Air Pollution Convergence and Economic Growth across European Countries

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Abstract

This paper analyses 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 and taking into account macroeconomic performance. 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, Convergence

JEL: O40, Q20, 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 of air pollutants and its already well studied harmful effects have raised the need of coordination at supra-national levels. The purpose of this article is to report facts on the evolution of air pollutants in European countries, member states of the European Union (EU). Such a description is addressed in connection with EU environmental regulation and taking into account macroeconomic performance.

The existing 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. Several authors have focused on the estimation of the well-known environmental Kuznets curve (Grossman and Krueger (1995), Holtz-Eakin and Selden (1995), Panayotou (2000) and Selden and Song (1994), among many others). Those papers connect the evolution of per capita pollution levels with the evolution of GDP levels. 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. 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.

To simultaneously study the role of output growth as well as output and pollution levels we build upon the methods largely used for the analysis of income convergence and growth.[1] As in this literature we develop comparisons across countries and pollutants so as to preliminary explore what variables are correlated with emissions to motivate further theoretical analysis. Differently from it we do not pursue here either a test of alternative convergence parameters or a structural interpretation of any estimates. We are not aware of any convergence analysis in the environmental literature, to the best of our knowledge.

The issue of convergence in pollution levels seems specially relevant at a time in which environmental regulation is primarily dictated by EU directives. First, we would like to know whether EU environmental policy is likely to be confronted to systematic differences in emission levels across countries. We explore two kinds of convergence. One is the convergence of a given national path towards some limit (presumably positive) level of pollution. The other is whether the paths of different countries get closer to each other over time. Second, we would like to evaluate the degree of fulfillment of emission ceilings controlling for growth and initial conditions. Finally, a quantitative assessment could be useful to test alternative theories on pollution compliance, emission right markets and so on.

We start by reporting facts on the evolution of air pollution over a panel of countries from 1990 to 2000 and five different pollutants.[2] We study similarities across the pollution level paths of those countries and we present some evidence on possible convergence of those paths conditioning on its initial pollution level. This preliminary evidence suggests that initial emissions level (as a proxy for the state of the emissions technology) contributes to explaining pollution dynamics. But also, we find that initial income or income dynamics may capture determinants of emissions growth rates. The question is then how these patterns of cross-country differences in pollution dynamics can be understood within a model of economic growth.

Our analysis proceeds in a neoclassical growth and convergence framework, both in pollution and income. We propose a simple model of environmental quality and capital accumulation that allow us to restrict the observations we have on growth and air pollution. We follow most of the papers in the recent literature [e.g. Stokey (1998)] dealing with environmental pollution in that pollution is proportional to final output with an intensity that depends upon the stock of accumulated residuals. Residuals accumulate in turn from unabated emissions and the non biologically recovered (exponentially) part of the stock. 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 growth framework.

In applying the competitive equilibrium of this optimal growth economy with pollution to data on emissions, 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. Firstly, there is evidence of convergence in the twofold sense aforementioned. In particular, the limit pollution level of national paths is conditional on GDP growth, rather than absolute. In other words, we predict that two countries with different GDP growth rates along the sample period, exhibit pollution paths that converge to different levels. In a sense, this is quite natural: the emission level of a country reflects not only its activity level, but also its industrial structure, which has a strong persistence in time. Secondly, compared to the average behavior across countries and after discounting its differences due to GDP growth and initial level of pollution, it is remarkable how apparently different countries, such as Germany and Poland, have performed relatively well in all of the pollutants considered. In the other extreme, Portugal, Spain and Greece have done badly off. More generally, the air pollution paths of the new EU entrants are relatively more determined by its macroeconomic performance. Thirdly, there remain indeed unexplained patterns that can be meaningfully related with regulation and differences in abatement preferences and technologies. These findings have remarkable consequences in evaluating the evolution of emissions in terms of the targets signed for 2010.

The rest of the paper is organized as follows. Next section reviews the most relevant EU pollution agreements in the 90's, whereas Section 3 describes the data and preliminary evidence. Section 4 presents the theoretical framework of analysis we propose and discusses the constraints this imposes for the empirical analysis and implied convergence equations.

We present the empirical results along Section 5. In this section we also connect our results on convergence with the emission ceilings that are now ruling in EU zone. The last section present some concluding remarks.

2 A look at EU air pollution regulation in the 90's

The alarming discoveries that researchers have made during last decades upon the effects that both transboundary pollutants and greenhouse gases have on the environment, have led governments of most industrialized countries to enforce their action to control such effects.[3] 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, while its official engagement on the greenhouse gases emissions problem came in 1992, through the adoption of the *United Nations Framework Convention on Climate Change* (UNFCCC). It is evident that, by now, several countries are involved in coordinated international actions towards the most important air pollution issues.

In this scenario we concentrate on the European Union (EU) environmental action upon the main sources of air pollution. 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 both SO_2 and CO_2 emissions come from the combustion processes to generate energy. The EU effort in regulating these activities inside its territory is mostly represented by legislation and it is always in line with the international agreements in force.

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.

EU action on the CO_2 emissions problem started under the UNFCCC and is in line with the main scope of the convention that is 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 ambiguous 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 (2000), as part of a general strategy to face the environmental effects of greenhouse gases. The *Emissions Trading Scheme*, legally introduced by Directive n. 87 (2003), 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.

It is clear that 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.

3 The Data and preliminary evidence

The data set contains annual country-level information on emissions of air pollutants obtained from the European Environment Agency (EEA) as well as income and population data from the Summers-Heston V.6 database across European countries for 1990-2000 period.[4] Specifically, we take annual national emissions, measured in kilotons, of the main air pollutants: CO, NO_2, NMVOC, SO_2 and CO_2. We analyze separately each pollutant, which allows to observe to what extent there is heterogeneity across them. The countries of our study are all of the EU15 except Luxembourg and five representative new members: Czech Republic, Hungary, Poland, Slovakia and Slovenia (for ease of exposition, we shall call them the *entrants*). The selection of Eastern countries is determined by data availability. Throughout the paper we find useful to refer to three subsamples of countries: *EU14* (EU15 excluded Luxembourg), *EU10* (EU14 excluding Greece, Ireland, Portugal and Spain — we call them *incumbents-middle income*), and the whole set (*EU19*) which contains EU14 and the Eastern Countries described above. The sample period considered is the maximum sample length with no missing values.[5] Data on countries' population and real chained per capita Gross Domestic Product (GDP), measured in international thousands 1996 dollars, are taken from the Penn World Table 6.1 with the same frequency and sample period as the emissions data. All variables are used in per capita terms.

[INSERT TABLE 1: basic statistics]

Table 1 reports the basic statistics on economic growth and pollution emissions. Virtually all of the countries have steadily increased its GDP along the nineties. The cross country average per annum growth rate has been 2.1%, 2.4% and 1.8% for the whole set of countries, EU14 and EU10, respectively. At the same time there has been a general reduction in polluting emissions, but the figures change substantially among pollutants. This is specially so between CO_2 and the rest: while roughly a half of the countries have diminished their CO_2 emissions, we observe reductions for all other pollutants in most of the countries.

Concerning the 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%, whereas the largest reduction has taken place in Germany and U.K., with -1.4% on average. With respect to the new EU members, Slovenia, for instance, has had an important per annum increment of 1.9%, though their per capita emissions rank the 4th lowest in 2000. Regarding other pollutants, the largest and smallest reduction has been for SO_2 and NO_2, respectively. Across sets of countries, Eastern countries are located below the mean on average emission reductions, whereas the group of Greece, Ireland Portugal and Spain is always above the mean. Also, NMVOC has the most uniform pattern (-2.7% on average) whereas NO_2, CO and SO_2 exhibit the largest reduction within EU10. 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 some others, like Belgium and Austria, for some pollutants are slightly above the mean.

