Air Pollution and the Macroeconomy across European Countries

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Abstract

This paper analyzes the role of macroeconomic performance in shaping the evolution of air pollutants in a panel of European countries from 1990 to 2000. The analysis is addressed in connection with EU environmental regulation. We start by documenting the patterns of cross-country differences among different pollutants. We then interpret these differences within a neoclassical growth model with pollution. Three main pieces of evidence are presented. First, we analyze the existence of convergence of pollution levels within European economies. Second, we rank countries according to its performance in terms of emissions and growth. Third, we evaluate the evolution of emissions in terms of the targets signed for 2010.

Key words: Economic Growth, Air Pollution, Europe's environmental policy integration

JEL: O40, Q50, E10, O52

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1 Introduction

The control of the air pollution levels has been one of the most challenging issues in the environmental policy of developed countries over decades. The strong transboundary character of most air pollutants and its already well studied harmful effects have raised the need of coordination at supra-national levels. The European Union (EU) is an institutional framework where coordinated air pollution regulation and economic policy have environmental and macroeconomic consequences of utmost concern. The purpose of this article is to study the contribution of the macroeconomy to the differences in the evolution of air pollutants across EU countries. The analysis is addressed in connection with EU environmental regulation. This regulation builds upon international agreements to accomplish emission ceilings within a committed date.

We propose a model of pollution and growth to give a measure for different countries and different pollutants of the macroeconomic cost to fulfill air pollution targets. We start by documenting the evolution of air pollution over a panel of EU countries from 1990 to 2000. This sample period corresponds to the information set that EU countries had at the time the emission ceilings to be met by 2010 were fixed. We analyze separately the three main air pollutants subject to regulation: Nitrogenous Dioxide (NO_2), Sulphur Dioxide (SO_2) and Carbon Dioxide (CO_2).[1] Then we use neoclassical growth theory to organize the evidence and to conduct policy analysis.

The empirical literature on pollution and growth offers two main insights. Firstly, the idea that with development, pollution is likely to go up and then down: the well-known environmental Kuznets curve (EKC). Several authors have focused on the estimation of the EKC (Grossman and Krueger (1995), Holtz-Eakin and Selden (1995), Panayotou (2000) and Selden and Song (1994), among many others).[2] Secondly, the finding that the costs of keeping emissions below some standards would increase with higher levels of GDP growth [e.g. Jorgenson and Wilcoxen (1993)]. Therefore, vigorous economic growth can affect pollution dynamics in the short-run.

The first piece of evidence relates pollution paths to GDP in levels, whereas the second relates pollution paths to GDP growth. Little effort has been made to simultaneously study the role of output growth and output levels in shaping the evolution of air pollutants, to the best of our knowledge. We explore similarities across the pollution paths of the countries in our sample and we present evidence that the countries with initially higher levels of emissions seem to have reduced emissions faster than

[1] For ease of exposition we omit the analysis for Carbon Monoxide (CO) and Non-Methane Volatile Organic Compounds (NMVOC) emissions. This part of the analysis is available upon request. See also Álvarez et al. (2004) for more details.

[2] There is also a body of theoretical literature that derives such relation from the fundamental assumption of considering the air quality as a normal good (see Kelly (2003) for a recent discussion). However, whether all countries are bounded to go in the long run along the same Kuznets curve or, contrarily, there are country-specific Kuznets curves remains an open question.

those with lower levels. This evidence suggests to condition the countries' emission paths on its initial emissions level, as a proxy for the state of the emissions technology. We provide also evidence that initial income or income dynamics capture determinants of emissions growth rates. On top of that, over the 90s, the ratio of pollution emissions to GDP shows a downward trend. The question is then how these patterns in pollution dynamics can be understood within a model of economic growth.

Our approach is to construct a quantitative model that nests an optimal neoclassical growth framework with a neoclassical model of pollution in a way consistent with this preliminary evidence. We follow Stokey (1998) in that pollution is proportional to final output with an intensity that depends upon the stock of accumulated pollutants.[3] Pollutants accumulate in turn from unabated emissions and the non biologically recovered (exponentially) part of the stock. Hence, pollution is a negative externality of the production technology that harms health. The abatement technology is costly in terms of output, as in Copeland and Taylor (2003). Differences in the flow of pollution that goes to the stock per period are interpreted as cross-country differences in abatement preferences and/or technology. These features augment an otherwise neoclassical optimal growth framework.

The model suggests a procedure to take into account income growth and income levels in the pollution process. For its empirical implementation we build upon the methods largely used for the analysis of income convergence and growth.[4] Differently from it, we do not pursue here either a test of alternative convergence parameters or a structural interpretation of any estimates. Rather, we would like to know whether EU environmental policy is likely to be confronted to systematic differences in emission levels across countries. We find that despite the important differences among pollutants, the observed patterns are consistent with simple neoclassical technological assumptions. Simple as it is, our analysis brings us interesting messages.

In line with the prediction of the neoclassical growth model, we report evidence that emission growth rates in the 90s are negatively related to 1990 emission levels across European counties. Furthermore, we find an heterogenous pattern among countries emission paths that is partially explained by heterogeneity among their respective GDP trajectories. Our model also supports this evidence. As a consequence, the empirical analysis allows us to rank the sample of countries according to their environmental performance over the 90s, taking into account their initial emission levels and their macroeconomic conduct over the same period. As an example, Germany, UK and Poland have performed relatively well in all of the pollutants considered. In

[3] Recently, Brock and Taylor (2004) extends the neoclassical Solow-Swan model to include pollution emissions as a by product of total output (the Green Solow model). They show that the model generates good predictions in line with evidence on emissions, emissions intensities and pollution abatement costs.

[4] The early empirical literature on growth and convergence, since Barro and Sala-i-Martin (1992), is surveyed and discussed in Klenow and Rodrí guez-Claré (1997), De la Fuente (1997) and Durlauf and Quah (1999) among others.

the other extreme, Portugal, Spain and Greece have done badly off.

Additionally, we calibrate our model economy in order to measure the cost - in terms of economic growth - of fulfilling the emission reduction targets to be attained by 2010 in the EU zone. Basically, we compare the transitional dynamics towards 2010 under a business-as-usual scenario with the one consistent with the targets. Our simulation exercise indicates that the cost to attain the targets for NO_2 and CO_2 is remarkably higher than for SO_2.

The rest of the paper is organized as follows. Next section describes the data and shows some preliminary evidence. Section 3 presents the model that disciplines the empirical analysis and implied convergence equation. Section 4 proceeds with the empirical analysis. In Section 5, we perform our simulation exercise in order to evaluate the cost of attaining the emission targets now ruling in the EU zone. Section 6 concludes.

2 The data and preliminary evidence

The data set contains annual country-level information on emissions of air pollutants, income and population in the EU for the 1990-2000 period. This sample corresponds to the information set that EU countries had at the time the emission ceilings to be met by 2010 were fixed. Specifically, we take national emissions from the European Environment Agency (EEA), measured in kilotons, of the main air pollutants: NO_2, SO_2 and CO_2. Income and population data are taken from the Summers-Heston V.6 database. All variables are measured in per capita terms. In Appendix A we briefly describe the data and give a look at EU air pollution regulation.

The countries of our study are all of the EU15 except Luxembourg, and five representative new member states: Czech Republic, Hungary, Poland, Slovakia and Slovenia (for ease of exposition, we shall call them the *entrants*). This selection of Eastern European countries is determined by data availability. Throughout the paper, we find also useful to refer to three subsamples of countries: *EU14* (EU15 excluding Luxembourg), *EU10* (EU14 excluding Greece, Ireland, Portugal and Spain - we call them *middle-income* countries), and *EU19*, which contains EU14 and the Eastern countries described above. Complete data with no missing values are available for EU19 since 1990.

Given that emissions of air pollutants are from a different nature, we analyze separately each pollutant, which allows to observe to what extent there is heterogeneity across them.

2.1 Basic statistics

Table 1 reports the basic statistics on growth in per capita income and pollution emissions. Virtually, all countries have steadily increased its GDP along the 90s.

On average, the cross-country annual growth rate has been 2.1%, 2.4% and 1.8% for EU19, EU14 and EU10, respectively. At the same time, there has been a general reduction in polluting emissions. The figures vary substantially among pollutants, but we observe reductions in emissions for most EU countries. The exception is the case of CO_2 for which only about a half of the countries have diminished their emissions.

[INSERT TABLE 1 ABOUT HERE]

Focusing on CO_2 emissions, within the EU14 zone, the group of Greece, Ireland, Portugal and Spain has experienced the largest increments, with a cross-country average annual growth of 3.6%. The largest reduction has taken place in Germany and UK, with -1.4% on average. With respect to the new EU members, Slovenia, for instance, has had an important annual increment of 1.9%, even though it started with one of the lowest per capita emissions in the rank. Regarding the other pollutants, the largest reduction has been for SO_2, at the same time the largest dispersion occurs. NO_2 emissions are in an intermediate case with more similar initial conditions and reduction rates in this pollutant.

Across sets of countries, Eastern countries are located below the mean on emission reductions, whereas the group of Greece, Ireland, Portugal and Spain is always above the average. Also, NO_2 and SO_2 emissions exhibit the largest reduction within EU10 countries. Correspondingly, while some of the EU10 countries, like Germany and UK, are significantly below the mean, some others, like France and Italy, are around the mean and others, like Belgium and Austria, are slightly above the mean for some pollutants.

2.2 A description of pollution growth rates

One way to organize the data for a systematic analysis of cross-country differences can be taken from the literature on convergence and growth. The idea is to evaluate the ability of the convergence hypothesis to explain why some countries have reduced emissions faster than others. This hypothesis with pollution data implies that 1990-2000 pollution growth will tend to be inversely related to 1990 level of emissions.

As an example, the UK exhibited a notoriously higher level of NO_2 emissions than Austria in 1990 (see Table 1). At the same time the reduction rate in NO_2 emissions for the UK has been clearly more intense throughout the next ten years. However, this is not a general pattern in the data. For instance, Finland and France had similar falls in NO_2 emissions, but the initial level of the latter is one half that of the former. On the other hand, Germany and Belgium showed similar initial NO_2 per capita emissions, but the annual reduction rate of emissions was almost four points lower in the former than in the latter. Similar comparisons can be made for the other two pollutants under discussion.

In order to arrange these observations, Figures 1.1 to 1.3 (one for each pollutant) show the annual growth rates of per capita emissions from 1990 to 2000 against the logarithm of per capita emissions in 1990. The following cross-section regression summarizes the scatter plots:

$$GP_{i,00-90} = \alpha - \beta \log\left(P_{i,90}\right) + \varepsilon_i,$$

where $GP_{i,00-90}$ is the annual growth rate of per capita emissions in country i from 1990 to 2000, $\log\left(P_{i,90}\right)$ is the log of country i's per capita emissions in 1990 and α captures a set of common and unspecified control variables to be eventually incorporated.[5] For each pollutant, the regression lines for EU19, EU14 and EU10 are shown in each figure.

The estimated β coefficients for EU19, EU14 and EU10 are shown in Table 2. In general there is a negative and statistically significant slope associated to the fitted line. This suggests that initial levels may contribute to explaining why some countries have reduced emissions faster than others. Further, the evidence is in favor of absolute convergence within EU19 countries for NO_2, EU14 countries for CO_2 and EU10 countries for SO_2. This implies that the initial level of emissions could account for pollution dynamics to a different extent according to observable characteristics.

[INSERT FIGURES 1.1 to 1.3 ABOUT HERE]

[INSERT TABLE 2 ABOUT HERE]

One question is whether absolute convergence in pollution if any can be explained by GDP convergence or by a reduction in the dispersion of emission levels across EU economies. For the first part, the estimated β coefficients of the regression above in income variables are included in Table 2. The evidence is in favor of absolute convergence in GDP for EU14, mostly due to the Irish experience. For the second part, the so-called *σ-convergence* analysis asks whether the cross-country coefficient of variation in emission levels for year 2000 is smaller than for year 1990. The results in Table 2 show either no evidence of σ-convergence or a mild evidence in line with the β-convergence analysis. Therefore, though the evidence of convergence in pollution is weak, specially for SO_2, it is not weaker than for the GDP paths for the period under consideration.

