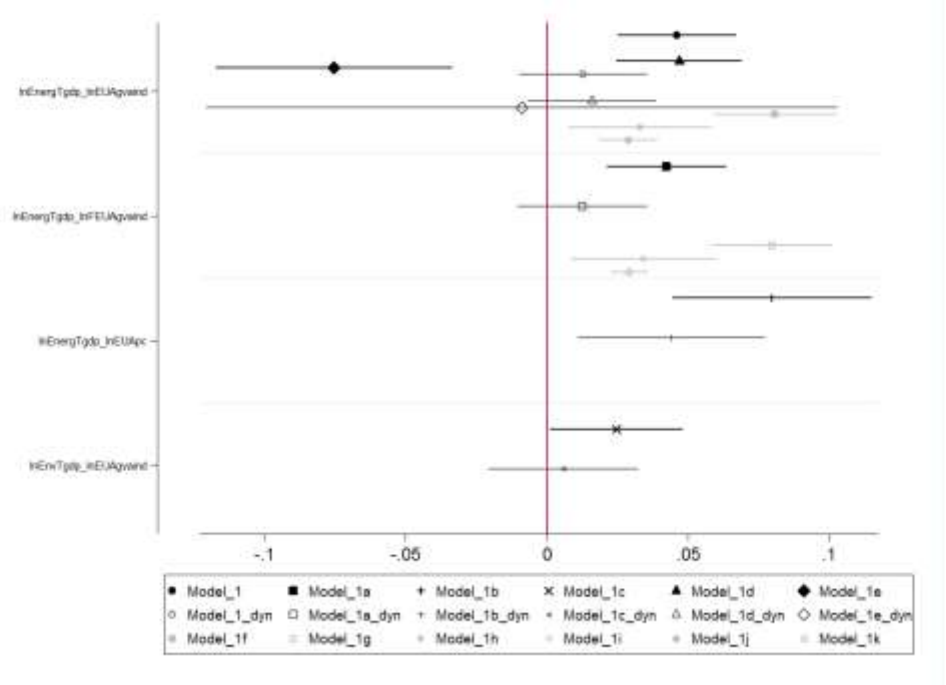
The analysis of the subsamples shows that, comparing the results for the EU15 and EU12 countries, the negative effects of taxes are more pronounced in the EU12 countries and that EU ETS is more effective in the EU15 countries. So, the functioning of both instruments appears to be better in the EU15. And finally, the results show that EU ETS was more effective during the second trading period.

Table 4. Marginal effects from model 1 and the corresponding robustness analysis models

Model		**Variables**				
		lnEnergTgdp	**lnEnvTgdp**	**lnEUAgvaind**	**lnFEUAgvaind**	**lnEUApc**
(1)		−0.01		−0.01		
(1a)		−0.01			−0.01	
(1b)		−0.01				0.01
(1c)			0.00 (I)	−0.03		
(1d)		−0.01		−0.01		
(1e)		−0.03 (II)		−0.05		
(1_dyn)		−0.03		−0.03		
(1a_dyn)		−0.03			−0.03	
(1b_dyn)		−0.22 (III)				−0.01
(1c_dyn)			0.00	0.00 (IV)		
(1d_dyn)		−0.03		−0.03		
(1e_dyn)		0.00		0.00		
(1f)	EU15==1	−0.01		−0.03		
(1g)	EU15==1	−0.01			−0.03	
(1h)	EU15==0	−0.03		0.022 (V)		
(1i)	EU15==0	−0.03			0.02 (VI)	
(1j)	2ndTP	−0.04		0.01		
(1k)	2ndTP	−0.04			−0.02	

Notes: Displayed marginal effects represent a percentage change in production cleanliness due to 1% change in regulatory variables at 5% significance level. At 10% significance, marginal effects are: (I) 0.02, (II) −0.10, (III) −0.00, (IV) −0.03, (V) 0.00, and (VI) −0.00.

Figure 1. Interaction terms' coefficients and confidence intervals across model 1 and corresponding robustness models



5.2. Industry-level Analysis

The results of the main empirical model estimated at the industry level (model 2) are shown in Table 5. Again, before discussing the regulation variables in more detail, we focus on production factors and other non-policy explanatory variables. Model 2 shows a negative impact of share of labor in the emissions on the production cleanliness at the industry level. This result is, however, not robust. Tables A4, A5, and A6 in the Appendix provide conflicting results on the role of labor in production cleanliness of the analyzed sectors — negative in the static models of the full sample, positive in dynamic models and for the EU15 subsample, and not significant for the EU12 subsample and for the second trading period. Capital, on the other hand, has, on average, a robust positive impact on their production cleanliness. The crisis and the share of renewables in the energy consumption show no significant impact on the regulated industries' production cleanliness in the model 2. The result for the crisis is again not very robust, as the robustness analysis estimates in the Appendix show. Interestingly, although the share of renewables appears mostly insignificant, a couple of models of the robustness analysis do find a negative relationship between renewables and production cleanliness (models 2b, 2c, 2i, 2j, and 2k). TFP and R&D, on the other hand, show robust positive impact on industry-level production cleanliness.