One way to organize the data for a more systematic analysis of cross-country differences can be taken from the literature on convergence and growth. The idea is that the annual growth rate of emissions should be viewed jointly with the initial emission levels. As an example, Finland and France have had similar falls in NO_2, but the initial level for the former is one half that of the latter. Therefore, comparatively, Finland has done better off as far as one is discounting initial levels. A starting point is to specify cross-section regressions of the form:

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

where $GP_{i,00-90}$ is the growth rate of per capita pollution emissions of a given type in country i from period 1990 to 2000, $\log (P_{i,90})$ 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. 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. Rather, we use this measurement instrument to discount the growth rate of pollution emissions from their initial levels and to preliminary explore what variables are correlated with the growth rate of emissions.

[INSERT Figures 1.1 to 1.5: β-convergence scatter plots]

A first description of cross-country differences in emissions behavior across pollutants is presented in Figures 1.1-1.5 (one for each pollutant). As discussed above, we have implemented cross-section regressions of emissions growth over the sample period against the 1990 emission level. A negative slope means that countries with initially (in 1990) higher emission levels have had larger reduction (β-convergence). In general, the figures show a negative slope, with the degree of dispersion varying among pollutants: SO_2 and CO show weaker evidence of convergence, whereas lower dispersion is appreciated for NO_2, NMVOC and CO_2. The β coefficient for different pools of countries are shown in Table 2. For most of pollutants, the slope is statistically more negative, or equivalently -there is more evidence of convergence- in the pool with all countries than when we restrict to EU14 or to EU10.

[INSERT TABLE 2: β and σ convergence]

Notwithstanding, a mild evidence is found in favor of EU14 β-convergence significance for CO_2 as well as EU10 significance for SO_2. Consequently, initial emissions levels may contribute to explaining pollution dynamics to a different extent according to observable characteristics. This is the first hypothesis we want to check. On the other hand, in most of the cases the incumbents-middle income countries are located together in the scatter plots. Likewise, the entrants appear together either substantially reducing emissions as for the case CO_2 or with very similar initial emissions but very dispersed dynamics for SO_2. However, these countries appear quite evenly distributed, for instance, with respect to NO_2. Further, in the case of NMVOC it is the whole set of countries that appears evenly distributed along the convergence line (economics does not play), while in the case of CO each group seems to have his own convergence line. Finally, the EU10 are in general very much distributed along the convergence line except for the case of SO_2 where clearly a different convergence line can be identified for them.

In light of this evidence we argue that initial income or income dynamics may capture some of the determinants of emissions growth rates. This is a second hypothesis. Further, controlling for this economic dimensions may allow to check for compatibility of these data with different regions of the environmental Kuznets curve, and eventually its entire inverted U-shape.

As a complementary analysis to the β-convergence, we might ask whether the cross-country coefficient of variation in emission levels for year 2000 is smaller than for year 1990. This is the so-called *σ-convergence*. The previous table shows either no evidence of σ-convergence or a mild evidence in line with the β-convergence. In summary, though the evidence of convergence is weak, specially for SO_2, it is not weaker than for the GDP paths (see Table 2) for the period under consideration.

Consequently, we find that in general the expansionary macroeconomic performance observed across European countries in the nineties coexists with a downward trend in per capita emissions among the more important air pollutants. Also, when taking into account initial conditions in emissions levels we have evidence in favor of larger reduction in air pollution intensity. This evidence is stronger the wider the set of countries that are incorporated into this descriptive analysis but there are differences related to observable characteristics. In terms of dispersion among countries through the different pollutants similar patterns can be described. In any case, cross-country income differences as well as income dynamics seem to contribute to explaining emissions growth rates.

Understanding the impact of the link between economic growth and the emissions of pollutants on the cross-country differences observed in pollution patterns could be enlightening for economists and policy makers. First, we ask whether income differences imply differences in the growth rate of pollution emissions for countries with similar initial level of emissions. Second, we would like to know whether different patterns can be described for different countries according to observable characteristics. Next, we present a simple model that we consider useful to answer these and other related questions.

4 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 pollutant.

For ease of exposition we rely on the aggregate economy to describe the economic environment. However, we will consider pollution as an externality, and therefore, our theoretical framework will be that of the non-regulated competitive equilibrium. A detailed description of the competitive equilibrium for the model economy described below is left for the Appendix.

Pollution emissions and aggregation

We can 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

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

where $\eta \in (0, 1]$ is the fraction of un-recycled pollutants that adds to the stock at any t and $\delta_z \in (0, 1)$ is the rate at which aggregate pollution is absorbed by the environment. Note that in this formulation the damage of emissions of vintage t is reduced by $\mathrm{e}^{-(\delta_z/\eta)t}$. The presence of η in the accumulation process of $\bar{Z}$ can be interpreted as an abatement intensity factor. For simplicity, we assume that this factor is exogenous and represents the current state of the abatement technology and no resources that affect the equilibrium - at least being subtracted from the National Output - are required for this activity.

Aggregate pollution emissions at time t, $\bar{P}(t)$, result from aggregation of individual emissions at the firm level. The way we motivate the competitive equilibrium in our framework relies precisely on aggregation over these emissions through weights which are a function of the aggregate states à la Romer.

Instead of specifying the flow of emissions at individual production units we assume that the pollution flow is well-approximated by a function of total output, $\bar{Y}$, corrected by a factor of dirtiness.[6] We consider that this factor depends positively on the stock of pollution to output ratio. In what follows we drop time subscripts when is not strictly necessary and small caps letters refer to variables measured in per capita and efficiency units. Therefore, aggregate pollution evolves according to

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

where $\tilde{B} > 0$, and ϕ and ψ, both in $[0, 1]$, are efficiency and elasticity parameters of the technology, respectively.

Neoclassical output growth

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

$$y = Ak^{\alpha}, \tag{3}$$

$$\dot{k} = y - c - (\delta + n + x)\,k, \tag{4}$$

where A is a constant, k is the physical productive capital, c is private consumption, dot denotes time derivative, $\alpha \in (0,1)$ 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]

For our purposes, it is convenient to rewrite the equation (2) in terms of the physical capital stock. Using (3), we have:

$$p = Bz^{\phi}k^{\theta}, \tag{5}$$

where $B = \tilde{B}A^{\theta/\alpha}$, $\theta = \alpha\,(\psi - \phi)$ and $\theta + \phi < 1$.

Given a pollution stock to output ratio, the higher ϕ, the dirtier would be the technology. We restrict $\phi < 1$, since otherwise we will have an economy with emissions of pollution, in per capita and efficiency units terms, growing without bound. In addition, a negative ϕ makes no sense. Moreover, the level of ϕ is expected to depend on the kind of pollutant, and to be fairly constant along time. Thus, the unique way to reduce the degree of dirtiness along time is by reducing the z/y ratio.

Clearly, the pollution to output elasticity is $\psi - \phi = \theta/\alpha$. As it is standard in the literature, we assume that parameters are constant over time and might be country-specific. Thus, for a given country, the pollution-output relationship is monotone along time. However, its sign might change across countries depending on θ, since α is positive. These implications are consistent with our sample observations.[8]

Optimal growth with pollution

The economy is populated by a continuum of identical infinitely lived households or dynasties that grow at rate n as stated above. Initial population is normalized to one and labor is inelastically supplied. These households 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. Households seek to maximize discounted lifetime utility and individual preferences are assumed to be represented by the instantaneous utility function $U\left[C, h\left(\bar{Z}\right)\right]$, which is a $\mathcal{C}^2$ mapping, strongly concave and increasing in both arguments. $h\left[\bar{Z}\right]$ is an indicator of the state of health that relates to the aggregate amount of pollution, $\bar{Z}$, with $h'(\cdot) < 0$. Caps letters without bar refers to per capita variables.

Each agent discounts future utility at a constant rate $\rho \geq n$.

Under these assumptions the competitive equilibrium for this optimal growth economy with pollution can be derived from the solution to the following problem:[9]

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

subject to

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

given $K(0) = K_0$ and the sequence of the aggregate pollution stock taken as given by nature according to the law of motion,

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

given $\bar{Z}(0) = \bar{Z}_0$, for which (1) gives a solution, provided $\bar{Z}(t)e^{-(\delta_z/\eta)t} \rightarrow 0$ as $t \rightarrow \infty$.