On the other hand, in all the cases the middle-income countries are located together in the scatter plots. Likewise, the entrants appear together, either substantially

[5] When written in income variables the regressions above have been motivated by an approximation to the neoclassical growth model. Moreover, estimates obtained from that strategy have been often interpreted through the so-called β-convergence analysis, named for the negative slope (a positive β) in the regression above. Here we do not pursue either a test of alternative β's or a structural interpretation of any estimates.

reducing emissions as for the case of CO_2, or with very similar initial emissions levels but very dispersed emissions growth rates as for SO_2. However, the entrants show up quite evenly distributed, for instance, with respect to NO_2. Finally, the EU10 are in general very much distributed along the convergence line except in the case of SO_2, where clearly a different regression line can be fitted for them.

This implies that, in addition to initial pollution, initial income and income growth may contribute to explaining the cross-country differences in pollution emissions. Indeed, the middle-income countries have been growing faster during the 90s while the entrants started from lower per capita GDP levels.

Consequently, we find that the expansionary macroeconomic performance observed across European countries in the 90s coexists with an intense downward trend in per capita emissions among the more important air pollutants. As a consequence, the ratio of pollution emissions to GDP shows a descending path along this decade. However, there are substantial differences among countries and pollutants related to observable characteristics. When taking into account initial conditions in emissions levels, we have evidence in favor of larger reduction in air pollution intensity, the higher the initial level of emissions is. This evidence on pollution convergence is not related to GDP convergence or σ-convergence. Rather, cross-country income differences, as well as income dynamics, seem to contribute to explaining the observed heterogeneity on emissions growth rates. Next, we present a simple model consistent with these and other related facts.

3 A model of growth and pollution dynamics

How can one understand these patterns of cross-country differences in pollution dynamics within a model of economic growth? A natural step is to consider the neoclassical growth model augmented to incorporate the dynamics of a stock of pollution. We rely on the aggregate economy to describe the economic environment and consider pollution as an externality. Therefore, our theoretical framework is that of the non-regulated competitive equilibrium.

Pollution emissions and aggregation

We start by specifying the aggregate amount of pollution at time t, say *Total Suspended Particulate* $\bar{Z}(t)$, as cumulative aggregate pollution emissions $\bar{P}(t)$ according to

$$\bar{Z}(t) = \eta \int_{-\infty}^{t} \bar{P}(s) e^{-(\delta_z/\eta)(t-s)} \, \mathrm{d}s, \tag{1}$$

where $\eta \geq 0$ represents a constant and exogenous factor of un-recycled pollutants that adds to the stock at any period t, and $\delta_z \in (0,1)$ is the rate at which aggregate pollution is absorbed by the environment. Therefore, the damage of emissions of vintage t is reduced by $e^{-(\delta_z/\eta)t}$.

Aggregate pollution emissions result from aggregation of individual emissions at the firm level. We assume that the aggregate pollution flow is well-approximated by a function of total output corrected by a factor of dirtiness.[6] This factor depends positively on the stock of pollution to output ratio. In what follows, we drop time subscripts when it is unambiguous. In addition, capital letters (without bar) refer to per capita variables whereas small caps refer to variables in per capita and efficiency units. Thus, we assume that pollution emissions, in per capita and efficiency units, evolve according to

$$p = \tilde{B}\left(\frac{z}{y}\right)^{\phi} y, \tag{2}$$

where $\tilde{B} > 0$ and $\phi \in [0,1]$ are an efficiency and an elasticity parameter of the pollution technology, respectively. We allow for exogenous technology improvements in the emission process. Specifically, we let $\tilde{B} := \tilde{B}_0 e^{-x_b t}$, $x_b \geq 0$. As we discuss below, this assumption makes long-run predictions of the model be consistent with the empirical evidence for most European countries.

Neoclassical output growth and abatement

As in the neoclassical growth framework, output evolves as a consequence of exogenous technical change and physical capital accumulation that comes from investment,

$$y = A_0 k^{\alpha}, \tag{3}$$
$$\dot{k} = \varsigma y - c - (\delta + n + x) k, \tag{4}$$

where dot denotes time derivative, $A_0 > 0$ is a constant technological factor, k is the physical productive capital, c is private consumption, $\alpha \in (0,1)$ is the elasticity of physical capital to output, $\delta \in [0,1]$ is the physical capital depreciation rate and n and x are the population and technological progress growth rate, respectively.[7] System (3)-(4) is standard except for ς. As in Copeland and Taylor (1994, 2003), among many others, we assume that there is a fraction of output, ςy, with ς in $(0,1]$, to consume or invest, and the rest is devoted to abatement activities. Thus, the parameter η in the law of motion of the pollution stock and ς are positively related, i.e., $\varsigma = g(\eta)$. Since our analysis is positive and not normative, we consider η and ς as exogenous.

[6] Stokey (1998) analyzes a model of sustainable development where final output can be produced by a variety of known techniques which differ in pollution intensity. As in Stokey's model we deal with environmental pollution as proportional to the level of production, where the use of increasingly clean techniques reduces the pollution/output ratio. Differently from her we do not model the choice of pollution intensity. Instead, we interpret differences in the dirtiness of existing production techniques as cross-country differences in the state of abatement technologies. See also Aghion and Howitt (1998).

[7] This writing in per capita efficiency units comes from assuming constant returns to scale in all factors productivity (including labor) in the production function specified in levels.

Using (3), we can rewrite (2) as

$$p = Bz^{\phi}k^{\alpha(1-\phi)}, \tag{5}$$

where $B := \tilde{B}A_0^{1-\phi}$. We restrict $\phi < 1$ in order to have a bounded growth of pollution emissions.

Competitive equilibrium with pollution

The economy is populated by a continuum of identical infinitely lived households that grow at the constant rate n. Initial population is normalized to one and labor is inelastically supplied. Household's preferences are represented by an instantaneous CRRA utility function

$$U(C, \bar{Z}) = \frac{\left(C^{\nu}h(\bar{Z})^{1-\nu}\right)^{1-\sigma} - 1}{1-\sigma},$$

where C is the household's individual consumption and $h(\bar{Z})$, with $h' < 0$, is an index of the state of health as a function of the aggregate stock of pollution; $\nu \in [0, 1]$ gives the relative importance of consumption in welfare and $1/\sigma$, $\sigma > 0$, is the constant intertemporal elasticity of substitution. We take $h(\bar{Z}) := \frac{\bar{Z}^{-\varepsilon}}{\varepsilon}$, where ε is the constant elasticity of the health function over $\bar{Z}$.

In the competitive economy we consider individual households cannot affect the stock of pollution. They take into account the effect that the aggregate stock of pollution exerts on their health, without having control on the emissions flow that depends on firms. Under these assumptions, the competitive equilibrium for the competitive economy with pollution can be derived from the solution to the following problem:

$$\max_{\{C(t)\}_{t\geq 0}} \int_0^{\infty} e^{-(\rho-n)t}U\left(C(t), \bar{Z}(t)\right) dt, \tag{6}$$

subject to

$$\dot{K}(t) = \varsigma Y(t) - (\delta + n)K(t) - C(t), \tag{7}$$

and to the law of motion of the aggregate pollution stock

$$\dot{\bar{Z}}(t) = \eta\bar{P}(t) - \delta_z\bar{Z}(t), \tag{8}$$

given $K(0) = K_0$, $\bar{Z}(0) = \bar{Z}_0$ and with discount factor $\rho \geq n$. Indeed, condition (1) gives a solution for (8), provided $\bar{Z}(t)e^{-(\delta_z/\eta)t} \to 0$ as $t \to \infty$.

Equilibrium conditions

Competitive equilibrium conditions, for variables in per capita and efficiency units, are the following:

$$\frac{\dot{c}}{c} = \frac{1}{1-v(1-\sigma)}\left\{\varsigma\alpha A_0 k^{\alpha-1} - [\rho+\delta+x(1-v(1-\sigma))] - (1-\sigma)(1-v)\varepsilon\left(x+n+\frac{\dot{z}}{z}\right)\right\}, \quad (9)$$

$$\frac{\dot{k}}{k} = \varsigma A_0 k^{\alpha-1} - \frac{c}{k} - (\delta+n+x), \quad (10)$$

together with border constrains: $c > 0$ and $k > 0$ and the transversality condition

$$\lim_{t\to\infty} k(t)e^{\left[-\int_0^t\left(\varsigma\alpha Ak(s)^{\alpha-1}-n-\delta-x\right)ds\right]} = 0, \quad (11)$$

that places a limit on the accumulation of private capital. In accordance with (9), although the representative household takes the sequence of z as given, the non-separability assumption of $U(C,\bar{Z})$ makes that the *observed* change in the stock of pollution end up affecting the consumption-investment decision.

The dynamics of the economy is characterized by (9) and (10), together with the dynamics for z, that comes directly from (8) and (5),

$$\frac{\dot{z}}{z} = \eta Bz^{\phi-1}k^{\alpha(1-\phi)} - (\delta_z + x + n). \quad (12)$$

Balanced growth path (bgp)

From equilibrium conditions, it is straightforward to show that per capita levels of consumption, output and physical capital grow at an exogenous rate along the bgp given by $x > 0$, while per capita emissions and the stock of pollution grow at a rate of $x - x_b/(1-\phi)$, which maybe null or negative. From (9)-(12), it is clear that $\dot{c}/c = \dot{k}/k = 0$ and $\dot{z}/z = \dot{p}/p = -x_b/(1-\phi)$. Hence, the following variables would be constant along the bgp: $\tilde{z}_t := z_t e^{(x_b/(1-\phi))t}$ and $\tilde{p}_t = p_t e^{(x_b/(1-\phi))t}$. Thus, steady state levels of c, k and $\tilde{z}$ are given by

$$k_s = \left\{\frac{\varsigma A_0\alpha}{[\rho+\delta+x(1-v(1-\sigma))] + (1-\sigma)(1-v)\varepsilon[x+n-x_b/(1-\phi)]}\right\}^{1/1-\alpha},$$

$$c_s = \{\varsigma A_0 k_s^\alpha - k_s[\delta+n+x-x_b/(1-\phi)]\},$$

$$\tilde{z}_s = \left(\frac{B_0\eta}{\delta_z+x+n-x_b/(1-\phi)}\right)^{1/(1-\phi)} k_s^\alpha.$$

Along the bgp, the per capita pollution/output ratio is given by

$$P(t)/Y(t) = \left(\frac{\eta}{\delta_z + x + n - x^b/(1-\phi)}\right)^{\phi/(1-\phi)} B_0^{1/(1-\phi)} e^{-(x_b/(1-\phi))t},$$

which decreases at a constant rate $x_b/(1-\phi)$. The transversality condition (11) requires that the steady state rate of return, $\alpha\varsigma A_0 k_s^{\alpha-1}$, to exceed the steady-state growth rate of the economy, $x+n$. That condition implies the following restriction among parameters:

$$\rho > n + \nu(1-\sigma)x - \varepsilon(1-\nu)(1-\sigma)(x + n - x_b/(1-\phi)),$$

which also ensures the utility function in (6) be bounded from above. Indeed, with $\varepsilon = 0$ and $\nu = 1$ we have the standard condition $\rho > n + (1-\sigma)x$.

Dynamics and convergence equation

By log-linearization of system (9)-(12) around the steady-state we characterize the local dynamics (see Appendix). Under the usual stability conditions, we obtain log-linear solutions for the state variables of the form $\log k(t) = m_1(\log \tilde{z}_0, \log k_0, t)$ and $\log \tilde{z}(t) = m_2(\log \tilde{z}_0, \log k_0, t)$. Plugging these solutions for k and $\tilde{z}$ into log-linearized (3) and (5) and the definitions of technologies, a relationship between pollution and output can be derived as

$$\log \tilde{p}(t) - \log \tilde{p}(0) = \pi_0 + \pi_1(\log y(t) - \log y(0)), \quad (13)$$

where π_0 depends on $(\log \tilde{p}_0, \log y_0)$ in a non-trivial manner. From (13), we can derive a convergence equation in discrete time for per capita emission growth of the following type:

$$GP_t = \tau_0 + \tau_1 \log P_{t-T} + \tau_2 \log Y_{t-T} + \tau_3 GY_t, \quad (14)$$

where $GP_t := \frac{1}{T}\log(P_t/P_{t-T})$ and $GY_t := \frac{1}{T}\log(Y_t/Y_{t-T})$, that is, the annual growth rate of per capita pollution and output, respectively, from period $t-T$ to t.