The analysis of the regulatory variables' impact shows that both instruments, on average, contribute to the cleaner production of the regulated industries in the EU, both individually and together, as the estimated coefficients in Table 5 and derived marginal effects in Table 6 clearly show. Contrary to national-level results, an increase in the share of energy taxes in GDP by 1% is expected to increase production cleanliness by 0.16%. A decrease in the share of EP in the industrial GVA will, on average, also increase industrial production cleanliness in the EU by 0.118% (Table 6). And although these marginal effects are still quite small, they are more pronounced than at the aggregate level.

Table 5. Estimation output for industry level production cleanliness (model 2)

MODEL	**(2)**
VARIABLES	**lnGVAindGHGenergy**
lnLGHGenergy	−0.153**
	(0.054)
lnKGHGenergy	0.822***
	(0.062)
lnEnergTgdp	0.092***
	(0.024)
lnEUAgvaind	−0.224***
	(0.037)
lnEnergTgdp_lnEUAgvaind	0.176**
	(0.050)
dHCpc	0.074
	(0.082)
lnTFR	−0.124
	(0.087)
lnTFP	2.130***
	(0.206)
dRD	0.098*
	(0.042)
lnRENEW	−0.045
	(0.024)
T	−0.001
	(0.004)
Crisis	0.006
	(0.012)

Constant	−48.55*** (4.458)
Observations	178
Number of groups	27

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Robustness analysis of the industry-level model is again conducted using alternative variables (models 2a to 2f), alternative, dynamic panel, methodology (models 2_dyn to 2f_dyn) and different subsamples (models 2g to 2l). Models 2a, 2b and 2c replace the regulation variables from model 2, models 2d and 2e use alternative emissions variables (GHGenind and GHGets instead of GHGenergy), and model 2f uses factor and product prices instead of factor quantities as independent variables, following equation (7). Models 2_dyn to 2f_dyn are estimated using Arellano and Bond (1991) methodology. Models 2g to 2l are estimated on the EU15 and EU12 subsamples independently, as well as for all of the countries but just for the 2nd trading period.

Estimation output of these 19 models is provided in Tables A4 – A6 of the Appendix and Table 6 below shows the marginal effects derived from these estimation results.

The results on the effects of the two policy instruments on production cleanliness appear to be robust in their conclusions that there are no adverse effects of any of them. The models of the robustness analysis mainly confirm their positive effects, whereas some of them find no statistically significant effect. An increase in the share of taxes has a positive impact on the industrial production cleanliness in all of the models except for the most of dynamic models (Table 6) and for the EU12 countries. Favorable marginal effects of the EU ETS on the production cleanliness at the industrial level prove to be more robust, with only three models finding no statistically significant relationship.

Again, it should be noted that the effect stemming from the interaction of the two analyzed instruments in this PM does not appear to be robustly positive. Namely, only eight of nineteen robustness checks show a positive impact of this PM, whereas the rest do not find any significant effect from the policy interaction (Figure 2).

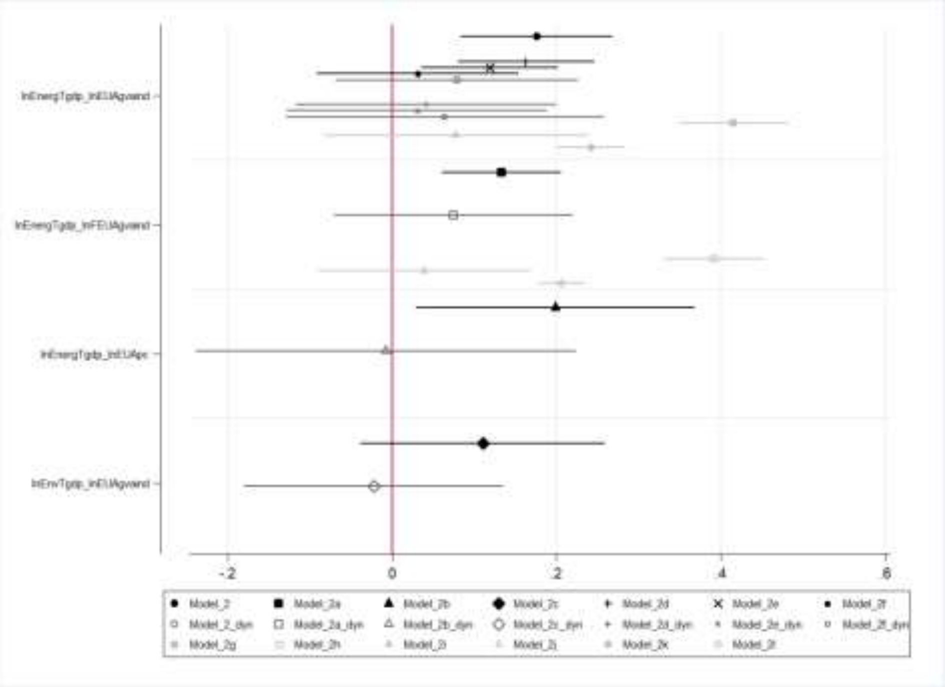
And finally, the analysis of the subsamples showed that when comparing the results for the EU15 and EU12 countries, there are positive effects from taxes in the EU15 countries, whereas EU12 countries, on average, do not see positive (nor negative) effects of energy taxes. Also, EU15 countries see more beneficial effects from the emissions trading than the EU12 countries (Table 6). In addition, the interaction of these two policy instrument does not yield positive effects on production cleanliness in the EU12, whereas it does in the EU15 countries (Figure 2). More beneficial effects of the EU ETS are also found for the second trading period compared to the full sample (Table 6).