We consider a particular functional form for the instantaneous utility function to get optimal conditions. For a non-separable version of U, we assume a CRRA function of the following type:

$$U(C,\bar{Z}) \;=\; \frac{\left(C^{\nu}h(\bar{Z})^{1-\nu}\right)^{1-\tau}-1}{1-\tau},\;\tau>0,\;\nu\in[0,1] \tag{9}$$

where v means the relative importance of consumption in welfare and $1/\tau$ is the intertemporal elasticity of substitution, which is constant. We define $\varepsilon_{h,z}$ as the elasticity of the 'health' function over $\bar{Z}$. As we will see later, it is required this elasticity being constant for a balanced growth equilibrium to exist. A candidate for $h(\bar{Z})$ is $\frac{D\bar{Z}^{-\varepsilon}}{\varepsilon}$, where $\varepsilon_{h,z}=-\varepsilon$ and D measures the impact of health on aggregate welfare.

Equilibrium conditions

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

$$\frac{\dot{c}}{c} \;=\; \frac{1}{\tilde{\tau}}\left(\alpha A k^{\alpha-1}-[\rho+\delta+x\tilde{\tau}]-(1-\tau)(1-v)\varepsilon\left(x+n+\frac{\dot{z}}{z}\right)\right), \tag{10}$$

$$\frac{\dot{k}}{k} \;=\; A k^{\alpha-1}-\frac{c}{k}-[\delta+n+x], \tag{11}$$

with $\tilde{\tau}=1-v(1-\tau)$, and together with border constrains: $c>0$ and $k>0$ and the transversality condition

$$\lim_{t\to\infty} k(t)e^{\left[-\int_0^t\left(\alpha A k^{\alpha-1}-n-\delta-x\right)ds\right]}=0, \tag{12}$$

that places a limit on the accumulation of private capital.

The dynamics of the economy is characterized by (10), (11) together with the dynamics for z, that comes directly from (8) and (5),

$$\frac{\dot{z}}{z}=\eta B z^{\phi-1}k^{\theta}-(\delta_z+x+n), \tag{13}$$

the three equations give us a system of differential equations in c, k and z.

The balanced growth path:

It is straightforward to show that all variables grow at a constant rate along a balanced growth path (bgp). Hence, their per capita levels are growing at an exogenous rate given by x. Assuming constant levels of η and B, from (13), z also grows at a zero rate and its per capita level at the x rate. Pollution grows at the same constant rate. Under this condition, and provided $x > 0$, the model predicts a situation in the bgp along which output per capita and pollution per capita are growing at the same rate.

Notice that this long-run prediction may change if either η or B fall throughout time, thus our model would be consistent with a situation in which output per capita is growing and per capita emissions are raising at a lower rate than output or is constant or is falling (i.e., the pollution/output ratio falls with the degree of development, as predicted by the EKC).

Setting $\dot{c}/c = \dot{k}/k = \dot{z}/z = 0$ in (10)-(13), we obtain steady state levels of stationary variables,

$$
\begin{aligned}
k_s &= \left(\frac{A\alpha}{[\rho + \delta + x\tilde{\tau}] + (1-\tau)(1-v)\varepsilon\,(x+n)} \right)^{1/1-\alpha}, &(14)\\
c_s &= \left[A\,(k_s)^{\alpha} - k_s\,(\delta + n + x) \right], &(15)\\
z_s &= \left(\frac{B\eta}{\delta_z + x + n} \right)^{1/(1-\phi)} (k_s)^{\theta/(1-\phi)}. &(16)
\end{aligned}
$$

The degree of dirtiness along the bgp of the pollution technology is given by,

$$
\left(\frac{z_s}{y_s} \right)^{\phi} = A^{-\phi} \left(\frac{B\eta}{\delta_z + x + n} \right)^{\phi/(1-\phi)} (k_s)^{\frac{\phi(\theta - \alpha(1-\phi))}{(1-\phi)}}. \qquad (17)
$$

The pollution/output ratio along the bgp is constant and equal to:

$$p_s/y_s = BA^{(\theta-\alpha(1-\phi)-\phi)}\left(\frac{B\eta}{\delta_z + x + n)}\right)^{\phi/(1-\phi)}(k_s)^{\frac{(\theta-\alpha(1-\phi))}{(1-\phi)}}, \quad (18)$$

which is constant along the bgp.

Notice that the relationship of these ratios with respect to k_s depends on whether $(\theta - \alpha(1-\phi))$ is positive or negative. Moreover, since a higher elasticity parameter ε reduces k_s and z_s, the relationship of these two ratios with respect to ε crucially depends on this sign.

The transversality condition (12) requires that the steady state rate of return, $\alpha A k_s^{\alpha-1} - \delta$, to exceed the steady-state growth of the economy, $x+n$. That condition implies the following restriction among parameters:

$$\rho > n + \nu(1-\tau)x - \varepsilon(1-\nu)(1-\tau)(x+n), \quad (19)$$

which also ensures the utility function in (6) be bounded from above.[10]

The Dynamics:

We log-linearize (10)-(13) around the steady-state (see Appendix). The non-separability assumption of $U(C, h(\bar{Z}))$ affects to the intertemporal condition of consumption, and thus to the investment plans and finally to the evolution of the stock of pollution thought the indirect effect over capital accumulation. Observing the current aggregate stock of pollution $\bar{Z}(t)$, households react with higher consumption under increments of both the stock of pollution and capital, since those increments reduces the marginal utility of consumption. However, in the non-separable case, we can not obtain explicit expressions for eigenvalues or eigenvectors of the transition matrix, which precludes the possibility of identifying the coefficients associated to the variables with structural parameters of the economy.

Assuming a separable utility function of the type,

$$U(C,\bar{Z}) \quad = \quad \frac{C^{1-\tau}-1}{1-\tau}+h(\bar{Z}),\, \tau>0, \tag{20}$$

allows the dynamics of the economy being solved recursively, first for c and k (as in the standard Cass-Koopmans framework) and next solving for z, using the dynamics for k. Given initial conditions $k(0)-k_s$ and $z(0)-z_s$, the solution for k and z are given by:

$$k(t)-k_s \quad = \quad e^{-\beta t}\left(k(0)-k_s\right), \tag{21}$$

$$z(t)-z_s \quad = \quad \frac{\beta_{zk}}{\beta-\beta_{zz}}\left(e^{-t\beta}-e^{-t\beta_{zz}}\right)(k(0)-k_s)+e^{-t\beta_{zz}}\left(z(0)-z_s\right), \tag{22}$$

where the expressions of the $\beta' s$ are shown in the Appendix.

The dynamics for pollution and the convergence equation

For the non-separable case, from (21), (22), (3) and (5), the dynamics for $y(t)$ and $p(t)$ are given by:

$$y(t)-y_s=(y(0)-y_s)\,e^{-\beta t}, \tag{23}$$

$$p(t)-p_s=(p(0)-p_s)\,e^{-\beta_{zz}t}+\left(e^{-\beta t}-e^{-\beta_{zz}t}\right)\lambda\left(y(0)-y_s\right), \tag{24}$$

where

$$\lambda=\left(1+\frac{\beta_{zk}}{\beta-\beta_{zz}}\frac{\phi}{\theta}\right)\frac{\theta}{\alpha}. \tag{25}$$

As it is standard, the term β indicates how rapidly the output per capita in efficiency units approaches its steady-state value, while the convergence speed of the economy's pollution emission is determined by β_{zz}.[11] As in the neoclassical framework for output, the abatement parameter η and the level of pollution technology B do not affect the speed of convergence of pollution emissions. Because of the Cobb-Douglas specification, two offsetting forces cancel out: first, given Z, a higher η leads to higher accumulation of residuals and thus to a faster convergence; second, a higher η raises the steady state stock of pollution and hence lowers the average pollution in the proximity of the steady state, which reduces the speed of convergence. A similar argument could be made regarding B. Therefore, given δ_z, x and n, the speed of convergence in pollution is determined by the dirtiness parameter, ϕ: the higher ϕ, the faster convergence. Being $\beta_{zk} > 0$, ϕ and $\alpha > 0$, the sign of λ depends on θ and on the relationship between the two convergence speed parameters β and β_{zz}.