The non-separability between consumption and health services precludes identification of the π's and the τ's in terms of the structural parameters of the model. However, under additive separability in U we can explicitly solve for the local dynamics. For instance, if we consider instantaneous utility represented by

$$U(C, \bar{Z}) = \frac{C^{1-\sigma} - 1}{1-\sigma} + h(\bar{Z}),\ \sigma > 0, \quad (15)$$

the optimal conditions in this case correspond to setting $\nu = 1$ in all the equations under the non-separability assumption above.

Given initial conditions $k(0) - k_s$ and $\tilde{z}(0) - \tilde{z}_s$, the solutions for k and $\tilde{z}$ are

$$
\begin{aligned}
k(t) - k_s &= e^{-\beta t}\left(k(0) - k_s\right), && (16)\\
\tilde{z}(t) - \tilde{z}_s &= e^{-t\beta_{zz}}\left(\tilde{z}(0) - \tilde{z}_s\right) + \frac{\beta_{zk}}{\beta_{zz} - \beta}\left(e^{-t\beta} - e^{-t\beta_{zz}}\right)\left(k(0) - k_s\right), && (17)
\end{aligned}
$$

provided $\beta_{zz} \neq \beta$. The expressions of the β^s are shown in the Appendix, for $\nu = 1$ in this case. The rest of the variables of the model are straightforward from the latter equations, in particular

$$
y(t) - y_s = \left(y(0) - y_s\right)e^{-\beta t}, \tag{18}
$$

$$
\tilde{p}(t) - \tilde{p}_s = \left(\tilde{p}(0) - \tilde{p}_s\right)e^{-\beta_{zz}t} + \left(e^{-\beta t} - e^{-\beta_{zz}t}\right)\lambda\left(y(0) - y_s\right), \tag{19}
$$

where

$$
\lambda = \left((1-\phi) + \frac{\beta_{zk}}{\beta_{zz} - \beta}\frac{\phi}{\alpha}\right). \tag{20}
$$

Using (18) and (19), we can write

$$
\tilde{p}(t) - \tilde{p}(0) = \left(\tilde{p}(0) - \tilde{p}_s - \lambda\left(y(0) - y_s\right)\right)\left(e^{-\beta_{zz}t} - 1\right) + \lambda\left(y(t) - y(0)\right). \tag{21}
$$

From (21), we can derive in a standard way the per capita emission growth convergence equation:

$$
\begin{aligned}
GP_t = {} & x(1-\lambda) - x_b/(1-\phi) + \left[\left(1 - e^{-\beta_{zz}T}\right)/T\right]\left(\tilde{p}_s - \lambda y_s\right) && (22)\\
& - \left[\left(1 - e^{-\beta_{zz}T}\right)/T\right]\log P_{t-T} + \lambda\left[\left(1 - e^{-\beta_{zz}T}\right)/T\right]\log Y_{t-T} + \lambda GY_t.
\end{aligned}
$$

Notice that the model imposes restrictions between the coefficients of the regressors, which must be considered in the empirical analysis.

As it is standard, the term β indicates how rapidly the output approaches its bgp, which is highly affected by α. Alternatively, the speed of convergence of the economy's pollution emissions is determined by β_{zz} (see Appendix). Similarly to the neoclassical growth framework for output, the abatement parameter η and the level of the pollution technology B_0 do not affect the speed of convergence of pollution emissions. Therefore, given δ_z, x and n, the dirtiness parameter ϕ determines the speed of convergence in pollution: the higher ϕ, the slower convergence. Notice also that, being $\beta_{zk} > 0$, $\phi, \alpha > 0$, the sign of λ depends on the relationship between the two convergence speed parameters β and β_{zz}, which depends in turn on the relationship between α and ϕ, respectively.[8]

[8] In a Solow-Swan version of the model (i.e., assuming a constant saving rate), it is easy to show that $\beta = (1-\alpha)(\delta + x + n)$, hence $\lambda = (1-\phi)\left[\frac{(\delta_z + x + n - x_b/(1-\phi)) - \alpha(1-\phi)(1-\alpha)(\delta + x + n - x_b/(1-\phi))}{(1-\phi)(\delta_z + x + n - x_b/(1-\phi)) - (1-\alpha)(\delta + x + n - x_b/(1-\phi))}\right]$. Assuming that $\delta_z = \delta$, it holds that $\lambda = \frac{(1-\phi)}{(\alpha-\phi)}\left(1 - \alpha(1-\phi)(1-\alpha)\right)$ and, provided all parameters are inside [0,1], the sign of λ only depends on $(\alpha - \phi)$.

4 Empirical analysis

So far we have provided preliminary evidence of faster decline in emissions the higher its 1990 level.[9] There is also evidence that income dynamics play a role in pollution dynamics. The model of pollution and growth we propose suggests a procedure to take into account the macroeconomic performance of the countries. Also, the model imposes cross-equation restrictions in the parameters of the process that is followed by pollution.

Next, we explore regression evidence on macroeconomic and environmental patterns consistent with the theoretical model. We proceed as follows. First we implement cross-section regressions. The cross-section equation provides an indicator of convergence, but its main advantage is that it allows a direct analysis of the residuals. Thus, we ask whether income discrepancies imply differences in the growth rate of pollution emissions for countries with similar initial level of emissions. Then we implement a panel data analysis with fixed effects to account for unobserved heterogeneity and other factors outside the model.[10] Of course, the question of whether national emission levels are somehow converging or not does not answer to the question of whether countries are expected to meet the targets on national pollution ceilings within date. We shall later use the panel data estimates to evaluate the macroeconomic content of environmental policy.

4.1 Cross section regression

The cross-section equation follows from (22) and can be written as

$$GP_{i,00-90} = \alpha - \beta \log P_{i,90} + \delta \log Y_{i,90} + \varphi GY_{i,00-90} + \varepsilon_i,$$

where $\delta = \beta\varphi$ and the index i runs across countries. For each pollutant, Table 2 reports the cross-section estimates for the regression above. The coefficient of the 1990 level of emissions gives us a measure of absolute convergence *corrected* for both the 1990 GDP and 1990-2000 GDP growth effects. According to this estimate the convergence hypothesis is reinforced for NO_2 in EU19, for CO_2 in EU14 and for SO_2 in EU10.

[9] This evidence is consistent with a model of exponential depreciation in the stock of pollution, where the emissions flow is generated from decreasing returns on the pollution stock. A version of such a model can be described in our framework with

$$\begin{aligned} P &= \tilde{B} Z^{\phi_z} \\ \dot{Z} &= \eta P - (\delta_z + n) Z \end{aligned}$$

[10] Further, emissions are measured imperfectly and errors for a country persists over time as Selden and Song (1994) pointed out.

The residuals of the cross-section regressions contain interesting information. A negative residual indicates that the corresponding country has reduced its pollution level beyond what is expected conditional on its income growth and initial income and pollution levels. For each pollutant, Figures 2.1 to 2.3 show the residuals of the previous cross-section regression. For ease of comparison these residuals are displayed jointly with both the corresponding residuals of the β-convergence analysis of Section 2 and the observed deviations with respect to the cross-country average emission growth.

With the exception of Ireland, the middle-income countries - Spain, Portugal and Greece - show significant positive residuals for each pollutant. The case of Ireland illustrates the importance of taking into account the GDP growth effect from the primitive convergence equation. Omitting the per capita GDP growth rate, this country shows a poor environmental performance. Alternatively, taking into account its important per capita GDP increase along the 90s, its position turns out to be within the set of *clean* countries. Thus, among the middle income countries only Ireland tend to reduce emissions faster.

[INSERT FIGURES 2.1 to 2.3 ABOUT HERE]

Likewise, Germany and UK seem to be reducing emissions above average once income dynamics are taken into account. On the other hand, the new EU members, the entrants, tend to reduce emissions slower once we control for initial levels and growth. Among them, Poland exhibits the best environmental performance for all pollutants.

The adjustments in the size of the residuals tend to be smaller within EU10 countries, but they are often relevant (mixed evidence). Also they are less significant for SO_2. Finally, dynamics of CO_2 exhibit the more homogeneous pattern across countries, whereas dynamics of SO_2 still suggest sizeable cross-country differences.

4.2 Panel data analysis

We specify a panel data model with fixed effects.[11] The specification stage shows significant differences in the relationship between pollution growth and income depending upon the EU region considered. Following Eq. (22) and in order to account for this feature, the panel representation can be written as,

$$GP_{i,t} = \alpha_i - \beta \log P_{i,t-T} + X_{i,t-T}\delta + GX_{i,t}\varphi + v_{i,t}, \tag{23}$$

[11] An homogeneity F-residual test suggests the use of a model in which the parameter α is country-dependent. The Haussman test does not reject the fixed effect model hypothesis. We use non-linear least squared method to implement the restriction on parameters. All inference is based on the White heteroskedasticity-consistent covariance matrix.

where $\delta = \begin{pmatrix} \delta_1 & \delta_2 & \delta_3 \end{pmatrix}'$, $\varphi = \begin{pmatrix} \varphi_1 & \varphi_2 & \varphi_3 \end{pmatrix}'$, $X = \begin{pmatrix} \log Y & D_1 \log Y & D_2 \log Y \end{pmatrix}$ and $GX = \begin{pmatrix} GY & D_1 GY & D_2 GY \end{pmatrix}$; D_1 and D_2 are country-specific dummy variables, with $D_1 = 1$ for the middle-income countries and 0 otherwise, and $D_2 = 1$ for the entrants and 0 otherwise; again, we impose $\delta = \beta\varphi$ in the above panel regression. Finally, α_i captures the inherent - and time invariant - heterogeneity in pollution emissions among countries that is not explained by the income growth average and the average level of income.

The diagnosis stage shows significant negative residuals (on average for all countries). There are a number of factors, like technological changes and the impacts of environmental regulation, that might cause that residuals of the regression to be systematically negative. We want to estimate Eq. (23) without regard to these latter factors. To this purpose, we include time dummies in the above regression when they result significant, which is equivalent to differencing each observation from its contemporaneous cross-sectional mean. We find that except for CO_2, time effects are negative and highly significant since 1993, exhibiting a stronger effect from 1997 (Kyoto protocol). This trend can be interpreted as the impact of environmental regulation. Indeed, the most relevant time effects are shown for SO_2, which is the pollutant with the largest tradition of EU directives of pollution control.

Table 3 summarizes the estimates from the fixed effect model for NO_2, CO_2 and SO_2. These estimates are computed over the whole set of countries, EU19, and over EU14 and EU10 as well. As can be seen from the point estimates, the pollution level has a significant positive effect on the rate of decline of emissions for all pollutants. The only exception across all the set of countries considered is the convergence coefficient for SO_2 when we consider the EU10 subgroup. The non-significance of β in this case coincides with the strongest significant role across pollutants and subsamples of output growth (the φ coefficient) instead. Comparing pollutants, convergence during the 90s has been more significant for CO_2, followed by NO_2.

[INSERT TABLE 3 ABOUT HERE]

The effect of the output growth rate on the pollution growth rate is always positive. However, the estimates of the $\varphi's$ in the table suggest substantial differences according to the pollutant and the EU region considered. Notice that those φ_j associated to the middle-income countries, φ_2, and the entrants, φ_3, capture the net effect for the group with respect to the EU10. Thus, we conclude that output growth goes with pollution growth with relatively more intensity for the middle-income countries than for the entrants in the case of CO_2 and NO_2, and more than for the EU10 countries once the entrants are left apart. The opposite occurs for SO_2, where the role for output growth is more intense for EU10 than for the whole set of countries.

The patterns that emerge are quite interesting. In the case of NO_2 there is evidence that vigorous economic growth produces a slowdown in the reduction of emissions for the middle-income countries. Similarly occurs with CO_2, where the role of output growth is even stronger for these countries.

Convergence and growth estimates taken together suggest that pollution levels and the macroeconomy have a substantial role in explaining NO_2 pollution growth. The effect of these variables is found to be significant even if the middle-income countries are left apart. However, the effect of output growth on pollution growth vanishes in the case of CO_2, once middle-income countries are excluded from the sample. Therefore, correcting for the macroeconomy enhances the role of pollution levels but do not justify the pattern of emissions of CO_2 by the entrants. This pattern may be related with differences with in abatement technologies.

Alternatively, the results suggest that SO_2 emissions dynamics tend to be governed by GDP growth. This finding is significantly different for EU10 than for the rest of the countries. The role of GDP growth is always relevant as the estimates from the EU10 subsample show. However, this role seems of a different nature with SO_2 than with the other pollutants. For the rest of countries and pollutants, it is income and pollution dynamics more than output growth that play the leading role.