Table 6. Marginal effects from model 2 and the corresponding robustness analysis models

MODEL	**VARIABLE**				
	lnEnergTgdp	lnEnvTgdp	lnEUAgvaind	lnFEUAgvaind	lnEUApc
(2)	0.16		−0.12		
(2a)	0.18			−0.18	
(2b)	1.22				0.00 (I)
(2c)		0.19	−0.22		
(2d)	0.16		−0.12		
(2e)	0.14		−0.13		
(2f)	0.13		−0.25		
(2_dyn)	0.00		−0.19		
(2a_dyn)	0.00			−0.22	
(2b_dyn)	0.00				0.00
(2c_dyn)		0.00 (II)	0.00 (III)		
(2d_dyn)	0.00		−0.17		
(2e_dyn)	0.00		−0.17		
(2f_dyn)	0.00		−0.22		
(2g) EU15==1	0.20		−0.15		
(2h) EU15==1	0.21			−0.20	
(2i) EU15==0	0.00		−0.14		
(2j) EU15==0	0.00			−0.16	
(2k) 2ndTP	0.10		−0.25		
(2l) 2ndTP	0.08			−0.41	

Notes: Displayed marginal effects represent a percentage change in production cleanliness due to 1% change in regulatory variables at 5% significance level. At 10% significance, marginal effects are: (I) 0.12, (II) 0.16 and (III) −0.14.

Figure 2. Interaction terms' coefficients and confidence intervals across model 2 and corresponding robustness models



5.3. Discussion

The results obtained from this ex post analysis lead us to several conclusions regarding the effectiveness of the environmentally related taxes and emissions trading permits in the EU during the period from 2005 to 2012. First, there are, on average, differences in their effects at the national compared to industrial level. We find negative impact of taxes on production cleanliness at the aggregate level, but positive effect at the level of regulated industries. Also, there is a smaller positive effect of the EU ETS at the national compared to the industry level. In general, contrary to the aggregate economy, there are no adverse effects for the industrial production cleanliness from neither of the instruments. This difference is most likely due to the limited availability of the substitutes for the products of the regulated industries, so the cost of regulation is taken on mostly by the final consumers.

Second, contrary to the expectations based on the related literature, both at the national and industrial level, at their current design, EP system appears to be more effective at reaching the cleaner production than the taxes. This is despite the fact that, in theory, revenues from taxes can be recycled and revenues from EU ETS cannot. This might be due to the specific design issues, such as tax exemption policies (Lin and Li 2011), causing more modest emission reductions, and/or the lack of the tax revenue recycling (Patuelli, Nijkamp and Pels 2005), causing higher costs for the economies than necessary. In addition, the fact that the taxes are managed at the country level makes it difficult to coordinate their efforts and ensure their use exclusively for achieving environmentally related goals. EU ETS, on the other hand, is mostly managed at the European level, so its design, performance and effectiveness at reaching environmentally related goals is closely monitored and managed at the European level, with the sole purpose of achieving specific emissions reductions at the minimal cost for the economies. However, without controlling for the specifics of the tax and emissions trading design in the econometric analysis, the reasons for this (based on available ex ante analyses, unexpected) advantage of emissions permits remain an open question.

Third, it is not clear whether there are positive effects from the interaction of the instruments in this particular PM; however, on average, the analysis did not show any negative ones. This finding appears to be in line with findings such as the study by Kai Schlegelmilch and Maike Bunse (2006) which stresses the complementarity of the two instruments. However, although there are apparently no significant efficiency losses that, for example, Christoph Böhringer, Henrike Koschel and Ulf Moslener (2008) as well as Skou Andersen (2010) warn about, to have the best results in this second-best setting policy coordination should be prioritized (Goulder, 1998).

And the fourth conclusion regarding the effectiveness of the taxes and permits in the EU is that both instruments appear to be more effective in achieving cleaner production in the EU15 than in the EU12, although those differences are more pronounced in the case of taxes than EP, both at the aggregate and industry level. This result in the case of EP is in line with Raguž Krištić (2017) study that found no significant difference in the effectiveness of the EU ETS in EU15 and EU12 industries. It is an interesting result because EU12 were given more permits than they actually needed on the grounds of fairness and there was no pressure to reduce the emissions. The positive effects on the production cleanliness in the EU12 must have come from production increase and in EU15 from both emission reductions and slower production growth. However, again, without controlling for the idiosyncratic specifics of the tax and emissions trading design in the econometric analysis on a country-by-country basis, the reasons for this difference in the effectiveness of both instruments between EU12 and EU15 countries remain unknown.