A similar equation for $p(t)$ can be obtained under the non-separable case, but that precludes the possibility of characterizing explicitly the parameter λ.

Using (23), condition (24) can be rewritten in terms of $p(0)$, $y(0)$ and $y(t)$,

$$p(t) - p(0) = (p(0) - p_s - \lambda (y(0) - y_s)) \left(e^{-\beta_{zz} t} - 1\right) + \lambda (y(t) - y(0)) . \qquad (26)$$

From (26), we can derive in a standard way the emission growth convergence equation in discrete time, taking a year as the unit of time:

$$\begin{aligned} GP_{i,t} &= x(1-\lambda) + \left[\left(1 - e^{-\beta_{zz} T}\right)/T\right](p_s - \lambda y_s) - \left[\left(1 - e^{-\beta_{zz} T}\right)/T\right] \log P_{i,t-T} \quad (27) \\ &\quad + \lambda \left[\left(1 - e^{-\beta_{zz} T}\right)/T\right] \log Y_{i,t-T} + \lambda GY_{i,t}, \end{aligned}$$

where $GP_{i,t} = \frac{1}{T}\log(P_{i,t}/P_{i,t-T})$ and $GY_{i,t} = \frac{1}{T}\log(Y_{i,t}/Y_{i,t-T})$, that is, the annum growth rate of per capita pollution and real GDP, respectively, in country i, from period $t-T$ to t. Notice that the model imposes restrictions between the coefficients of the regressors, which must be considered in the empirical analysis.

5 Empirical Analysis

The analysis of convergence in pollution dynamics consists of regressing the total emissions growth for a set of countries and a given sample period on their initial levels. The results of this analysis conform the preliminary evidence that has been presented along Section 3. We conclude from this analysis that there is some preliminary evidence of absolute β-convergence. This suggests that a standard model of exponential depreciation in the stock of pollution together with a flow of emissions generated from decreasing returns on the pollution stock might be a rough description of pollution dynamics.[12]

However, there is also evidence that income dynamics play a role in pollution dynamics. The model of growth and pollution dynamics we propose suggests a procedure to take into account the macroeconomic performance of the countries. The objective is twofold. Firstly, to evaluate the ability of our model to account for observations. Secondly, to identify sources of cross-country differences with implications for theory, both additional structure and additional control variables.

Our empirical analysis starts with cross-section regression. The cross-section equation provides an indicator of partial β-convergence, but its main advantage is that it allows a direct analysis of the residuals. However, the cross-country heterogeneity makes the cross-section equation misspecified. To permit unobservable country-specific heterogeneity as well as to take into account the yearly evolution in income and pollution levels we augment the convergence analysis through panel regressions.[13] With respect to the cross-section regression, it provides for each pollutant a ranking among countries according to their position compared to a common expected pollution emission and economic growth paths throughout the nineties. Also, as far as we handle the information of the entire sample we obtain more efficient estimations.

For each pollutant: i) we give a first evidence of convergence within European countries; and ii) we provide a ranking among these countries, according to their relative position in an global expected pollution emission trajectory throughout the nineties.

Two comments are in order. Firstly, in this analysis we abstract away from the industrial structure of each country. The industrial structure would clearly help to explain the difference across countries in the evolution of the national pollution levels, but here we focus on finding those differences rather than on explaining them. Secondly, the question of whether national emission levels are somehow converging or not does not answer -at least directly- to the question of whether countries are expected to accomplish with the targets on national pollution ceilings within date.

5.1 Cross section regression

From (27), the cross-section equation is:

$$G\hat{p}_{i,00-90} = \alpha - \beta\hat{p}_{i,90} + \delta_1\hat{y}_{i,90} + \delta_2 G\hat{y}_{i,00-90} + \varepsilon_i,$$

where $\delta_1 = \beta\delta_2$ and the index i runs across countries. The Table 2 reports the cross-section estimates for the regression implied by the theoretical model. These estimates appear for each pollutant where corrected β-convergence refers to corrected by initial GDP and GDP growth. The coefficient of the 1990 emission level gives us (discounted by the GDP effect) a measure of β-convergence, which is comparable with the analysis shown in Section 3. Notice that differences are minor. However, the ability of the convergence hypothesis to explain why some reduced emissions faster than others is reinforced for NO_2 in EU19, for CO_2 in EU14 and for SO_2 in EU10. In the case of NMVOC the evidence in favor of the convergence hypothesis is reinforced in every group while for CO the correction goes against the convergence hypothesis in all groups. We will proceed later with a fixed effect panel data approach in order to interpret more appropriately the parameter estimations.

Nevertheless, the residuals contain interesting information. A negative residual indicates that the corresponding country has reduced its pollution level beyond what is expected conditioned on its growth rate and initial output and pollution levels. In this sense we refer to it as a *clean* country whereas we associate a positive residual to a *dirty* country. Figures 2.1 to 2.5 show the residuals of the previous cross-section regression. For the sake of comparison these residuals are reported jointly with the corresponding residuals of the β-convergence analysis of Section 3 as well as the observed deviations with respect to the cross-country average emission growth.

With the exception of Ireland, the incumbents-middle income countries - Spain, Portugal and Greece - show in general significative positive residuals for each pollutant. On the other hand, Germany and UK are the most unambiguous examples of clean economies among EU14. The case of Ireland illustrates the importance of discounting the GDP growth effect from the primitive convergence equation. Omitting the per capita GDP growth rate, this country shows a bad environmental performance, but instead, due to its important per capita GDP raise along the nineties, its position turns out to be within the set of *clean* countries. With respect to the new EU members, the entrants, Poland shows the best performance for all pollutants but CO.

In general, entrants tend to reduce emissions slower once we control for initial income levels and GDP growth. Among incumbents-middle income, only Ireland tend to reduce emissions faster (grow clean) indeed. Among EU10 adjustments tend to be smaller, but often relevant (mixed evidence). Also, dynamics of CO_2 exhibit the more homogeneous pattern across countries, whereas dynamics of SO_2 suggest sizeable cross-country differences.

[INSERT FIGURES 2.1 to 2.5 AROUND HERE]

5.2 Panel data analysis

In the cross-section convergence equation, we do not take into account the yearly evolution of the pollution levels within the sample period. In addition, regarding pollution emissions, we appreciate an important heterogeneity among the European countries considered. The need to account for this economic differences suggest a panel data analysis with fixed effects.[14]

From (27), the panel representation is:

$$G\hat{p}_{i,t} = \alpha_i - \beta\hat{p}_{i,t-T} + \delta_1\hat{y}_{i,t-T} + \delta_2 G\hat{y}_{i,t} + v_{i,t}, \tag{28}$$

where $\delta_1 = \beta\delta_2$ and α_i captures the inherent heterogeneity among countries.

A test on homogeneity suggests the use of a model in which the parameter α is country-dependent. As standard, β and δ's are common to all countries. Additionally, we have applied the Haussman test and the result suggests the use of a fixed effect model, instead of the alternative random effects model. We use non-linear least squared method for pooled regressions. Inference exercises are based on the White heteroskedasticity-consistent covariance matrix. Table 3 summarizes parameter estimates from the fixed effect panel estimation for the five pollutants considered over the whole sample, EU19. The table also presents results considering: *1)* former EU15 states excluded Luxembourg (EU14), that is excluded what we called the entrants *2)* EU14 excluded what we called the incumbents-middle income: Greece, Ireland, Portugal and Spain (EU10).

[INSERT TABLE 3 ABOUT HERE]

Let us start with the estimates obtained for NO_2. With this pollutant all coefficients are found significant in EU19 and EU14 subsamples while they are not for EU10. In particular, β-convergence is a robust finding for those subsamples larger than EU10. The effect of output growth, parameter λ, is found to be negative once we control for particular country's subgroups. Notice that λ captures the net effect for the group. Thus, the estimates suggest that output growth goes with pollution growth for the incumbents-middle income and the new entrants substantially more than for EU10. Similar interpretations can be given to the results obtained for CO_2 but in this case $\beta-$ convergence is found in all subsamples and strongest (and significant) macroeconomic effects are found for incumbents-middle income. Finally, a clearer role for output growth is found for SO_2 over the whole sample of countries, over the new entrants for NMVOC and non significant economic effects for CO.