5 Evaluating the macroeconomic content of environmental policy

Several actions are in the direction of limiting emissions of pollutants considered noxious for human health and ecosystems, without discriminating their sources. Emissions ceilings to be met by 2000 (on SO_2, NO_2 and CO_2) were fixed in the Community's Fifth Environmental Action Programme (5EAP) in 1993, while those to be met by 2010 have been set in Directive 2001/81, as part of the National Emissions Ceilings Directives (NECD) common position. Consequently, the member states had essentially the same information at the time of establishing the targets that we have used in our estimation. The limits on CO_2 are established according to the Kyoto Protocol correspondingly. Targets on emissions for Eastern European countries have not been set up to now.

To evaluate the macroeconomic content of emissions' ceilings imposed by the EU environmental regulator, one may ask whether the predictions of the empirical model overtake or fall short of the targets signed for 2010. For different countries and regions, we first evaluate the evolution of emissions predicted by the estimates of the empirical model. Then, we examine the gap between predictions and the targets. Finally, we look at the transitions obtained with a calibrated version of the theoretical model under alternative scenarios.

5.1 Targeted levels of pollution emissions

We start with an evaluation of emission ceilings conditional on initial emissions, pollution dynamics and the macroeconomy from 1990 to 2010. To this purpose, we take the estimates of the panel data analysis β, φ and the fixed effects α, as a measure of the business-as-usual emissions. Further, for each country, given its initial per capita levels of emissions and GDP (at 1990), we fix annual population and economic growth rates, n and γ, equal to their average values over the 90s. With these assumptions, rather than computing emissions period-by-period, by recursive substitution on (23) from T to $T+K$, one gets

$$\begin{aligned} \log\left(P_{T+K}\right)-\log\left(P_{T}\right) &= \gamma\delta_2\sum_{j=0}^{K-2}\delta_1^j\left(K-j-1\right) \\ &\quad +\left(1-\delta_1^K\right)\left[\left(1-\delta_1\right)^{-1}\left(\delta_0+\delta_2\log\left(Y_T\right)\right)-\log\left(P_T\right)\right], \end{aligned} \tag{24}$$

where $\delta_0 := \alpha+\varphi\gamma$, $\delta_1 := 1-\beta$ and $\delta_2 := \varphi\beta$ correspond to the parameter estimates obtained for the panel when time and region dummies are included. Notice that α and γ are country-specific, φ is region-specific and β is common to all countries.

Any target on per capita pollution emission levels can be expressed in the form of

$$\log\left(P_{T+K}/P_T\right)\leq\gamma_\tau-Kn, \tag{25}$$

with γ_τ being the change in aggregate pollution emissions between initial period T and $T+K$, with K=20. Using (24), we rewrite (25) as,

$$\log\left(P_T\right)-\lambda\log\left(Y_T\right)\geq\frac{1}{1-\left(1-\beta\right)^K}\left(Kn-\gamma_\tau\right)+\frac{\alpha}{\beta}+\gamma\varphi m\left(K,\beta\right), \tag{26}$$

where $m\left(K,\beta\right) := \frac{1}{\beta}+\frac{\beta}{1-(1-\beta)^K}\sum_{j=0}^{K-2}\left(1-\beta\right)^j\left(K-j-1\right)$. One way to interpret this evaluation is that the target based on environmental policy is met whenever the initial pollution intensity for a particular country in 1990 is large enough compared with the pollution path implied by the empirical model.

For each country of EU14, we compare the target τ on emissions to be attained by 2010 with the level of emissions that solves (26) with equality, τ^*. The results from this exercise are shown in Tables 4.1 to 4.3, one for each pollutant. To give a sense of the heterogeneity across countries, the left panel in these tables reports the emissions ceilings targeted for 2010 (the first column), together with the percentage reduction (or increment) for each pollutant per year starting at 1990, that each country must reach by 2010. The third column in each table shows also how each country is doing: that is, it compares the levels at 2000 with that at 1990. The last column in the left panel shows what is left to get the target when comparing levels at 2000 with that to be attained by 2010.

[INSERT TABLE 4.1 to 4.3 ABOUT HERE]

With the exception of Greece, that is allowed to raise its emissions on all the pollutants considered, the rest of the countries have the purpose to abate their emissions in a significant amount. For instance, for NO_2 the richer countries such as Germany, France, Netherlands, Sweden and UK have the target of reducing by 2010 a 50% to 60% their emissions at 1990. On the other hand, countries like Portugal, Spain, Italy, Finland, Belgium or Ireland have a less restrictive target, specially for the low income countries among these. For SO_2, this ranking is similar, but the required reduction is stronger. For instance, the target for Germany is a reduction of 90%, while for Portugal is 44%, and Greece is allowed to raise by a 6% its emissions in this case. Finally, Ireland, Portugal, Spain and Sweden are allowed to raise emissions of CO_2, while other countries such as Denmark and Germany have the target of reducing by 2010 a 21% their CO_2 emissions at 1990.

In general, for NO_2 and SO_2, countries have reduced their emissions during the 90s. However, in the case of NO_2, the target is close enough just for a few number of countries: only Italy and UK have achieved up to now reductions above what it is left. In terms of CO_2, just Finland, France and Sweden are in a good position to achieve the target. Germany and UK are also doing well, and they are in a good way to get the target by 2010. For the rest of countries, to achieve the target is going to be a difficult task.

We use the empirical model to measure the difficulty to get the target. The right panel in Tables 4.1 to 4.3 reports the corresponding predictions with the estimates of the empirical model. The last column shows the implied ratios of the predicted emissions levels to the targets, τ^*/τ, for each EU14 country and pollutant. Several results are of interest from this evaluation. First, only Portugal and Greece are predicted to be below the targets imposed for NO_2 once we take macroeconomic performance into account. The model prediction is relatively close to the target only for Italy and Finland in this case, but no substantial deviations are predicted for all other countries except clearly for Ireland. Again the target for Ireland seems to be too stringent compared with those for Portugal and Greece that appear to be relatively generous. Secondly, more dispersion can be observed with respect to CO_2 emissions while no single member state is predicted to be below the target. This fact may have consequences over the tradable permits market of utmost concern. Finally, all of the EU14 are predicted to be well below imposed emission ceilings in the case of SO_2 except again Ireland. This fact may suggest that a long lasting history of corrective actions, as the several control programs for SO_2 emissions demonstrate, is associated to more realistic emissions ceilings.

Interestingly, the descriptive methodology we propose gives a measure for potential targets to be tracked by new-entrants based on the relative performance of current

EU member states and the macroeconomy. Next, we use the theoretical model to evaluate the costs associated to converge compared to overtake the target.

5.2 The impact of targets on pollution and growth

We use the fully specified theoretical model, with non-separable preferences and abatement costs, to asses the costs in terms of output associated to convergence to the target committed by 2010. To this purpose, we compare the transitional dynamics of pollution emissions and output towards either the actual EU emissions ceilings, or towards predicted emissions levels according to the estimates of the empirical model. These alternative emission levels are implemented through permanent differences in the abatement intensity factor, η. For each pollutant, we focus on the three regions (EU10, EU14 and EU19) under consideration.

Values of the parameters

We need to assign values to parameters in order to simulate the model economy and investigate its quantitative implications. Since our data set covers a few variables over a large number of countries and some of them are unobserved, a complete calibration and estimation strategy goes beyond the scope of this paper. Rather, standard parameters are set to values commonly used in the literature and the remaining parameters are selected based on our data set and the estimates above.

We select a period in our model to be the natural year. The labor elasticity in the Cobb-Douglas technology is assumed to be 0.6, thus we set $\alpha = 0.4$. For the private capital depreciation rate, we use $\delta = 0.1$ for yearly data. We normalize to one the scale of total output and pollution emissions in per capita and efficiency units, so that $A_0 = B_0 = 1$. We use $\sigma = 1.5$ as assumed by Prescott and others, and a discount factor $\rho = 0.1$. With respect to the growth processes, $n = 0.01$ and $x = 0.02$, and we assume that per capita pollution emissions are constant along the bgp, so we set $x_b = x(1-\phi)$. Finally, for the health function we consider $\varepsilon = 0.5$ together with a consumption-health elasticity of $\nu = 0.75$, as in Kelly (2003).

Technology and preference parameters are assumed to be equal across pollutants (NO_2, CO_2 and SO_2) and European areas (EU10, EU14 and EU19) under consideration. The differences across simulations will come from the parameters of the pollution technology and the abatement cost function, together with the different initial positions and final emissions targets.

The abatement cost function is assumed to be logistic, $g(\eta) = 1 - (1+\eta)^{-\psi}$, with $\eta \geq 0$ and $\psi > 0$. This is a common choice to represent growth in forests, animal species and renewable resources in general (its inverse). We interpret the unbounded input as a minimum intervention by agents so that there is always some abatement costs.

We have no references about specific parameters of the abatement cost function, the pollution technology and the initial pollution stock. Our strategy consists of calibrating simultaneously $Z(0)$, ψ, ϕ and δ_z for a given η, whose selection will be discussed below. To this purpose, we first set $1-\varsigma$, the percentage of output devoted to abatement, in accordance to OECD statistics. This implies on average 0.015 for EU10 countries and 0.0075 for the middle-income EU countries. We do not have reliable statistics for the entrants, and we assume $1-\varsigma = 0.005$ for them. Given η, the parameter ψ in the abatement cost function is then chosen to match the levels of $1-\varsigma$ of each EU region. Secondly, we assume that the economy starts with a $K(0)$ that is 5% below its benchmark bgp. Then, for given $K(0)$, $Z(0)$ is chosen to fit the average share of pollution emissions with respect to real GDP in 2000 for each EU area. Finally, using the estimates for β and λ in the empirical analysis, ϕ and δ_z are identified under the separability case.[12] Table 5 summarizes parameter values for the benchmark economy, together with region specific and pollutant specific parameters that are calibrated using the aforementioned strategy.

[INSERT TABLE 5 ABOUT HERE]

The differences in initial conditions, the ratio P/Y, reflect the relative positions by 2000 across regions and pollutants. For instance, in EU10, the ratio is 0.420 in CO_2, 0.124 in NO_2 and 0.044 in SO_2. On the other hand, according to our estimates and identification scheme, the rate at which air pollution is absorbed by the environment, δ_z, ranges between 0.2 for SO_2 and 0.3 for CO_2. Uninformed guesses of this parameter vary substantially in existing literature. Finally, the elasticity parameter ϕ of the pollution technology ranges between 0.45 for SO_2 and 0.03 for CO_2. The small elasticity reflects a lower weight of the dirtiness of the technology, z/y, with respect to the capital stock k in the process of pollution emissions. Note that the capital stock is the common factor in the pollution technology. Therefore, for a given level of output, the return of abatement effort is expected to be higher for SO_2 than for CO_2. As we discuss next, the differences in δ_z and ϕ are also important since they govern the speed of convergence in pollution emissions.

Pollution emissions experiment

The measure of the impact of targeting emission levels we discuss can be understood as the outcome of the following thought experiment. Let us assume that the economy has been one with pollution and output paths described by the average behavior captured with the empirical model. Then, in 2000, the economy engages in a permanent abatement effort η consistent with the target τ to be met by 2010. We compare the path associated with this abatement effort with the one corresponding to the

[12] Shioji (2001), among others, follows a similar strategy to calibrate for US and Japan the elasticity of public capital in an economy growth model.

business-as-usual emissions. In terms of the theoretical model, the business-as-usual scenario corresponds to a permanent abatement effort η^* which is consistent with the τ^* predicted by the empirical model. Figures 3.1 to 3.3 show the results of this experiment for the three pollutants (NO_2, CO_2 and SO_2) and the three regions (EU10, EU14 and EU19) under consideration, starting at 2000 and for the next 20 years. Two sets of main results emerge from these graphs: differences between committed and expected paths and differences in the cost in terms of output to get the target.