Finally, it is interesting to stress the finding that, on average, crisis did not significantly affect production cleanliness in the EU, neither at the national nor industrial level. The results from this paper are not in line with the conclusions from the available literature that suggest that there was a partial switch to more dirty production inputs during the crisis.

6. CONCLUSION

The aim of this paper was to bridge the gap in the existing empirical literature by providing an ex post analysis of the effectiveness of both environmental taxes and emissions trading in achieving cleaner production, that is, higher production per unit of emissions in the EU. Our analysis did not robustly confirm the hypothesis that, in addition to their individual contributions, combined use of environmental taxes and EP yields synergistic benefits in terms of cleaner production. However, we did robustly confirm that there are no negative effects on the production cleanliness from the interaction of these instruments.

Additionally, we found a couple of other interesting robust results. First, we found that, on average, the effects of both instruments are more beneficial for the regulated industries than at the national level. Second, emission trading is, on average, more effective than taxes at achieving increases in production cleanliness. Third, both instruments appear to be more effective in the EU15 than in the EU12. And fourth, the crisis did not significantly affect production cleanliness in the EU.

There are limitations of the study that should be stressed. The first limitation is the short period of just 8 years. The analysis covered just the first two EU ETS trading periods, because the coverage and the design of this system in the third period (2013–2018) has changed too much to make the data from all of the three trading periods comparable. The second limitation is due to imperfect comparability between the industry sectors classified by the Intergovernmental Panel on Climate Change (IPCC) (which categorizes emissions) and those classified by the Statistical classification of economic activities in the European Community (NACE) (which categorizes output). That is why the production cleanliness variables at the industrial level can be viewed only as approximations of the real production cleanliness of the regulated sectors. And third, this paper focuses on systematic uncertainty over the cost and benefits of pollution abatement and hence the optimal quantity and price of pollution. It does not, however, control for idiosyncratic uncertainty regarding imperfections and specifics of the regulatory design on a country-by-country basis and/or regional basis as well as on an instrument basis. It would be extremely informative to use the data on differences in the regulatory designs of both instruments in every country which could hopefully provide us with some answers as to why emissions trading is currently more effective than taxes and why there are such significant differences between EU12 and EU15 countries. This is the avenue for future research.

Finally, several recommendations for the economic policy can be drawn from the conclusions of this empirical research. From the results of the analysis it is obvious that stricter regulation through the decrease of available tradable EP imposes itself as the more effective approach to achieve cleaner production in the EU. Models suggest that further tightening of environmental tax regulation, especially through additional environmentally related (energy) taxes in their present form, although favorable at the industry level, would be counterproductive at the aggregate level. The changes in the design of the environmental tax system and its interaction with the EU ETS could be beneficial. However, there are many areas of policy interactions that need to be examined to find the exact answer to the question what precisely needs to be changed in the current design of the environmental taxes and their interactions with the EU ETS. However, this is beyond the scope of this study.

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APPENDIX

Table A1. Robustness analysis for model 1 – alternative variables

MODEL	**(1a)**	**(1b)**	**(1c)**	**(1d)**	**(1e)**
VARIABLES	**lnGDPGHG**	**lnGDPGHG**	**lnGDPGHG**	**lnGDPCO2**	**lnGDPGHG**
lnLGHG	0.452***	0.462***	0.452***		
	(0.022)	(0.021)	(0.026)		
lnKGHG	0.486***	0.476***	0.475***		
	(0.015)	(0.010)	(0.016)		
lnEnergTgdp	−0.026***	0.419**		−0.027**	−0.067*
	(0.007)	(0.121)		(0.008)	(0.029)
lnEUAgvaind			−0.033**	−0.035***	0.012
			(0.009)	(0.006)	(0.033)
lnEnergTgdp_lnEUAgvaind				0.047**	−0.075**
				(0.015)	(0.028)
dHCpc	0.012	−0.001	−0.002	0.012	−0.318**
	(0.053)	(0.037)	(0.047)	(0.054)	(0.128)
lnTFR	0.040***	0.045***	0.040***	0.037**	0.154*
	(0.010)	(0.008)	(0.011)	(0.013)	(0.077)
lnTFP	1.021***	0.979***	0.985***	1.041***	0.442**
	(0.038)	(0.022)	(0.038)	(0.044)	(0.147)
dRD	0.033**	0.038***	0.034**	0.034**	−0.022
	(0.012)	(0.010)	(0.010)	(0.012)	(0.031)
lnRENEW	−0.013*	−0.013***	−0.015*	−0.013*	0.046
	(0.006)	(0.003)	(0.007)	(0.006)	(0.024)
T	0.001	0.002*	0.002*	0.001	0.024***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.004)
Crisis	0.003*	0.001	0.002	0.003*	0.030***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.006)
lnFEUAgvaind	−0.040***				
	(0.008)				
lnEnergTgdp_lnFEUAgvaind	0.043**				
	(0.014)				
lnEUApc		−0.037**			
		(0.012)			
lnEnergTgdp_lnEUApc		0.080**			
		(0.023)			
lnEnvTgdp			−0.019*		
			(0.009)		
lnEnvTgdp_lnEUAgvaind			0.025		
			(0.016)		
lnLCO2				0.453***	
				(0.022)	
lnKCO2				0.498***	
				(0.017)	
Lnw					0.019
					(0.159)
Lnr					0.011
					(0.055)
INFcpi					0.003
					(0.002)
Constant	−20.53***	−19.82***	−19.65***	−21.06***	−2.267
	(0.878)	(0.588)	(0.889)	(1.022)	(3.522)
Observations	178	180	178	178	178
Number of groups	27	27	27	27	27