We interpret these findings in favor of our model specification as capturing most of the dynamics of NO_2 emissions together with an important part of CO_2 and SO_2 emissions, possibly over components of a different nature. The whole picture of empirical evidence up to this point is less conclusive for both NMVOC and CO.

Is it possible to be more precise on simple elements that can be incorporated to the simple theory discussed in this paper? To this purpose an alternative convergence model that includes time effects dummies is also estimated. This specification can be justified by any assumed permanent differences in efficiency between the pollution technology and the path for per capita income with balanced growth. Remember that up to this point it has been assumed instead that the pollution-output ratio is constant along the balanced growth path. Also, notice that these time dummies should not capture any business cycle component since these effects are already in output growth. Table 4 reports parameter estimates for this alternative model with time dummies common to all countries, again for the five pollutants considered.

[INSERT TABLE 4 ABOUT HERE]

The results show that the estimated β is significantly positive for all pollutants. These estimates are similar and significant regardless the set of countries considered, except for the significance in the SO_2 convergence coefficient when we consider the EU10 subgroup. The stronger evidence of convergence is found within the EU10 group. Comparing pollutants, convergence during the 90's has been faster for CO_2, followed by NO_2, CO and NMVOC. These results reinforce the evidence in favor of accepting β-convergence within European countries in terms of pollution emissions.[15] That is, in favor of the hypothesis that the evolution of emissions of air pollutants in the short-run is substantially determined by their initial levels (as a proxy for the state of the *pollution technology*).

Likewise, output growth effects are reinforced under this specification. The corresponding estimates are found with the right signs and under economically meaningful interpretations related to macroeconomic performance combined with sources of emissions. More precisely, in the case of NO_2 it is vigorous economic growth that produced a slowdown in the reduction of emissions for incumbents middle-income, something that is not present for entrants but that it is always relevant as the EU10 subsample estimations show. Similarly occurs with CO_2 where the role of output growth is even stronger for incumbents middle-income. Convergence and growth estimates in this case jointly suggest pollution dynamics across EU14 of a different nature of that when incorporating the entrants. We argue this is related with differences in abatement technologies. Alternatively, the results suggest that SO_2 emissions dynamics tend to be governed by GDP growth. This seems to be so in a way significantly different for EU10 than for the rest of countries and also of a different nature than for the rest of pollutants. In relative terms, for the rest of countries and pollutants it is income and pollution dynamics that play the leading role.

Finally, time dummies are negative and significant since 1993, and particularly exhibiting a stronger effect from 1997 (Kyoto) except for CO_2 (so for all other pollutants): a trend that can be interpreted as environmental regulation. This finding combined with the differential effect for EU10 in SO_2 emissions, the pollutant with the largest tradition of EU directives against, stresses the potential role for regulation elements to be incorporated in a simple model of pollution and growth. Overall, we interpret these findings as evidence in favor of a description of pollution dynamics in favor of a descending branch of the EKC in the case of NO_2, two region-specific EKCs in the case of CO_2 and a very different pattern between EU10 and the rest of countries with respect to SO_2 emissions.

Consequently, we take this econometric specification as a good measurement instrument to report facts on the short-run dynamics of pollution and growth. Also, this specification allows to obtain preliminary estimates of structural parameters for a stylized representation of a pollution technology. Indeed, pollution dynamics and GDP growth relationship (sign) fixes model λ and therefore structural θ. These numbers combined with β estimates imply values of ψ and ϕ that can be tested for robustness among pollutants. This test should proceed through variants of the model specification proposed in this paper calibrated to account for the aforementioned sources heterogeneity among pollutants.

5.3 Targeted emissions' levels

We have focused so far on the evolution of emissions of air pollutants once we take macroeconomic performance into account. We have quantitatively characterized some degree of dispersion across time, and among countries and pollutants. Part of this dispersion relates to the heterogeneity of the targeted emission levels imposed by the EU regulator. This heterogeneity responds to differences of starting conditions, but also to the purpose for harmonization to eliminate and prevent distortions of competition in the common market.

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_x, NMVOC and CO_2) have been 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. The limits on CO_2 are established according to the Kyoto Protocol correspondingly.

To give a sense of the heterogeneity across countries, Table 5.1-5.5 reports the emissions ceilings targeted (for 2000 as well as those for 2010). With the exception of Greece, that is allowed to raise its emissions on all the pollutants considered, the rest of countries have the purpose to abate their emissions in a significative amount. For instance, for NO_x and NMVOC, the richer countries such as Germany, France, Netherlands, Sweden and United

Kingdom 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 poorer countries. Greece is on the extreme since it is allowed to raise emissions. 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%. Finally, the target on CO_2 is of a 8% reduction for the whole EU15.

[INSERT TABLE 5.1-5.5 ABOUT HERE]

The first column of Table 5.1-5.5 report the percentage reduction (or increment) for each pollutant, starting at 1990, that each country must reach by 2010. The second column shows how each country is doing: that is, it compares the levels at the 2000 with that at 1990. The third column shows what is left to get the target, when comparing current levels (levels at 2000) with that to be attained in 10 years.

In general, for NO_x, SO_2 and NMVOC, countries have reduced their emissions during the last 10 years. However, the target is close enough just for a few number of countries. In terms of CO_2, just Finland, France and Sweden are in a good position. Germany and United Kingdom are also doing well, and they are on a good way to get the target by 2010. But for the rest of countries, to achieve the target is going to be a difficult task. Our purpose is to use the previous model to measure the difficulty to get the target and the cost, in terms of welfare and economic growth, to get the target. The consequence that this fact is going to have over the future trading emission market is an issue of utmost concern among politicians.

6 Conclusions

Data on air pollution from the EEA reveals that polluting intensity has decreased over the nineties in most EU member states. Moreover, the countries with higher level of emissions seems to have reduced emissions faster than those with a lower level. Despite this common trend there are important sources of heterogeneity among pollutants and among countries. This heterogeneity does not seem associated to substantial differences in the production technologies or the sources of emissions of 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 output growth.

Some of these patterns are consistent with a simple neoclassical model of pollution growth, such as the one we propose, that have two important features. First, the evolution of emissions in the short-run is substantially determined by initial levels of emissions that can be interpreted as a proxy for the state of the pollution technology. Second, under vigorous economic growth a slowdown in the reduction of emissions can be expected. We focus on alternative convergence equations implied by this model, applied to a panel of European countries and pollutants, to explore these issues. 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 is the coexistence of both β-convergence and a descending branch of an environmental Kuznets curve (EKC) associated to the evolution of emissions of some pollutants once corrected by macroeconomic performance (constrained estimation). There is also evidence of region-specific descending branches of EKCs that can be associated to the process of adoption of abatement technologies and its diffusion. These results are quite robust to the pollutant considered. In particular, the reported facts for SO_2 emissions suggest a different pattern for the richest countries in the European Union. We interpret this finding in favor of a role for EU environmental regulation. Also, a contagion effect to classical air pollutants from the concern on climate change can be identified.

7 References

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8 Appendix

8.1 Data description

We take pollution emissions data as collected under the CLRTAP methodology by the European Environment Agency (EEA). The EEA is a special EC body, established by a Regulation of the European Council in 1990. It releases data on air pollutants for most European countries and covers many ozone precursors and acidifying, collected under the CLRTAP methodology and many greenhouse gases, now object of a specific EC monitoring and inventory scheme.

Our analysis is based on national emissions of CO, NO_x, NMVOC, SO_2 and CO_2. 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 all new Members except Cyprus, Estonia, Lithuania and Malta, making in this way a balanced sample of twenty countries. Unfortunately, in the case of CO_2, data from Greece, Slovenia and Hungary are missing. Data on real chained *per capita* Gross Domestic Product (GDP) are taken from the Penn World Table 6. They are measured in international thousands 1996 dollars and cover all countries involved in our analysis. Frequency of both emissions and GDP data is annual. For our empirical analysis, we focus on 1990-2000 period. For any convergence model, all variables will be expressed in per capita terms.