[INSERT FIGURES 3.1 to 3.3 ABOUT HERE]

Starting with CO_2, Figure 3.2 shows that the trend of the expected path (business-as-usual) and the committed path (EU target) clearly diverge. On the contrary, transitions for NO_2 and SO_2 (Figures 3.1 and 3.3, respectively) exhibit a process of GDP growth together with a reduction in emissions both under the expected and the committed paths. In fact, the expected path stays above the committed path for NO_2, whereas the opposite occurs for SO_2. Hence, the calibrated model predicts substantial differences in the relative position of the expected path with respect to the committed path for the different pollutants. An interpretation of this finding is that either EU countries are not doing well for some pollutants or the committed targets have not been properly established according to the macroeconomy. This circumstance is particularly apparent for CO_2.

Correspondingly, the cost in terms of output to converge to the target is specially important for CO_2. Consider for instance the EU10 case. The convergence to the average target is achieved at a cost that represents roughly 10% of output by 2020, as compared with the business-as-usual scenario. On the other hand, the business-as-usual scenario implies an increase in per capita emissions of about 4% in the next 20 years. This number has to be compared with the 12% reduction required in terms of the average target for this region by 2010, that ends up by 2020 with roughly a 13% reduction. Hence, there is an intense pollution-growth trade-off to achieve the committed target for CO_2. A welfare analysis exceeds the scope of this experiment.

The output cost to get the target by 2010 is substantially smaller for NO_2 and negligible in the case of SO_2. Although the differences in SO_2 emissions reduction are remarkable along the alternative paths, in this case the business-as-usual trajectory remains above the committed one. These differences emphasize the good performance that EU countries (specially for EU10 members) have had in terms of SO_2 emissions abatement along the 90s. However, since the target is not particularly tight and convergence to the pollution balanced growth path is slow, the output-pollution trade-off does not appear as particularly intense. Indeed, the fastest speed of convergence in pollution corresponds to CO_2. This circumstance, combined with the important distance between the expected and the committed output-pollution paths, gives in all of the cases the more important output costs.

An intermediate situation in terms of the output cost to the target and the speed of convergence in pollution occurs for NO_2. This motivates a further comparison along pollutants and regions. To this purpose, the last row shows normalized transitions. On the one hand, in the case of NO_2, we find no difference among groups while looking to business-as-usual emissions and growth. However, EU10 and EU14 transitions to the target are closer than EU19 path. Somewhat the opposite occurs with SO_2. Transitions to the predicted values reinforce the evidence with respect to the commons in EU10 and EU14. Transitions to the target confirm the specific element for EU10: tighter regulation. These differences seem to represent small output costs here while substantial differences in output costs can be found for different regions by required convergence to EU NO_2 average targets for the region. On the other hand, the costs in output to achieve the targets for CO_2 seem equally important across all regions considered. It is worth noting that the higher gap between business-as-usual emissions and EU targets correspond to considering the EU14 region.

6 Conclusions

The European Environment Agency (EEA) data reveal that air pollution intensity has decreased over the 90s in most EU member states. Moreover, the countries with initially higher levels of emissions seem to have reduced emissions faster than those with lower levels. Despite this common trend, there are important sources of heterogeneity among pollutants and among countries. This heterogeneity does not seem to be associated with substantial differences in the production technologies or in the sources of emissions of the pollutants over this decade. Rather, an important part of this heterogeneity is observable, implied by region-specific differences that can be related to the level of economic development and to the rate of output growth.

These patterns are consistent with a simple model of pollution and growth, where the initial level of emissions can be interpreted as a proxy for the state of the pollution technology. The convergence equation derived from the theoretical model is used to explore these patterns over a panel of EU countries and pollutants. This allows us to give a measure on the degree of convergence in pollution emissions as well as to rank countries in terms of their emissions and macroeconomic performance. Leading this ranking are Germany, United Kingdom and Poland, and on the other extreme we find the Czech Republic, Portugal, Spain and Greece.

Another feature of the data that emerges from the model based estimated equation is the coexistence of β-convergence and a descending branch of an Environmental Kuznets Curve (EKC), associated to the evolution of emissions of NO_2, once we control by the macroeconomic performance of the different countries. There is also evidence of region-specific descending branches of EKCs in the case of CO_2. These separated branches can be associated to differences in the processes of adoption and diffusion of abatement technologies between EU14 and the Eastern countries. Finally, the reported facts for SO_2 emissions suggest a different pattern for the richest countries in the EU once we control for the macroeconomy. We interpret this finding in favor of a role for EU environmental regulation that has a long standing tradition for this pollutant among these countries. Also, a contagion effect to classical air pollutants from the concern on climate change can be identified.

Finally, we contribute to an evaluation of the macroeconomic content of the targets signed by the EU member states for 2010. We find that European countries are likely to miss their targets for NO_2 and CO_2 emissions compared to those for SO_2. Also, a relative measure of the degree of fulfilment of targets is obtained which is meaningfully related with the macroeconomy. The impact of stronger actions towards pollution control has been shown to be statistically significant and economically important.

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Appendix A: Pollution emissions data

The Data sources

The data on pollution emissions are taken from the European Environmental Agency (EEA). Those data are based on reports that each member state submits periodically to the EEA. They can be downloaded from:

http://themes.eea.eu.int/Specific_media/air/data. Our analysis is based on national emissions of NO_2, SO_2 and CO_2. Among transboundary pollutants, we focus attention on NO_2 and SO_2 since they are the main sources of air pollution and therefore, subject to the more important regulation. CO and NMVOC receive also attention by the EEA but for ease of exposition we omit the analysis on them. The most important greenhouse gas is represented by CO_2.

Most of the anthropogenic emissions of NO_2, CO and NMVOC are contained into the exhaust gases of motor vehicles. An important proportion of NMVOC emissions is due to the use of solvents in certain industrial activities and part of NO_2 emissions and the highest proportion of SO_2 and CO_2 emissions come from the combustion processes to generate energy.

The international community legal response to the transboundary pollution problem came in 1983, when the *Convention on Long-Range Transboundary Air Pollution* (CLRTAP) entered into force. The pollution emissions data reported in the EEA website follow the CLRTAP methodology. Emissions data are all expressed in kilotons. In the case of the pollutants under the CLRTAP, we analyze all European Union (EU) members except Luxembourg, and among the new entrants, Cyprus, Estonia, Latvia, Lithuania and Malta. Therefore, we consider a balanced sample of nineteen countries.

The GDP data are the purchasing-power adjusted values from version 6 of the Penn World Table. They are measured in international thousands 1996 dollars and cover all countries involved in our analysis. The population data are also from this database. These data can be downloaded from

http://pwt.econ.upenn.edu/php_site/pwt_index.php. Frequency of pollution emissions, population and GDP data is annual. The selected sample period is 1990-2000. This sample period corresponds to the information set that EU countries had at the time the targets to be met by 2010 were established.

A look at EU air pollution regulation

In the case of road transport emissions, starting in 1970, the EU established binding "emissions limit values" for the concentration of CO, NO_2 and NMVOC in the gases produced by vehicles operation. These limits are introduced as technical requirements of the vehicles engines by means of specific Directives that, as a whole, represent the largest part of EU environmental legislation. The Community has worked out also measures in the industry sector; it has issued Directives imposing "emissions ceilings" for NMVOC coming from special industrial activities and Directives establishing limits to the "sulphur content" of liquid fuels adopted in large combustion plants to generate energy, to control SO_2. Usually Directives fix time frames together with the quantitative targets and both are mandatory for each Member State.

The international community official engagement on the greenhouse gases emissions problem came in 1992, through the adoption of the *United Nations Framework Convention on Climate Change* (UNFCCC). EU control programs started in line with the main scope of the convention that was to stabilize by 2000, in industrialized countries, anthropogenic CO_2 emissions at 1990 levels. The Community effort is mainly represented by the adoption of voluntary agreements and only in some cases is supported by legislative measures. After the UNFCCC, the international community proposed the Kyoto Protocol in 1997, under which the developed world agreed to reduce greenhouse gases emissions to 5% below 1990 levels, between 2008 and 2012. The EU showed a stronger commitment by fixing a more ambitious target: a cut of 8% over the same period. In order to reach Kyoto targets, the EU adopted, inside its territory, some specific programs. For example, the *Greenhouse Gas Emissions Trading and Climate Change Programme* by 2000, as part of a general strategy to face the environmental effects of greenhouse gases. The *Emissions Trading Scheme*, legally introduced by Directive 2003/87, is a procedure whereby allowances of greenhouse gases emissions are allocated to industries, according to the environmental targets of their governments. It is a system where individual firms can emit more than their permissions, conditional of finding firms that have emitted less than their permitted limits and are willing to sell their "spare" allowances. Companies involved in the process can be regulated either by national authorities or by the European Commission, in line with the principle of subsidiarity. Together with the trading scheme, the Commission emphasizes also the need of improving fiscal systems on a proper environmental basis. However no concrete progresses in this direction have been made until now.

The EU strategy to combat CO_2 emissions is still at a starting phase and maybe this is the main reason for the lack of specific legislation covering the economic activities directly responsible of such emissions. In contrast, the regulation on acidification processes and particularly related to SO_2 emissions has a long standing tradition.

Appendix B: the log-linearization

Log-linearizing (9)-(12) around the steady-state leads to

$$\begin{pmatrix} \overset{\bullet}{\log(c)} \\ \overset{\bullet}{\log(k)} \\ \overset{\bullet}{\log(z)} \end{pmatrix} = \begin{pmatrix} 0 & -\beta_{ck} & \beta_{cz} \\ -\beta_{kc} & \beta_{kk} & 0 \\ 0 & \beta_{zk} & -\beta_{zz} \end{pmatrix} \begin{pmatrix} \log c - \log c_s \\ \log k - \log k_s \\ \log z - \log z_s \end{pmatrix}, \tag{27}$$

where the subscripts of the β's recall their respective position in the transition matrix. The non-zero elements of that matrix are:

$$\begin{aligned}
\beta_{ck} &= \frac{1}{1-v(1-\sigma)} \left\{ (1-\alpha)\left[\delta+\rho+(1-v(1-\sigma))\,x\right] \right. \\
&\qquad \left. +\varepsilon\,(1-\sigma)\,(1-\nu)\left[(1-\alpha\phi)\,(x+n-x_b/(1-\phi))+\alpha(1-\phi)\delta_z\right] \right\}, \\
\beta_{cz} &= \frac{\varepsilon\,(1-\phi)\,(1-\sigma)\,(1-v)\,(\delta_z+n+x-x_b/(1-\phi))}{1-v(1-\sigma)}, \\
\beta_{kc} &= \frac{\left[\delta+\rho+(1-v(1-\sigma))\,x\right]+\varepsilon(1-\nu)\,(1-\sigma)\,(x+n-x_b/(1-\phi))}{\alpha} - (\delta+n+x)\,, \\
\beta_{kk} &= \rho-n-\nu\,(1-\sigma)\,x+\varepsilon(1-\nu)\,(1-\sigma)\,(x+n-x_b/(1-\phi)), \\
\beta_{zk} &= \alpha(1-\phi)\,(\delta_z+n+x-x_b/(1-\phi))\,, \\
\beta_{zz} &= (1-\phi)\,(\delta_z+n+x-x_b/(1-\phi))\,.
\end{aligned}$$

Notice that β_{kk} and β_{kc} are positive by the transversality condition, which is a standard result.[13] As mentioned in the text, the non-separability assumption of the utility function precludes the possibility of having analytical expressions for eigenvalues or eigenvectors of the transition matrix in terms of the primitive parameters of our model economy.

Instead, such analytical computation is feasible whenever assuming that U is additively separable, that is, U given by (15). The corresponding log-linearized system has a transition matrix with $\beta_{cz} = \beta_{kz} = 0$, and thus it can be solved recursively: first for c and k (as in the standard Cass-Koopmans framework) and then for z using the obtained dynamics for k. The solution for k is standard:

$$k\,(t) - k_s = e^{-\beta t}\,(k\,(0) - k_s)\,, \tag{28}$$

where $-\beta$ is the stable eigenvalue of the transition matrix, which is given by

$$\beta = \left(\beta_{kk}^2 + 4\beta_{ck}\beta_{kc}\right)^{1/2} - \beta_{kk}. \tag{29}$$

[13] β_{kc} can be rewritten as $\frac{\beta_{kk}+(1-\alpha)(\delta+n+x)}{\alpha}$, which is clearly positive since $\beta_{kk} > 0$.