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A2. Robustness analysis for model 1 – dynamic panel analysis

MODEL	**(1_dyn)**	**(1a_dyn)**	**(1b_dyn)**	**(1c_dyn)**	**(1d_dyn)**	**(1e_dyn)**
VARIABLES	**lnGDPGHG**	**lnGDPGHG**	**lnGDPGHG**	**lnGDPGHG**	**lnGDPCO2**	**lnGDPGHG**
lnGDPGHG = L,	−0.049*	−0.048*	−0.029	−0.045*		0.065
	(0.027)	(0.027)	(0.029)	(0.027)		(0.132)
lnLGHG	0.469***	0.470***	0.462***	0.465***		
	(0.019)	(0.019)	(0.020)	(0.019)		
lnKGHG	0.503***	0.503***	0.510***	0.507***		
	(0.022)	(0.022)	(0.022)	(0.023)		
lnEnergTgdp	−0.029**	−0.029**	0.217*		−0.033**	0.037
	(0.015)	(0.015)	(0.111)		(0.014)	(0.069)
lnEUAgvaind	−0.027***			−0.027*	−0.027***	−0.053
	(0.010)			(0.0144)	(0.010)	(0.050)
lnEnergTgdp_lnEUAgvaind	0.013				0.016	−0.009
	(0.013)				(0.014)	(0.068)
dHCpc	0.038	0.040	0.030	0.035	0.038	−0.241*
	(0.028)	(0.028)	(0.027)	(0.028)	(0.028)	(0.130)
lnTFR	0.005	0.004	0.008	0.008	0.006	0.049
	(0.024)	(0.025)	(0.024)	(0.024)	(0.024)	(0.119)
lnTFP	0.978***	0.974***	0.995***	0.996***	0.980***	0.508**
	(0.039)	(0.040)	(0.039)	(0.037)	(0.039)	(0.231)
dRD	0.011	0.010	0.016*	0.013	0.011	0.016
	(0.009)	(0.009)	(0.009)	(0.009)	(0.009)	(0.043)
lnRENEW	−0.021**	−0.021**	−0.024***	−0.021**	−0.022***	0.071*
	(0.008)	(0.008)	(0.008)	(0.008)	(0.008)	(0.041)
T	0.002*	0.002*	0.002	0.002	0.002*	0.020***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.005)
Crisis	0.002	0.002	0.001	0.002	0.002	0.024***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.009)
lnFEUAgvaind		−0.028***				
		(0.010)				
lnEnergTgdp_lnFEUAgvaind		0.013				
		(0.014)				
lnEUApc			−0.037***			
			(0.013)			
lnEnergTgdp_lnEUApc			0.044**			
			(0.020)			
lnEnvTgdp				−0.014		
				(0.018)		
lnEnvTgdp_lnEUAgvaind				0.006		
				(0.016)		
lnGDPCO2 = L,					−0.051**	
					(0.023)	
lnLCO2					0.468***	
					(0.019)	
lnKCO2					0.508***	
					(0.022)	
Lnw						0.267
						(0.179)
Lnr						0.043
						(0.097)
INFcpi						0.002
						(0.002)
Constant	−19.48***	−19.40***	−20.23***	−19.89***	−19.53***	−5.710
	(0.969)	(0.987)	(0.960)	(0.938)	(0.957)	−4.214
Observations	149	149	150	149	149	149
Number of ID	27	27	27	27	27	27

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A3. Robustness analysis for model 1 – analysis of subsamples