8.2 The competitive equilibrium

Firms:

There exists a continuum of firms producing the single commodity good in the economy according to a standard *Cobb-Douglas* function presenting constant returns to scale in efficiency units of labor and capital. Assuming all firms are identical and adopt the same capital intensity, aggregate output evolves according to,

$$\bar{Y} = A\bar{K}^{\alpha}\left(e^{xt}\bar{L}\right)^{1-\alpha}, \alpha \in (0,1) \tag{29}$$

where $e^{xt}\bar{L}$ is efficiency labor, $\bar{K}$ is aggregate capital, α is the share of capital in gross output and A is a constant technology term. Firms pay the competitive-determined wage w for the labor it hires and the interest rate r for the capital they rent from households. $R = r + \delta$ is the rental price for unit of capital services, with $\delta \in (0,1)$ being the depreciation rate. Optimally leads to the usual marginal productivity conditions,

$$(r+\delta) = \alpha\frac{\bar{Y}}{\bar{K}}, \tag{30}$$

$$w = (1-\alpha)\frac{\bar{Y}}{\bar{L}}. \tag{31}$$

Provided that population, N, raises at a constant rate n, conditions (30) and (31) are equivalent to those for variables measured in per capita and efficiency units term, $y = \bar{Y}/Ne^{xt}$, $l = \bar{L}/Ne^{xt}$ and $k = \bar{K}/Ne^{xt}$. For aggregate output,

$$y = Ak^{\alpha}. \tag{32}$$

Hereinafter, small caps letters refer to variables measured in per capita and efficiency units term.

Pollution emissions:

Pollution is a side product of each firm's output, with a proportionally factor that maybe is time-varying. For variables is per capita and efficiency units term, pollution is given by (5) and its stock accumulates according with (13).

Households:

We assume a continuum of identical households that are the owner of the physical capital.

Initial population is normalized to one and labor is inelastically supplied. Each household allocates her resources between consumption and capital accumulation. Small caps letters refer to variables measured in per capita units. We solve the problem of a representative consumer. Decisions are made every period to maximize the discounted aggregate value of the time separable utility function,

$$\max_{\{C(t)\}_{t=0}^{\infty}} \int_0^{\infty} e^{-(\rho-n)t} U\left[C(t), h\left(\bar{Z}(t)\right)\right] dt,$$

where ρ is the discount factor, with $\rho > n$, the instantaneous utility U is a $\mathcal{C}^2$ mapping, strongly concave and increasing in both arguments. $h\left[\bar{Z}(t)\right]$ is an indicator of the state of health that relates to the aggregate amount of pollution stock, $\bar{Z}(t)$, with $h'(\cdot) < 0$. Consumer achieves the maximum level of welfare per unit of consumption under a pristine environment. We define $\varepsilon_{h,z}$ as the elasticity of the 'health' function over $\bar{Z}$, which is required to be constant for an equilibrium balanced growth equilibrium to exist. A candidate for $h(\bar{Z})$ is $\frac{D\bar{Z}^{-\varepsilon}}{\varepsilon}$, where $\varepsilon_{h,z} = -\varepsilon$ and D measures the impact of pollution on welfare.

The budget constraint for per capita variables is

$$C + \dot{K} \leq w + K\left[r - n\right],$$

every period.

The representative household faces a dynamic programing problem, in which corner solutions are avoided and restrictions hold with equality due to the special form of the instantaneous utility function and the fact that consumption and health are normal goods.

We consider a Cobb-Douglas and CES function for instantaneous utility function (9) for the non-separable version of U and (20) for a separable version.

Optimal conditions are directly written in per capita and efficiency units term: i) the consumption-saving decision,

$$\frac{\dot{C}}{C} = \frac{1}{\tilde{\tau}}\left(r - [\rho + x\tilde{\tau}] - (1-\tau)(1-v)\varepsilon\left(x + n + \frac{\dot{Z}}{Z}\right)\right), \tag{33}$$

with $\tilde{\tau} = 1 - v(1-\tau)$, ii) the budget constraint,

$$C + \dot{K} = w + K\left[r - n - x\right], \tag{34}$$

and border constraints: iii) $C > 0$ and $K > 0$ and iv) the transversality condition (12). For the separable case, the consumption-saving condition is the standard one,

$$\frac{\dot{C}}{C} = \frac{1}{\tau}\left[r - (\rho + \tau x)\right]. \tag{35}$$

Competitive equilibrium: (for variables in per capita and efficiency units term)

Given $K(0), Z(0) > 0$, the *competitive equilibrium* is a set of prices $\pi(t) = \{r(t), w(t)\}_{t\geq 0}$, a set of allocations $\{c(t), l(t), k(t), y(t)\}_{t\geq 0}$ and a path for emissions and pollution stock $e(t) = \{z(t), p(t)\}_{t\geq 0}$ such that: i) given $\pi(t)$ and $e(t)$, $\{c(t)\}_{t\geq 0}$ maximize households' welfare (they are consistent with (33)-(12)); ii) given $\pi(t)$ and $e(t)$, $\{k(t), l(t)\}_{t\geq 0}$ satisfy profit-maximizing conditions (they are consistent with (30)-(31)); iii) technology constraints hold: aggregate output $y(t)$ is produced according to (32) and total pollution emissions are generated from (5); iv) $z(t)$ accumulates according to (13); v) markets clear every period,

$$l(t) = 1. \tag{36}$$

By the Walrash law, combining (34) with (30), (31), and (36), we get the resource constraint for the overall economy:

$$c+\dot{k}+k\left[\delta+n+x\right]=y. \tag{37}$$

Condition (33) using (32) and (30), condition (37) using (32) and condition (13) give us a system of differential equations in c, k and z.

$$\frac{\dot{c}}{c} = \frac{1}{\tilde{\tau}}\left(\alpha K^{\alpha-1}-\left[\rho+\delta+x\tilde{\tau}\right]-(1-v)(1-\tau)\varepsilon\left(x+n+\frac{\dot{Z}}{Z}\right)\right), \tag{38}$$

$$\frac{\dot{k}}{k} = k^{\alpha-1}-\frac{c}{k}-\left[\delta+n+x\right], \tag{39}$$

$$\frac{\dot{z}}{z} = \eta B z^{\phi-1}k^{\alpha(\psi-\phi)}-(\delta_z+x+n), \tag{40}$$

that are equivalent to (10)-(13) in the main text.

8.3 The log-linearization

Under the non-separable case, log-linearizing (10)-(13) around the steady-state, we lead to the following system in c, k and z:

$$\begin{pmatrix} \overset{\bullet}{\log(c)} \\ \overset{\bullet}{\log(k)} \\ \overset{\bullet}{\log(z)} \end{pmatrix} = \begin{pmatrix} 0 & -\beta_{ck} & \beta_{cz} \\ -\beta_{kc} & \beta_{kk} & 0 \\ 0 & \beta_{zk} & -\beta_{zz} \end{pmatrix} \begin{pmatrix} \log c-\log c_s \\ \log k-\log k_s \\ \log z-\log z_s \end{pmatrix}, \tag{41}$$

where

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

Notice that β_{kk} and β_{kc} are positive by the transversality condition, which is a standard result, and all other $\beta's$ are also positive.

Under reasonable parameter restrictions, it is easy to prove that the dynamics of this system is of the saddle path type, with two negative eigenvalues, $\lambda_1^{(-)}$ and $\lambda_2^{(-)}$, and one unstable, $\lambda_3^{(+)}$, associated to the control variable. Thus, the solution if of the following type:

$$
\begin{pmatrix} \log(c(t)/c_s) \\ \log(k(t)/k_s) \\ \log(z(t)/z_s) \end{pmatrix} = d_1 \begin{pmatrix} v_{11} \\ v_{12} \\ v_{13} \end{pmatrix} e^{t\lambda_1^{(-)}} + d_2 \begin{pmatrix} v_{21} \\ v_{22} \\ v_{23} \end{pmatrix} e^{t\lambda_2^{(-)}} + d_3 \begin{pmatrix} v_{31} \\ v_{32} \\ v_{33} \end{pmatrix} e^{t\lambda_3^{(+)}}.
$$

Setting $d_3 = 0$ to avoid the unstable eigenvalue, and given $\log(k(0)/k_s) = \log(k_0/k_s)$ and $\log(z(0)/z_s) = \log(z_0/z_s)$, we get a solution for $\log k(t)$ and $\log z(t)$ depending on $\log(k_0/k_s)$ and $\log(z_0/z_s)$. However, the non-separability assumption of the utility function precludes the possibility of having explicit expressions for eigenvalues or eigenvectors, and we can not identify explicitly the coefficients associated to the variables with structural parameters of the economy.