The log-linearized dynamics for k and z is then given by

$$\begin{pmatrix} \dot{k} \\ \dot{\tilde{z}} \end{pmatrix} = \begin{pmatrix} -\beta & 0 \\ \beta_{zk} & -\beta_{zz} \end{pmatrix} \begin{pmatrix} k - k_s \\ \tilde{z} - \tilde{z}_s \end{pmatrix}, \tag{30}$$

whose solution is globally stable since the two eigenvalues, $-\beta$ and $-\beta_{zz}$, are negative. Using correspondingly associated and normalized eigenvectors, we have

$$\begin{pmatrix} k(t) - k_s \\ \tilde{z}(t) - \tilde{z}_s \end{pmatrix} = d_1 \begin{pmatrix} \frac{\beta_{zz}-\beta}{\beta_{zk}} \\ 1 \end{pmatrix} e^{-t\beta} + d_2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{-t\beta_{zz}}. \tag{31}$$

where d_1 and d_2 are constants to be determined from initial conditions, as usual.

Appendix of tables

Table 1. Cross-country comparisson: per capita GDP and pollution emissions (1990-2000)

	Real GDP pc			NO_2 pc			CO_2 pc			SO_2 pc		
	1990	2000	annual growth	1990	2000	annual growth	1990	2000	annual growth	1990	2000	annual growth
Den	21.8	26.6	2.2	5.5	3.9	-2.9	11.1	10.8	-0.2	3.4	0.5	-8.4
Swe	20.8	23.6	1.4	3.8	2.8	-2.5	6.4	6.2	-0.2	1.2	0.6	-5.0
Fin	20.3	23.8	1.7	6.0	4.6	-2.4	10.7	9.9	-0.8	5.2	1.4	-7.3
Fra	20.0	22.4	1.2	3.3	2.4	-2.8	6.5	6.8	0.6	2.3	1.0	-5.5
Bel	19.9	23.8	2.0	3.4	3.2	-0.4	12.5	14.1	1.3	3.6	1.6	-5.6
Aus	19.8	23.7	2.0	2.8	2.3	-1.5	7.2	8.0	1.1	1.0	0.4	-5.8
Ger	19.6	22.9	1.7	3.6	2.0	-4.4	12.5	10.3	-1.8	6.7	0.8	-8.8
Ned	19.5	24.3	2.5	3.9	2.7	-3.1	14.1	15.7	1.1	1.3	0.5	-6.2
Ita	19.3	21.8	1.3	3.4	2.4	-3.0	7.3	7.8	0.6	3.1	1.3	-5.8
UK	18.3	22.2	2.1	4.8	2.9	-4.0	10.4	9.3	-1.1	6.5	2.0	-6.9
Mean EU10	19.9	23.5	1.8	4.0	2.9	-2.7	9.9	9.9	0.1	3.4	1.0	-6.5
Std EU10	0.9	1.4	0.4	1.1	0.8	1.2	2.8	3.0	1.1	2.1	0.5	1.3
Spa	14.5	18.1	2.5	3.1	3.3	0.8	5.8	8.0	3.6	5.4	3.7	-3.1
Irl	14.2	26.4	8.6	3.4	3.3	-0.2	7.4	10.7	4.5	5.3	3.5	-3.5
Por	12.3	15.9	2.9	2.2	2.5	1.1	4.5	6.4	4.3	2.3	2.2	-0.5
Gre	12.0	14.6	2.2	2.9	3.0	0.7	8.0	9.6	2.0	4.9	4.6	-0.6
Mean EU14	18.0	22.1	2.4	3.7	3.0	-1.8	8.9	9.5	1.1	3.7	1.7	-5.2
Std EU14	3.3	3.6	1.9	1.1	0.7	1.8	3.0	2.8	2.0	2.0	1.3	2.5
Cze	13.6	13.7	0.1	5.3	3.1	-4.0	12.2	10.5	-1.4	18.2	2.6	-8.6
Sle	13.1	15.7	2.1	3.2	2.9	-0.7	6.8	8.0	1.9	9.8	5.0	-4.9
Sla	12.0	11.4	-0.5	4.1	2.0	-5.2	8.1	6.9	-1.5	10.3	2.3	-7.8
Hun	9.6	10.4	0.9	2.3	1.9	-2.0	6.5	5.5	-1.6	9.7	4.9	-5.0
Pol	6.6	9.2	4.0	3.4	2.2	-3.5	8.6	7.5	-1.3	8.4	3.9	-5.4
mean EU19	16.2	19.5	2.1	3.7	2.8	-2.1	8.8	9.1	0.6	5.7	2.3	-5.5
Std EU19	4.5	5.6	1.9	1.0	0.7	1.9	2.7	2.6	2.0	4.2	1.6	2.4

Keys: Den: Denmark, Swe: Aweden, Fin: Finland, Fra: France, Bel: Belgium, Aus: Austria, Ger: Germany, Net: Netherland, Ita: Italy, UK: United Kindom,
Spa: Spain, Ire: Ireland, Por: Portugal, Gre: Greece, Cze: Czech Republic, Sle: Slovenia, Sla: Slovakia, Hun: Hungary, Pol: Poland
Groups: EU14 excludes Luxemburg from EU15; EU-10 excludes Spa, Ire, Por and Gre from EU14.

Table 2: Cross-section regressions of pollution growth rates (1990-2000)

		EU19		***EU14***		***EU10***	
GDP		β	p-value	β	p-value	β	p-value
	β-convergence(1)	0.0056	0.3429	0.0282	0.0698	0.0041	0.4405
	σ-convergence						
	Std of log 90	0.3205		0.2024		0.0461	
	Std of log 00	0.3302		0.1785		0.0570	
NO2		Beta	P-value	Beta	P-value	Beta	P-value
	β-convergence(1)	0.0475	0.0299	0.0465	0.0275	0.0164	0.2200
	Corrected β-convergence (2)	0.0434	0.0164	0.0462	0.0294	0.0203	0.4219
	σ-convergence						
	Std of log 90	0.2701		0.2678		0.2487	
	Std of log 00	0.2373		0.2224		0.2523	
CO2		β	p-value	β	p-value	β	p-value
	β-convergence(1)	0.0270	0.0601	0.0284	0.0281	0.0068	0.2891
	Corrected β-convergence (2)	0.0245	0.0265	0.0272	0.0125	0.0232	0.2603
	σ-convergence						
	Std of log 90	0.3123		0.3403		0.2999	
	Std of log 00	0.2737		0.2739		0.2965	
SO2		β	p-value	β	p-value	β	p-value
	β-convergence(1)	0.0224	0.1736	0.0175	0.2892	0.0396	0.0342
	Corrected β-convergence (2)	0.0189	0.2604	0.0283	0.3090	0.0439	0.0616
	σ-convergence						
	Std of log 90	0.7873		0.6349		0.6897	
	Std of log 00	0.8214		0.7837		0.5457	

(1) $GP_i = \alpha - \beta \cdot P_{1990} + \varepsilon_i$, where GP_i is the annual growth of pollution emissions, P, of country i between 1990 and 2000

(2) $GP_i = \alpha - \beta \cdot P_{1990} + \varphi \cdot GY_i + \beta \cdot \varphi \cdot Y_{1990} + v_i$, where GY_i is the annual income growth , Y, of country i between 1990 and 2000

Note: See Table 1 for the description of EU10, EU14 and EU19 groups.

Table 3: Panel estimations with fixed effects

	CO2			NO2			SO2		
	estimation	std	p-value	estimation	std	p-value	estimation	std	p-value
EU19									
β	**0.4515**	0.0867	0.0000	**0.2085**	0.0557	0.0002	**0.1074**	0.0652	0.1012
φ_1	0.0476	0.1475	0.7472	0.2013	0.1959	0.3057	**1.2810**	0.5197	0.0147
φ_2	**0.6867**	0.1724	0.0001	**0.3713**	0.2065	0.0738	-0.0145	0.5694	0.9797
φ_3	-0.0953	0.1939	0.6238	0.1175	0.2146	0.5848	-0.6835	0.5079	0.1801
EU14									
β	**0.5729**	0.1176	0.0000	**0.2411**	0.0644	0.0003	**0.1266**	0.0761	0.0985
φ_1	0.0208	0.1274	0.8703	0.0182	0.1802	0.9195	**0.9541**	0.5757	0.0999
φ_2	**0.7119**	0.1519	0.0000	**0.4820**	0.1889	0.0119	0.1987	0.5532	0.7200
φ_3	--	--	--	--	--	--	--	--	--
EU10									
β	**0.6469**	0.1277	0.0000	**0.3592**	0.1126	0.0020	0.1332	0.0975	0.1754
φ_1	0.0094	0.1179	0.9367	**0.4785**	0.2180	0.0308	**1.8166**	0.5545	0.0015
φ_2	--	--	--	--	--	--	--	--	--
φ_3	--	--	--	--	--	--	--	--	--

Note: Bold letters means estimations are significantly different from zero at least at a 10% level of significance.
$GP_{i,t}=\alpha+\beta \log P_{i,t-1}+\delta_1 Y_{i,t}+\delta_2 D_1 \cdot Y_{i,t}+\delta_3 D_2 \cdot Y_{i,t-1}+\varphi_1 GY_{i,t}+\varphi_2 D_1 \cdot GY_{i,t}+\varphi_3 D_2 \cdot GY_{i,t}+\varepsilon_{it}$, subject to $\delta_j=\beta \cdot \varphi_j$, j=1,2,3, where $D_1=1$ for middle-income countries and 0 elsewhere; $D_2=1$ for Eastern European countries and 0 elsewhere.
Time-dummy variables are included in the panel regression for NO_2 and SO_2.

Table 4.1. Policy implications: Targets for NO_2

	Data				Model		
	Target for 2010	Implied annual growth			Prediction for 2010	Implied annual growth	Prediction/Target
		since 1990	achieved	remaining		remaining	
Den	127	-2.76	-2.65	-3.89	189	-0.91	1.49
Swe	148	-2.72	-2.28	-4.08	217	-1.32	1.47
Fin	170	-2.17	-2.13	-2.80	208	-1.19	1.22
Fra	810	-2.87	-2.46	-4.34	1230	-1.40	1.52
Bel	176	-2.37	-0.15	-4.65	268	-1.85	1.52
Aus	103	-2.57	-1.04	-4.58	159	-1.63	1.54
Ger	1051	-3.15	-4.24	-3.59	1460	-1.09	1.39
Ned	260	-2.75	-2.69	-3.85	385	-0.90	1.48
Ita	990	-2.42	-2.91	-2.72	1180	-1.32	1.19
UK	1167	-2.89	-3.80	-3.21	1570	-0.86	1.35
Irl	65	-2.25	0.59	-4.80	154	2.32	2.37
Spa	847	-1.49	1.05	-3.65	1190	-1.07	1.41
Por	250	0.63	1.17	0.08	225	-0.93	0.90
Gre	344	0.93	1.07	0.72	290	-0.97	0.84
Cze	--	--	-4.10	--	248	-2.27	--
Sle	--	--	-0.79	--	52.5	-0.95	--
Sla	--	--	-5.05	--	96	-1.03	--
Hun	--	--	-2.23	--	153	-1.73	--
Pol	--	--	-3.45	--	845	0.08	--

Table 4.2. Policy implications: Targets for CO_2

	Data				Model		
	Target for 2010	Implied annual growth			Prediction for 2010	Implied annual growth	Prediction/Target
		since 1990	achieved	remaining		remaining	
Den	448.7	-1.05	0.17	-2.23	628	0.87	1.40
Swe	567	0.20	0.10	0.30	591.5	0.74	1.04
Fin	534.8	0.00	-0.42	0.44	544	0.62	1.02
Fra	3740	0.00	0.99	-0.90	3956	-0.37	1.06
Bel	1149.4	-0.38	1.62	-2.04	1386	-0.40	1.21
Aus	484.8	-0.65	1.70	-2.56	630	-0.34	1.30
Ger	7860.4	-1.05	-1.53	-0.68	9350	1.09	1.19
Ned	1986.8	-0.30	1.80	-2.03	2453	-0.16	1.24
Ita	3882.4	-0.33	0.81	-1.35	4265	-0.50	1.10
UK	5250.9	-0.63	-0.74	-0.55	5885	0.60	1.12
Irl	292.4	0.65	5.62	-2.77	693.4	7.15	2.37
Spa	2604.5	0.75	4.02	-1.80	3340	0.52	1.28
Por	563.5	1.35	4.48	-1.23	692	0.77	1.23
Gre	1019.2	1.25	2.43	0.06	1173	1.57	1.15
Cze	--	--	-1.45	--	1106	0.26	--
Sle	--	--	1.80	--	148.7	-0.67	--
Sla	--	--	-1.29	--	406.3	0.85	--
Hun	--	--	-1.86	--	554.5	0.09	--
Pol	--	--	-1.17	--	2995	0.36	--