MODEL	**(1f)**	**(1g)**	**(1h)**	**(1i)**	**(1j)**	**(1k)**
	EU15==1	**EU15==1**	**EU15==0**	**EU15==0**	**2ndTP**	**2ndTP**
VARIABLES	**lnGDPGHG**	**lnGDPGHG**	**lnGDPGHG**	**lnGDPGHG**	**lnGDPGHG**	**lnGDPGHG**
lnLGHG	0.487***	0.482***	0.458***	0.459***	0.428***	0. 429 ***
	(0.016)	(0.016)	(0.037)	(0.037)	(0.016)	(0. 016)
lnKGHG	0.477***	0.488***	0.467***	0.466***	0.535***	0. 531***
	(0.014)	(0.016)	(0.035)	(0.034)	(0.023)	(0. 025)
lnEnergTgdp	0.0005	0.001	−0.058***	−0.060***	−0.041***	−0. 040***
	(0.006)	(0.005)	(0.012)	(0.012)	(0.007)	(0. 007)
lnEUAgvaind	−0.071***		−0.021*		−0.029***	
	(0.006)		(0.011)		(0.011)	
lnEnergTgdp_lnEUAgvaind	0.081***		0.033**		0.029***	
	(0.012)		(0.014)		(0.006)	
dHCpc	−0.017	−0.014	0.055	0.057	0.119***	0. 117***
	(0.024)	(0.022)	(0.075)	(0.076)	(0.030)	(0. 034)
lnTFR	−0.009	0.002	0.077***	0.075***	0.081***	0. 072
	(0.009)	(0.004)	(0.007)	(0.007)	(0.029)	(0. 028)
lnTFP	1.018***	1.011***	1.019***	1.019***	1.065***	1. 044***
	(0.027)	(0.022)	(0.077)	(0.078)	(0.047)	(0. 055)
dRD	0.024***	0.022***	0.019	0.019	0.021***	0.019***
	(0.006)	(0.006)	(0.012)	(0.012)	(0.005)	(0. 006)
lnRENEW	−0.015**	−0.018***	0.016	0.016	−0.017***	−0. 017***
	(0.005)	(0.005)	(0.012)	(0.012)	(0.007)	(0.007)
T	0.000	0.000	0.001	0.001	0.001	−0. 001
	(0.001)	(0.000)	(0.002)	(0.002)	(0.001)	(0.001)
Crisis	0.005***	0.005***	−0.002	−0.002	0.004***	0. 004***
	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
lnFEUAgvaind		−0.075***		−0.023*		−0. 039***
		(0.010)		(0.012)		(0. 009)
lnEnergTgdp_lnFEUAgvaind		0.080***		0.034**		0.029***
		(0.012)		(0.014)		(0.004)
Constant	−19.71***	−19.66***	−21.34***	−21.32***	−21.85***	−21.38***
	(0.657)	(0.573)	(1.891)	(1.904)	(1.152)	(1.340)
Observations	100	100	78	78	100	100
Number of groups	15	15	12	12	26	26

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A4. Robustness analysis for model 2 – alternative variables

MODEL	**(2a)**	**(2b)**	**(2c)**	**(2d)**	**(2e)**	**(2f)**
VARIABLES	**lnGVAindGHGenergy**	**lnGVAindGHGenergy**	**lnGVAindGHGenergy**	**lnGVAindGHGenind**	**lnGVAindGHGets**	**lnGVAindGHGenergy**
lnLGHGenergy	−0.126**	−0.088	−0.154*			
	(0.050)	(0.046)	(0.074)			
lnKGHGenergy	0.797***	0.814***	0.842***			
	(0.066)	(0.083)	(0.063)			
lnEnergTgdp	0.125***	1.220**		0.097**	0.098**	0.131**
	(0.021)	(0.490)		(0.027)	(0.027)	(0.037)
lnEUAgvaind			−0.223**	−0.220***	−0.202***	−0.245***
			(0.064)	(0.040)	(0.040)	(0.044)
lnEnergTgdp_lnEUAgvaind				0.163**	0.119**	0.031
				(0.045)	(0.046)	(0.067)
dHCpc	0.098	0.027	0.016	0.065	0.034	0.070
	(0.075)	(0.039)	(0.104)	(0.089)	(0.095)	(0.144)
lnTFR	−0.178*	−0.048	−0.193*	−0.080	−0.009	−0.030
	(0.077)	(0.070)	(0.085)	(0.080)	(0.070)	(0.076)
lnTFP	2.037***	1.868***	1.993***	2.052***	1.895***	1.317***
	(0.155)	(0.113)	(0.169)	(0.182)	(0.157)	(0.270)
dRD	0.083*	0.131***	0.084	0.098*	0.071	0.007
	(0.039)	(0.031)	(0.043)	(0.041)	(0.042)	(0.062)
lnRENEW	−0.052*	−0.081***	−0.055**	−0.041	−0.025	−0.027
	(0.022)	(0.021)	(0.022)	(0.021)	(0.022)	(0.047)
T	−0.001	0.000	0.000	−0.003	−0.001	0.031***
	(0.004)	(0.005)	(0.004)	(0.005)	(0.005)	(0.006)
Crisis	0.006	−0.003	0.007	0.004	0.007	0.040**
	(0.011)	(0.011)	(0.012)	(0.014)	(0.012)	(0.011)
lnFEUAgvaind	−0.256***					
	(0.050)					
lnEnergTgdp_lnFEUAgvaind	0.133**					
	(0.040)					
lnEUApc		0.018				
		(0.035)				
lnEnergTgdp_lnEUApc		0.199*				
		(0.092)				
lnEnvTgdp			0.187**			
			(0.055)			
lnEnvTgdp_lnEUAgvaind			0.110			
			(0.081)			
lnLGHGenind				−0.152*		
				(0.063)		
lnKGHGenind				0.860***		
				(0.074)		
lnLGHGets					−0.138*	
					(0.064)	
lnKGHGets					0.812***	
					(0.078)	
lnw_ind						−0.035
						(0.115)
Lnr						0.203***
						(0.0310)
INFcpi						−0.00390
						(0.00214)