For the separable case, considering (20), we can obtain explicit expressions for the eigenvalues and eigenvectors of the above transition matrix. It is easy to show that the $\beta's$ of a similar transition matrix than that in (41) and the steady-state values for the separable case can be obtained by setting $\nu = 1$ in all related expressions. Thus, $\beta_{cz} = 0$ and other $\beta's$ are now simpler. Notice that the elasticity parameter ε does not appear in any expressions of the $\beta's$ nor of the steady-state levels. For instance, notice that β_{ck} adds a positive term under the non-separable assumption and β_{cz} is positive under this circumstance.

Being $\beta_{cz} = \beta_{kz} = 0$ ($\beta_{kz} = 0$ in both cases) allows for the system (41) being solved recursively, first for c and k (as in the standard Cass-Koopmans framework) and next solving for z, using the dynamics for k. Given initial conditions $k_0 - k_s$ and $z_0 - z_s$, we first get the standard solution for $k(t)$:

$$k(t) - k_s = e^{-\beta t} \left(k(0) - k_s \right), \tag{42}$$

with $-\beta$ being the stable eigenvalue of the transition matrix which is equal to

$$\beta = \left(\beta_{kk}^2 + 4\beta_{ck}\beta_{kc} \right)^{1/2} - \beta_{kk}. \tag{43}$$

Second, we can rewrite the condition for k as

$$\dot{k}(t) = -\beta(k(t) - k_s), \tag{44}$$

and combining it with the log-linear condition for $\dot{z}$, we lead to a system for z and k,

$$\begin{pmatrix} \dot{k} \\ \dot{z} \end{pmatrix} = \begin{pmatrix} -\beta & 0 \\ \beta_{zk} & -\beta_{zz} \end{pmatrix} \begin{pmatrix} k - k_s \\ z - z_s \end{pmatrix}, \tag{45}$$

whose solution is globally stable since the two eigenvalues, $-\beta$ and $-\beta_{zz}$, are negative,

$$\begin{pmatrix} k(t) - k_s \\ z(t) - z_s \end{pmatrix} = d_1 \begin{pmatrix} v_{11} \\ v_{12} \end{pmatrix} e^{-t\beta} + d_2 \begin{pmatrix} v_{21} \\ v_{22} \end{pmatrix} e^{-t\beta_{zz}}. \tag{46}$$

It is easy to show that a normalized eigenvector of this system can be:

$$\begin{pmatrix} v_{11} \\ v_{12} \end{pmatrix} = \begin{pmatrix} \frac{\beta-\beta_{zz}}{\beta_{zk}} \\ 1 \end{pmatrix}, \begin{pmatrix} v_{21} \\ v_{22} \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \tag{47}$$

Given initial conditions $k(0) - k_s$ and $z(0) - z_s$, the solution for k is the same as above and the solution for z is given by (22).

9 Appendix of tables

TABLE 1: Per capita real GDP and air pollutant emissions for European countries (1990-2000): Basic statistics

	Real GDP			***NO2***			***CO2***			***SO2***			***NMVOC***			***CO***		
	1990	***2000***	***annum growth***	***1990***	***2000***	***annum growth***	***1990***	***2000***	***annum growth***	***1990***	***2000***	***annum growth***	***1990***	***2000***	***annum growth***	***1990***	***2000***	***annum growth***
DEN	21.81	26.61	2.2	5.51	3.90	-2.9	11.06	10.83	-0.2	3.44	0.54	-8.4	3.19	2.47	-2.3	14.50	11.28	-2.2
SWE	20.79	23.64	1.4	3.78	2.82	-2.5	6.36	6.21	-0.2	1.24	0.62	-5.0	5.87	3.45	-4.1	14.03	9.45	-3.3
FIN	20.27	23.79	1.7	6.02	4.56	-2.4	10.73	9.90	-0.8	5.21	1.43	-7.3	4.49	3.11	-3.1	11.21	10.16	-0.9
FRA	20.02	22.36	1.2	3.27	2.37	-2.8	6.45	6.80	0.6	2.29	1.04	-5.5	4.31	2.84	-3.4	18.87	10.96	-4.2
BEL	19.88	23.78	2.0	3.35	3.21	-0.4	12.47	14.08	1.3	3.63	1.61	-5.6	2.75	2.27	-1.7	12.89	10.73	-1.7
AUS	19.81	23.68	2.0	2.75	2.34	-1.5	7.22	8.04	1.1	1.04	0.43	-5.8	3.86	2.34	-3.9	16.18	10.27	-3.7
GER	19.56	22.86	1.7	3.58	1.99	-4.4	12.54	10.26	-1.8	6.71	0.77	-8.8	4.52	2.07	-5.4	14.13	5.99	-5.8
NET	19.48	24.31	2.5	3.87	2.66	-3.1	14.14	15.66	1.1	1.28	0.48	-6.2	3.28	1.67	-4.9	7.55	4.39	-4.2
ITA	19.31	21.78	1.3	3.38	2.36	-3.0	7.32	7.78	0.6	3.08	1.30	-5.8	3.60	2.70	-2.5	12.60	9.04	-2.8
UKI	18.32	22.19	2.1	4.81	2.88	-4.0	10.43	9.29	-1.1	6.46	1.99	-6.9	4.20	2.28	-4.6	12.89	6.57	-4.9
IRE	14.16	26.38	8.6	3.37	3.30	-0.2	7.38	10.68	4.5	5.40	3.73	-3.1	4.10	3.75	-0.9	9.53	6.95	-2.7
SPA	14.48	18.05	2.5	3.10	3.34	0.8	5.83	7.95	3.6	5.31	3.46	-3.5	3.17	2.38	-2.5	11.44	7.39	-3.5
POR	12.31	15.92	2.9	2.24	2.48	1.1	4.48	6.42	4.3	2.31	2.20	-0.5	2.58	2.71	0.5	7.53	6.75	-1.0
GRE	11.97	14.61	2.2	2.85	3.04	0.7	8.02	9.60	2.0	4.85	4.57	-0.6	2.51	2.89	1.5	12.77	14.50	1.4
CZE	13.59	13.67	0.1	5.25	3.12	-4.0	12.16	10.49	-1.4	18.15	2.57	-8.6	4.26	2.21	-4.8	12.13	6.31	-4.8
SLE	13.05	15.74	2.1	3.15	2.92	-0.7	6.76	8.01	1.9	9.81	4.98	-4.9	2.20	2.01	-0.9	4.05	3.42	-1.6
SLA	11.98	11.41	-0.5	4.09	1.98	-5.2	8.14	6.93	-1.5	10.26	2.30	-7.8	4.77	1.57	-6.7	9.33	5.55	-4.0
HUN	9.60	10.44	0.9	2.30	1.85	-2.0	6.51	5.48	-1.6	9.74	4.85	-5.0	1.98	1.73	-1.3	9.62	6.31	-3.4
POL	6.60	9.22	4.0	3.36	2.17	-3.5	8.59	7.48	-1.3	8.42	3.91	-5.4	2.18	1.55	-2.9	19.43	8.96	-5.4
Mean(EU10)	19.92	23.50	1.8	4.03	2.91	-2.7	9.87	9.88	0.1	3.44	1.02	-6.5	4.01	2.52	-3.6	13.48	8.88	-3.4
Std-levels	0.92	1.37	0.43	1.06	0.79	1.15	2.83	3.04	1.05	2.10	0.54	1.30	0.89	0.52	1.21	2.98	2.39	1.49
Mean (EU14)	18.01	22.14	2.4	3.71	2.95	-1.8	8.89	9.54	1.1	3.73	1.73	-5.2	3.74	2.64	-2.7	12.58	8.89	-2.8
Std-levels	3.29	3.57	1.85	1.06	0.69	1.83	2.95	2.75	1.96	1.95	1.33	2.54	0.92	0.55	2.01	3.09	2.68	1.84
Mean(EU19)	16.16	19.50	2.1	3.69	2.80	-2.1	8.77	9.05	0.6	5.72	2.25	-5.5	3.57	2.42	-2.8	12.14	8.16	-3.1
Std-levels	4.45	5.60	1.85	1.04	0.69	1.86	2.74	2.63	1.99	4.22	1.56	2.36	1.05	0.61	2.08	3.80	2.76	1.77