Table 4.3. Policy implications: Targets for SO_2

	Target for 2010	Data: Implied annual growth since 1990	achieved	remaining	Model: Prediction for 2010	Implied annual growth remaining	Prediction/Target
Den	55	-3.45	-8.36	8.97	12.2	-5.79	0.22
Swe	67	-1.84	-4.81	2.18	19.2	-6.51	0.29
Fin	110	-2.88	-7.15	4.86	20	-7.30	0.18
Fra	375	-3.59	-5.27	-4.02	211	-6.63	0.56
Bel	99	-3.63	-5.44	-4.00	55.5	-6.64	0.56
Aus	39	-2.56	-5.63	1.14	11.1	-6.83	0.29
Ger	520	-4.51	-8.81	-1.82	139	-7.81	0.27
Ned	50	-3.69	-5.97	-3.51	28.8	-6.26	0.58
Ita	475	-3.64	-5.70	-3.68	238	-6.84	0.50
UK	585	-4.21	-6.80	-5.08	390	-6.72	0.67
Irl	42	-3.87	-2.96	-6.79	85	-3.51	2.02
Spa	746	-3.22	-2.91	-4.99	575	-6.14	0.77
Por	160	-1.51	-0.39	-2.73	94	-5.73	0.59
Gre	523	0.30	-0.20	0.83	210	-5.65	0.40
Cze	--	--	-8.60	--	66	-7.50	--
Sle	--	--	-4.95	--	31	-6.87	--
Sla	--	--	-7.71	--	29.3	-7.64	--
Hun	--	--	-5.19	--	140	-7.12	--
Pol	--	--	-5.29	--	515	-6.59	--

Table 5: Parameter values

Specific parameter values

	NO_2 EU10	NO_2 EU14	NO_2 EU19	CO_2 EU10	CO_2 EU14	CO_2 EU19	SO_2 EU10	SO_2 EU14	SO_2 EU19
P/Y(2000)	0.124	0.133	0.144	0.420	0.430	0.460	0.044	0.078	0.116
ζ	0.015	0.010	0.008	0.015	0.010	0.008	0.015	0.010	0.008
δz	0.270	0.260	0.270	0.300	0.280	0.290	0.180	0.190	0.180
ϕ	0.180	0.150	0.210	0.030	0.100	0.050	0.450	0.410	0.340
ψ	3.780	3.220	3.028	3.320	4.070	2.997	1.973	2.209	2.147
x_b	0.016	0.017	0.016	0.019	0.018	0.019	0.011	0.012	0.013

Common parameter values

ρ	υ	σ	ε	α	δ	x	n
0.100	0.750	1.500	0.500	0.400	0.100	0.020	0.010

Appendix of figures

Figure 1.1. NO_2 per capita emissions: β–convergence within European countries

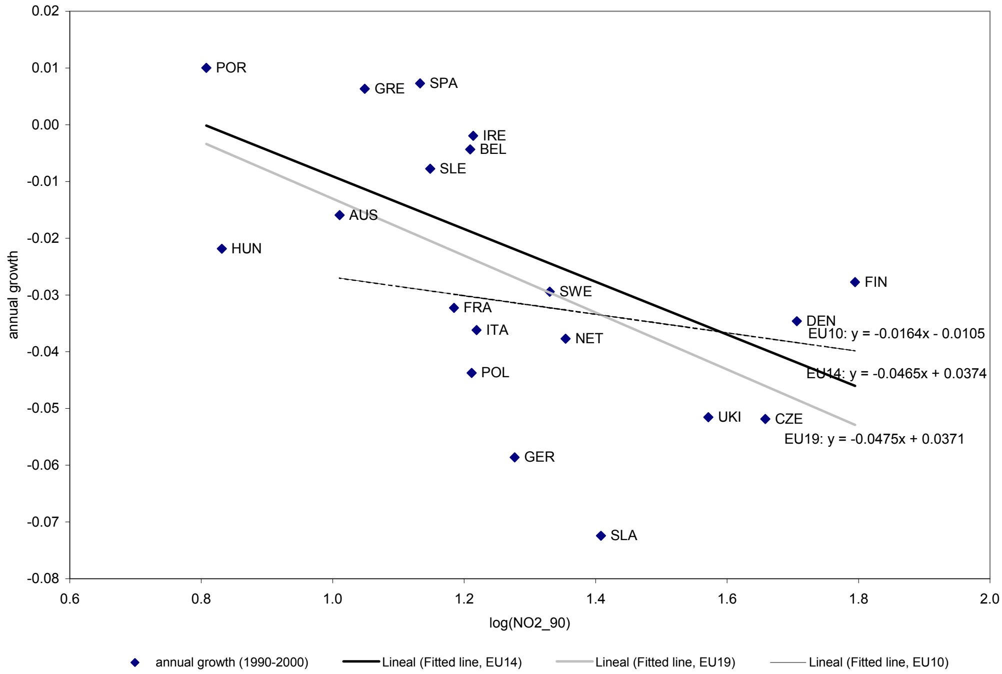

Figure 1.2. CO_2 per capita emissions: β-convergence within European countries

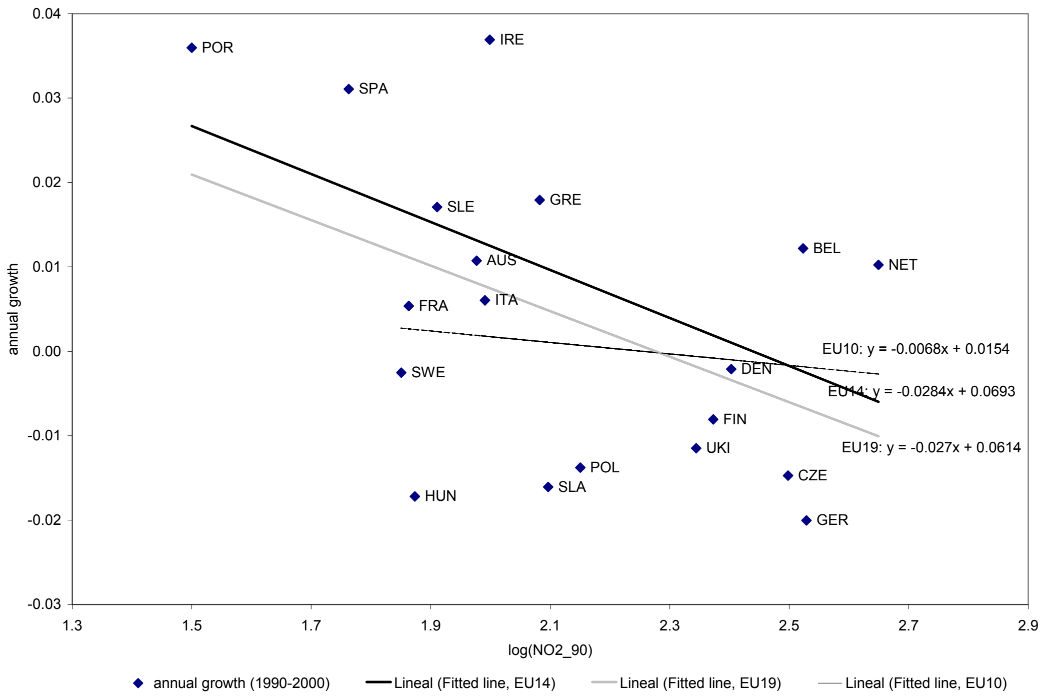

Figure 1.3. SO_2 per capita emissions: β-convergence within European countries

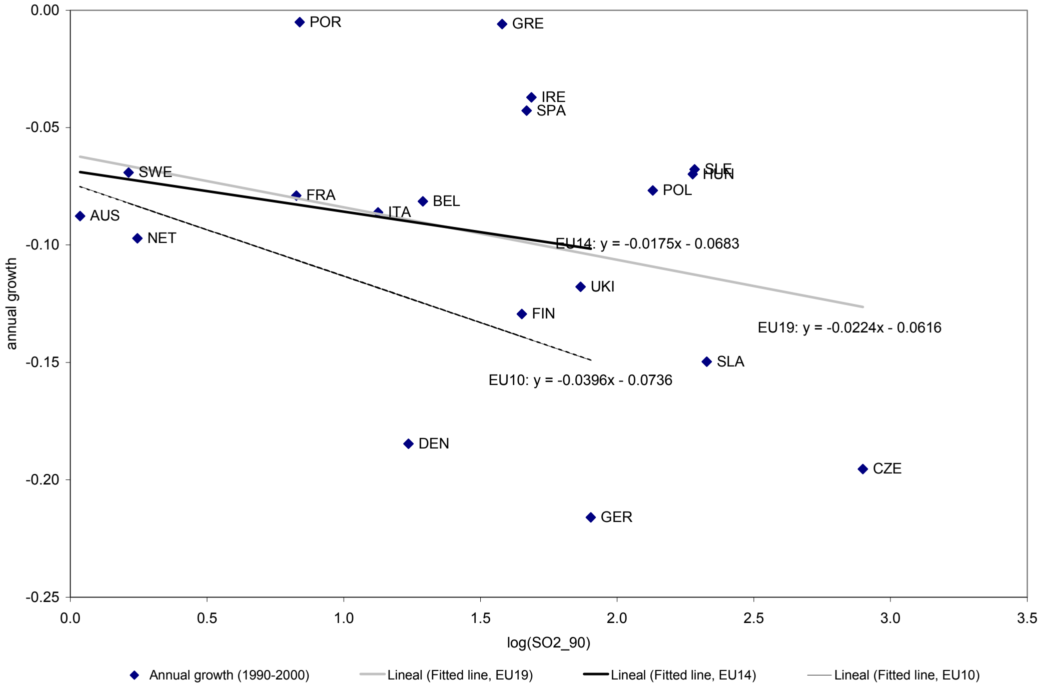

Figure 2.1: Relative Growth of per capita NO2 emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

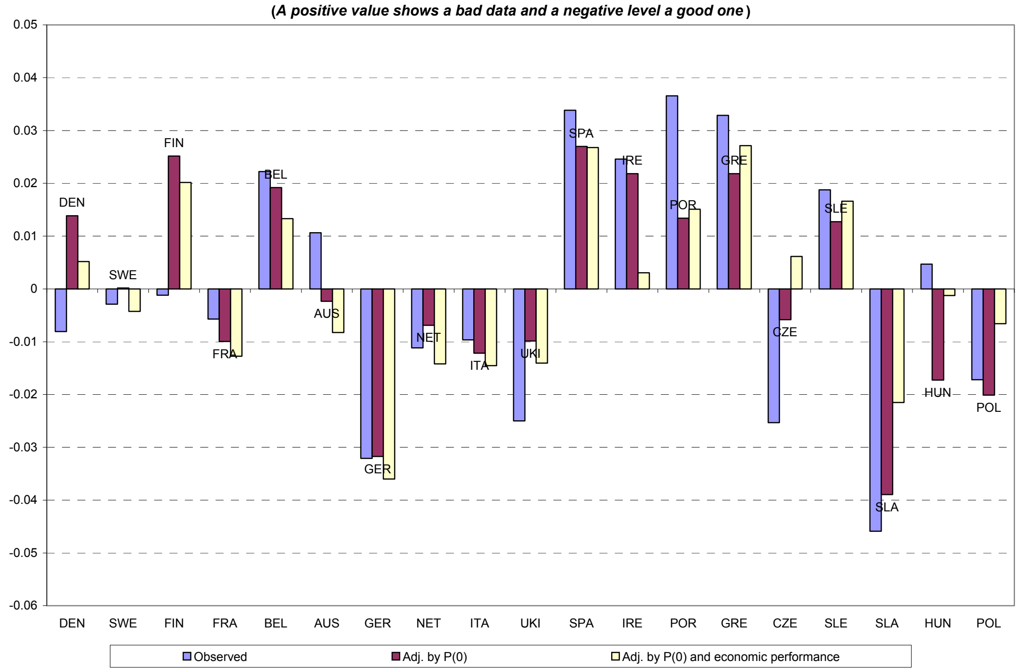

Figure 2.2: Relative Growth of per capita CO2 emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