Constant	−46.40***	−42.82***	−45.84***	−47.12***	−43.54***	−32.43***
	(3.335)	(2.412)	(3.752)	(3.989)	(3.457)	(6.044)
Observations	178	178	178	178	178	178
Number of groups	27	27	27	27	27	27

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A5. Robustness analysis for model 2 – dynamic panel analysis

MODEL	**(2_dyn)**	**(2a_dyn)**	**(2b_dyn)**	**(2c_dyn)**	**(2d_dyn)**	**(2e_dyn)**	**(2f_dyn)**
VARIABLES	lnGVAindGHGenergy	lnGVAindGHGenergy	lnGVAindGHGenergy	lnGVAindGHGenergy	lnGVAindGHGenind	lnGVAindGHGets	lnGVAindGHGenergy
lnGVAindGHGenergy = L,	0.184*	0.171	0.388***	0.233**			0.130
	(0.108)	(0.108)	(0.123)	(0.106)			(0.144)
lnLGHGenergy	0.177*	0.192**	0.232**	0.174*			
	(0.093)	(0.091)	(0.114)	(0.097)			
lnKGHGenergy	0.500***	0.478***	0.483***	0.510***			
	(0.110)	(0.108)	(0.131)	(0.115)			
lnEnergTgdp	0.008	0.019	−0.045		0.042	0.050	0.035
	(0.074)	(0.072)	(0.644)		(0.080)	(0.082)	(0.093)
lnEUAgvaind	−0.191***			−0.139*	−0.171***	−0.173***	−0.220***
	(0.052)			(0.072)	(0.055)	(0.056)	(0.069)
lnEnergTgdp_lnEUAgvaind	0.079				0.041	0.030	0.064
	(0.075)				(0.081)	(0.081)	(0.099)
dHCpc	0.080	0.086	0.143	0.072	0.084	0.051	−0.117
	(0.136)	(0.133)	(0.161)	(0.140)	(0.146)	(0.151)	(0.166)
lnTFR	−0.253**	−0.267***	−0.136	−0.273***	−0.249**	−0.246**	−0.179
	(0.104)	(0.102)	(0.121)	(0.104)	(0.112)	(0.121)	(0.149)
lnTFP	1.459***	1.407***	1.272***	1.424***	1.292***	1.431***	0.901***
	(0.208)	(0.205)	(0.242)	(0.201)	(0.229)	(0.220)	(0.309)
dRD	0.045	0.038	0.078	0.043	0.036	0.044	0.029
	(0.042)	(0.042)	(0.050)	(0.043)	(0.046)	(0.047)	(0.055)
lnRENEW	−0.004	0.002	0.017	−0.009	0.009	0.017	0.047
	(0.042)	(0.041)	(0.050)	(0.043)	(0.046)	(0.048)	(0.054)
T	0.001	0.001	−0.005	0.001	−0.004	−0.009	0.025***
	(0.005)	(0.005)	(0.006)	(0.005)	(0.006)	(0.006)	(0.007)
Crisis	−0.021*	−0.022**	−0.042***	−0.023**	−0.029***	−0.023**	0.007
	(0.011)	(0.011)	(0.013)	(0.011)	(0.011)	(0.011)	(0.014)
lnFEUAgvaind		−0.221***					
		(0.054)					
lnEnergTgdp_lnFEUAgvaind		0.074					
		(0.074)					
lnEUApc			0.079				
			(0.080)				
lnEnergTgdp_lnEUApc			−0.008				
			(0.118)				
lnEnvTgdp				0.156*			
				(0.087)			
lnEnvTgdp_lnEUAgvaind				−0.023			
				(0.081)			
lnw_ind							−0.012
							(0.141)
lnr							0.132
							(0.099)
INFcpi							0.001
							(0.003)
lnGVAindGHGenind = L,					0.313***		
					(0.119)		
lnLGHGenind					0.236**		
					(0.101)		
lnKGHGenind					0.496***		
					(0.120)		
lnGVAindGHGets = L,						0.352***	
						(0.108)	
lnLGHGets						0.239**	
						(0.107)	
lnKGHGets						0.550***	
						(0.115)	
Constant	−32.25***	−31.07***	−27.65***	−31.65***	−28.50***	−31.62***	−22.29***
	(4.794)	(4.724)	(5.620)	(4.673)	(5.273)	(5.039)	(5.473)