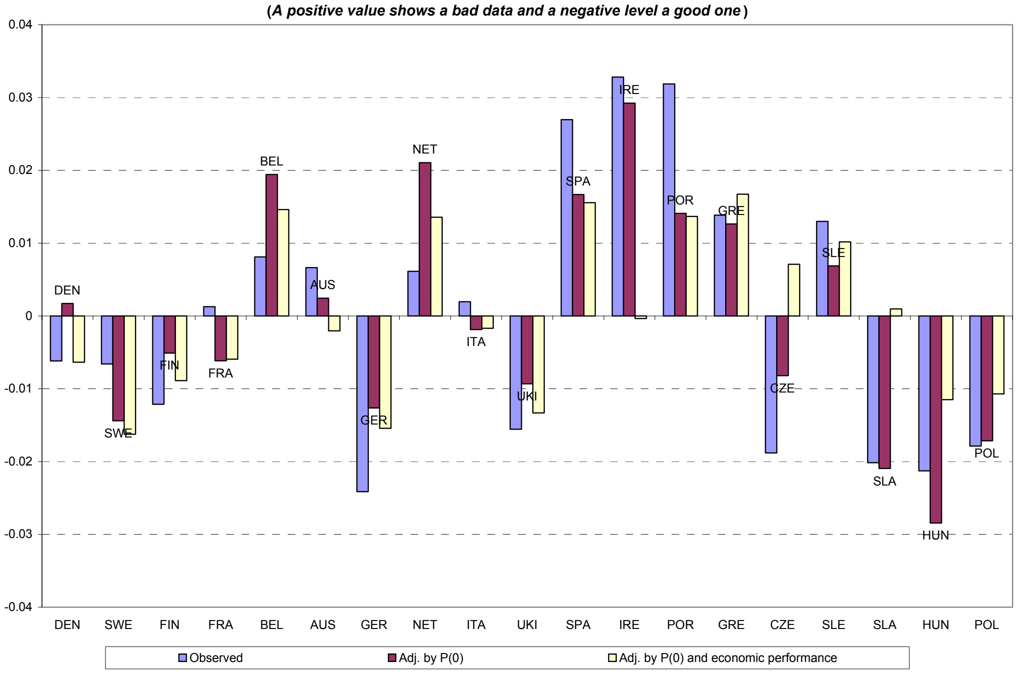

Figure 2.3: Relative Growth of per capita SO2 emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

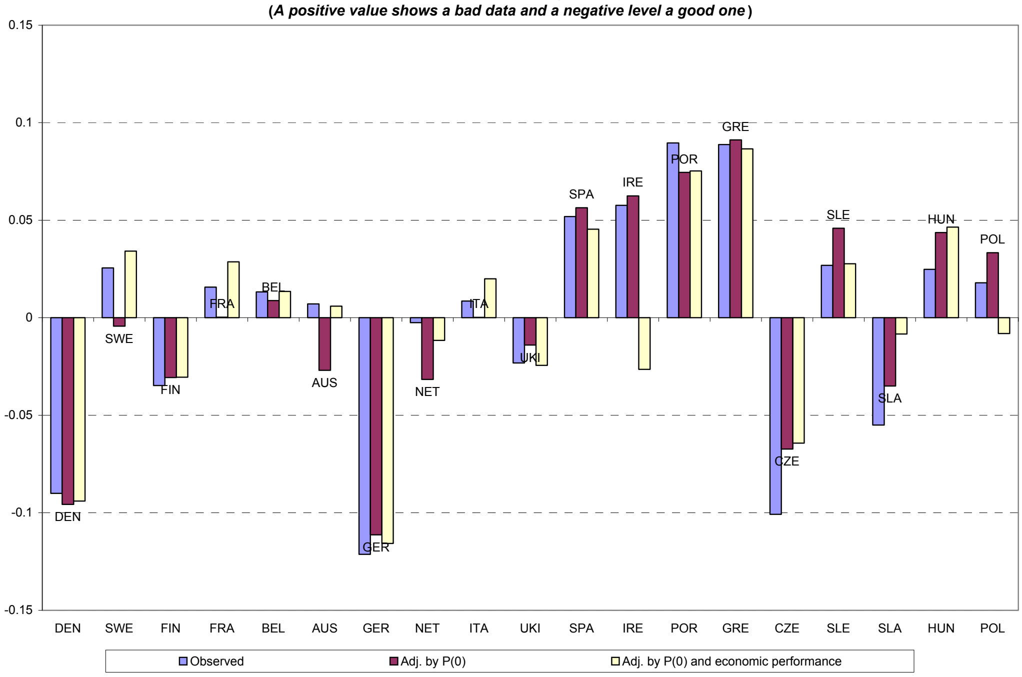

Figure 3.1. NO_2 pollution emissions experiment

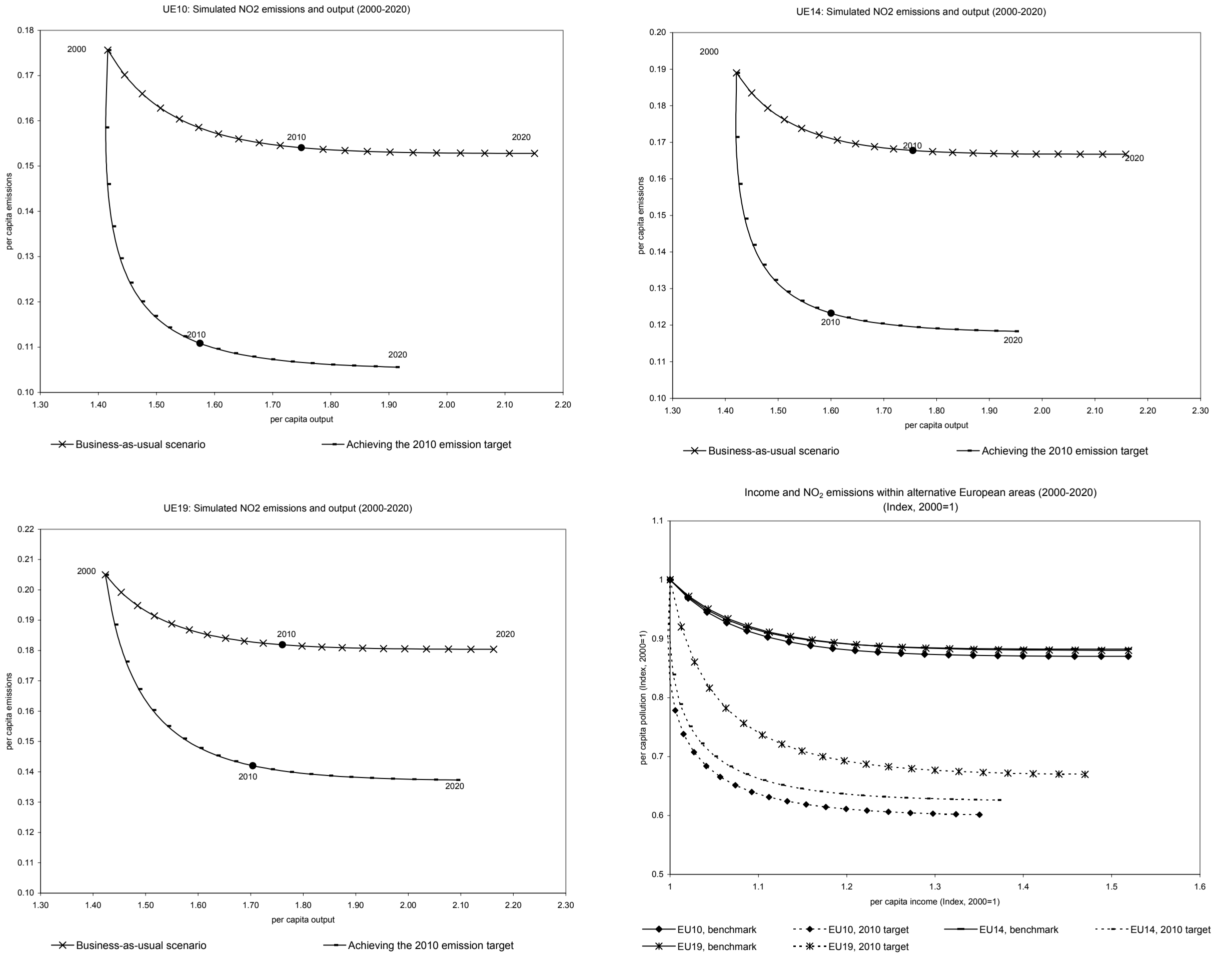

Figure 3.2. CO_2 pollution emissions experiment

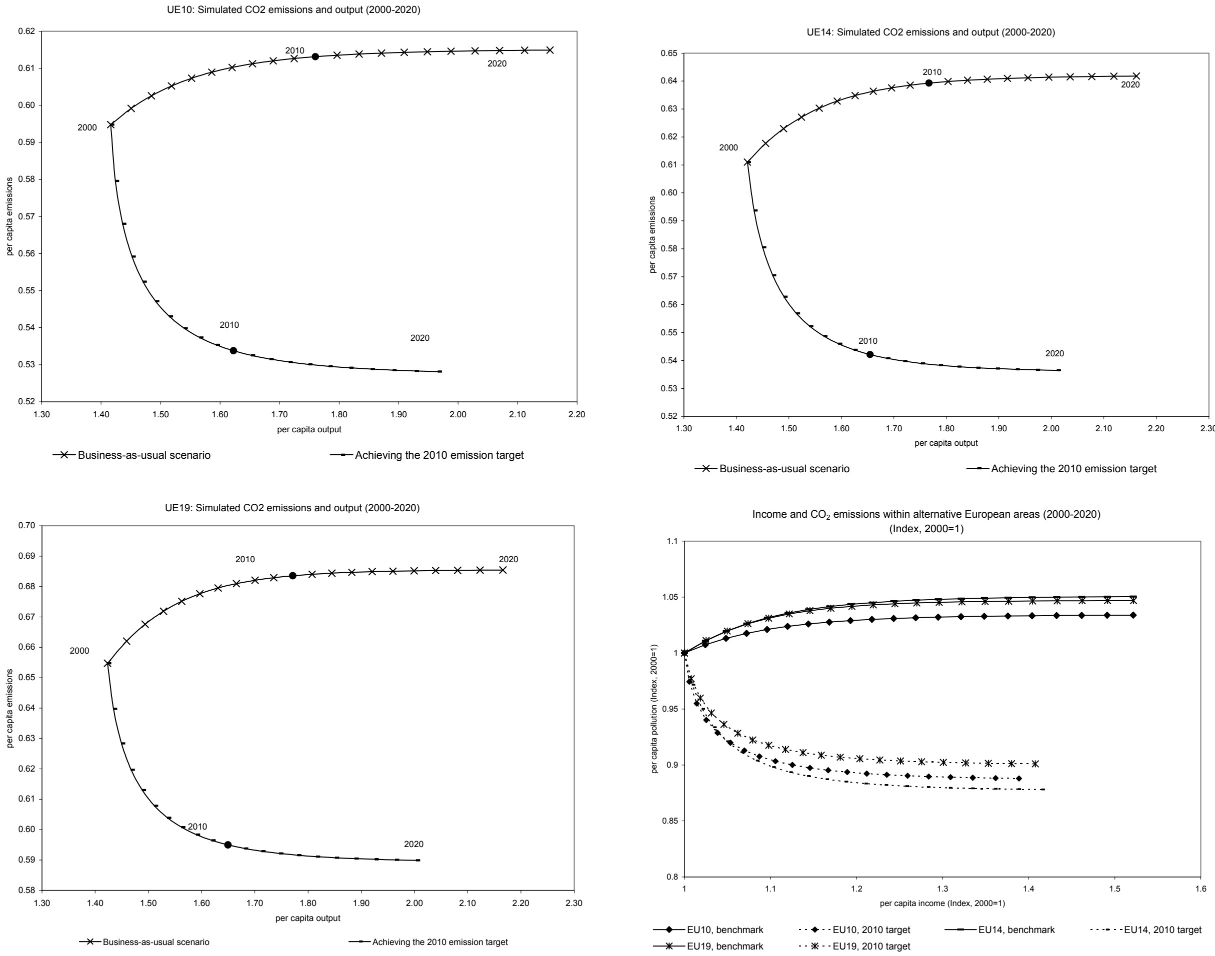

Figure 3.3. SO_2 pollution emissions experiment