Observations	149	149	149	149	149	149	149
Number of ID	27	27	27	27	27	27	27

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A6. Robustness analysis for model 2 – analysis of subsamples

MODEL	**(2g)**	**(2h)**	**(2i)**	**(2j)**	**(2k)**	**(2l)**
VARIABLES	**EU15==1 lnGVAindGHGenergy**	**EU15==1 lnGVAindGHGenergy**	**EU15==0 lnGVAindGHGenergy**	**EU15==0 lnGVAindGHGenergy**	**2ndTP lnGVAindGHGenergy**	**2ndTP lnGVAindGHGenergy**
lnLGHGenergy	0.035	−0.004	0.293***	0.300***	−0.189	−0.158
	(0.109)	(0.120)	(0.090)	(0.083)	(0.137)	(0.137)
lnKGHGenergy	0.567***	0.626***	0.429***	0.428***	0.890***	0.822***
	(0.105)	(0.106)	(0.048)	(0.045)	(0.132)	(0.115)
lnEnergTgdp	0.237***	0.243***	−0.064	−0.018	0.003	0.045
	(0.066)	(0.059)	(0.083)	(0.065)	(0.045)	(0.035)
lnEUAgvaind	−0.385***		−0.143***		−0.406***	
	(0.065)		(0.043)		(0.052)	
lnEnergTgdp_lnEUAgvaind	0.415***		0.077		0.242***	
	(0.031)		(0.073)		(0.020)	
dHCpc	−0.006	−0.004	0.254***	0.257***	−0.059	−0.106
	(0.144)	(0.123)	(0.059)	(0.053)	(0.123)	(0.145)
lnTFR	0.259*	0.313**	−0.218**	−0.264***	0.203***	0.033
	(0.134)	(0.117)	(0.091)	(0.076)	(0.061)	(0.057)
lnTFP	3.305***	3.211***	1.232***	1.198***	1.858***	1.505***
	(0.111)	(0.206)	(0.156)	(0.137)	(0.052)	(0.035)
dRD	0.024	0.007	0.019	0.015	0.092***	0.056***
	(0.055)	(0.052)	(0.032)	(0.032)	(0.010)	(0.012)
lnRENEW	−0.046*	−0.060**	−0.173***	−0.175***	−0.019	−0.033*
	(0.023)	(0.021)	(0.046)	(0.043)	(0.013)	(0.016)
t	0.005	0.003	0.026***	0.024***	0.007*	0.008***
	(0.003)	(0.003)	(0.004)	(0.003)	(0.004)	(0.002)
Crisis	0.029***	0.028***	−0.010	−0.010	0.014***	0.013***
	(0.007)	(0.005)	(0.00654)	(0.006)	(0.002)	(0.003)
lnFEUAgvaind		−0.415***		−0.155***		−0.537***
		(0.096)		(0.042)		(0.040)
lnEnergTgdp_lnFEUAgvaind		0.391***		0.039		0.206***
		(0.028)		(0.059)		(0.014)
Constant	−71.03***	−69.40***	−27.57***	−26.81***	−43.40***	−35.61***
	(2.072)	(3.808)	(3.664)	(3.207)	(1.325)	(0.734)
Observations	100	100	78	78	100	100
Number of groups	15	15	12	12	26	26

Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1

Table A7. Analyzed models’ diagnostics

	Modified Wald test for groupwise heteroskedasticity		**Wooldridge test for autocorrelation in panel data**		**Modified Hausman test**		**Sargan test**	
Models	**chi2(27)**	**Prob>chi2**	**F(1,25)**	**Prob > F**	**F(12,26)***	**Prob > F**	**chi2(20)**	**Prob>chi2**
(1)	2017.64	0.000	27.086	0.000	105.96	0.000	45.564	0.009
(1a)	2520.75	0.000	23.719	0.000	103.21	0.000	45.825	0.009
(1b)	794.01	0.000	27.057	0.000	196.28	0.000	44.680	0.001
(1c)	6016.23	0.000	31.188	0.000	75.81	0.000	46.344	0.001
(1d)	1925.01	0.000	26.367	0.000	150.28	0.000	52.651	0.001
(1e)	861.17	0.000	38.778	0.000	43.27	0.000	53.298	0.001
(2)	2914.27	0.000	31.438	0.000	40.04	0.000	56.486	0.000
(2a)	16927.32	0.000	32.337	0.000	30.61	0.000	56.082	0.000
(2b)	1106.63	0.000	61.445	0.000	19.66	0.000	34.790	0.021
(2c)	8155.09	0.000	31.426	0.000	52.03	0.000	50.951	0.000
(2d)	1833.61	0.000	36.396	0.000	61.75	0.000	50.194	0.002
(2e)	2726.89	0.000	38.065	0.000	53.79	0.000	39.057	0.007
(2f)	9802.37	0.000	26.768	0.000	17.81	0.000	46.748	0.001

*For models (1d) and (2e) F(13,26)