Keys: DEN: Denmark, SWE: Aweden, FIN: Finland, FRA: France, BEL: Belgium, AUS: Austria, GER: Germany, NET: Netherland, ITA: Italy, UKI: 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: Beta and sigma convergence within European Countries (1990-2000) for pollutant emissions

		EU19		EU14		EU10	
GDP	Sigma convergence						
	Std of log 90	0.3205		0.2024		0.0461	
	Std of log 00	0.3302		0.1785		0.0570	
		Beta	P-value	Beta	P-value	Beta	P-value
	Beta convergence(1)	0.0056	0.3429	0.0282	0.0698	0.0041	0.4405
NO2	Sigma convergence						
	Std of log 90	0.2701		0.2678		0.2487	
	Std of log 00	0.2373		0.2224		0.2523	
		Beta	P-value	Beta	P-value	Beta	P-value
	Beta convergence(1)	0.0475	0.0299	0.0465	0.0275	0.0164	0.2200
Corrected Beta convergence (2)		0.0434	0.0164	0.0462	0.0294	0.0203	0.4219
CO2	Sigma convergence						
	Std of log 90	0.3123		0.3403		0.2999	
	Std of log 00	0.2737		0.2739		0.2965	
		Beta	P-value	Beta	P-value	Beta	P-value
	Beta convergence(1)	0.0270	0.0601	0.0284	0.0281	0.0068	0.2891
Corrected Beta convergence (2)		0.0245	0.0265	0.0272	0.0125	0.0232	0.2603
SO2	Sigma convergence						
	Std of log 90	0.7873		0.6349		0.6897	
	Std of log 00	0.8214		0.7837		0.5457	
		Beta	P-value	Beta	P-value	Beta	P-value
	Beta convergence (1)	0.0224	0.1736	0.0175	0.2892	0.0396	0.0342
Corrected Beta convergence (2)		0.0189	0.2604	0.0283	0.3090	0.0439	0.0616
NMVOC	Sigma convergence						
	Std of log 90	0.3057		0.2436		0.2170	
	Std of log 00	0.2534		0.2097		0.2088	
		Beta	P-value	Beta	P-value	Beta	P-value
	Beta convergence (1)	0.0627	0.0105	0.0680	0.0134	0.0388	0.0876
Corrected Beta convergence (2)		0.0586	0.0028	0.0699	0.0101	0.0730	0.0359
CO	Sigma convergence						
	Std of log 90	0.3634		0.2611		0.2424	
	Std of log 00	0.3581		0.3168		0.3172	
		Beta	P-value	Beta	P-value	Beta	P-value
	Beta convergence (1)	0.0240	0.1341	0.0222	0.2447	0.0088	0.3941
Corrected Beta convergence (2)		0.0248	0.1400	0.0227	0.4990	0.0155	0.7356

(1): Pollutant growth = constant - beta*pollutant(0)

(2) Pollutant growth = constant - beta*pollutant(0) + lambda*GDP growth + beta*lambda*GDP(0)

Note: Cross section regressions for the beta-analysis. EU10, EU14 and EU19 are the same groups as in table 1

Table 3: Panel estimations with Fixed effects

	NO2			CO2			SO2			NMVOC			CO		
	estimation	*std*	*p-value*	*estimation*	*std*	*p-value*	*estimation*	*std*	*p-value*	*estimation*	*std*	*p-value*	*estimation*	*std*	*p-value*
EU19															
beta	**0.1026**	0.0475	0.0321	**0.4515**	0.0867	0.0000	-0.0482	0.0382	0.2080	-0.0068	0.0393	0.8624	**0.1182**	0.0678	0.0828
lambda	**-0.3112**	0.1848	0.0939	0.0476	0.1475	0.7472	**0.9498**	0.5471	0.0842	0.0152	0.1631	0.9258	-0.2323	0.3320	0.4850
lambda*dum1	**0.4519**	0.2515	0.0740	**0.6867**	0.1724	0.0001	-0.5870	0.7227	0.4178	-0.1951	0.2551	0.4453	-0.0861	0.3406	0.8007
lambda*dum2	**0.4243**	0.2227	0.0583	-0.0953	0.1939	0.6238	-0.6675	0.5467	0.2236	**0.7114**	0.2559	0.0060	0.0808	0.3172	0.7992
EU14															
beta	**0.1078**	0.0491	0.0299	**0.5729**	0.1176	0.0000	-0.0428	0.0438	0.3301	0.0336	0.0304	0.2709	**0.0759**	0.0409	0.0657
lambda	**-0.3288**	0.1842	0.0764	0.0208	0.1274	0.8703	0.8963	0.5605	0.1121	-0.1442	0.1608	0.3713	-0.0762	0.2755	0.7826
lambda*dum1	**0.4656**	0.2539	0.0688	**0.7119**	0.1519	0.0000	-0.5577	0.7259	0.4437	-0.1005	0.2707	0.7110	-0.2089	0.3223	0.5180
lambda*dum2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
EU10															
beta	0.0593	0.0439	0.1791	**0.6469**	0.1277	0.0000	-0.0556	0.0440	0.2100	0.0145	0.0294	0.6241	0.0705	0.0435	0.1078
lambda	-0.1639	0.1670	0.3286	0.0094	0.1179	0.9367	**1.0195**	0.5612	0.0723	-0.0662	0.1595	0.6789	-0.0569	0.2768	0.8376
lambda*dum1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
lambda*dum2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Pollutant growth(t)=Fixed effect-beta*pollutant(t-1)+lambda*gdp growth(t)+(beta*lambda)*gdp(-1), including multiplicative dummies in the EU19 and EU14 regression
Note: bold letters means estimations are significantly diiferent from zero at least at 10% level of significance
See note of table 1 for a description of countries included in the analysis
dum1=1, for SPA, GRE, POR and IRE; 0 elsewhere
dum2=1, for East Countries; 0 elsewhere
White Heteroskedasticity-Consistent Standard Errors and Covariance

Table 4: Panel estimations with Fixed effects and temporal dummies (common to all countries)

	NO2			CO2			SO2			NMVOC			CO		
	estimation	*std*	*p-value*	*estimation*	*std*	*p-value*	*estimation*	*std*	*p-value*	*estimation*	*std*	*p-value*	*estimation*	*std*	*p-value*
EU19															
beta	**0.2085**	0.0557	0.0002	**0.4316**	0.0905	0.0000	**0.1074**	0.0652	0.1012	**0.1141**	0.0463	0.0148	**0.2702**	0.0783	0.0007
lambda	0.2013	0.1959	0.3057	0.0232	0.2506	0.9262	**1.2810**	0.5197	0.0147	0.1559	0.2157	0.4709	**0.9198**	0.3867	0.0184
lambda*dum1	**0.3713**	0.2065	0.0738	**0.6944**	0.2016	0.0007	-0.0145	0.5694	0.9797	-0.0189	0.2203	0.9317	-0.4269	0.3357	0.2052
lambda*dum2	0.1175	0.2146	0.5848	-0.0977	0.2080	0.6393	-0.6835	0.5079	0.1801	**0.5219**	0.2206	0.0191	**-0.6796**	0.3450	0.0504
EU14															
beta	**0.2411**	0.0644	0.0003	**0.6188**	0.1127	0.0000	**0.1266**	0.0761	0.0985	**0.1256**	0.0388	0.0015	**0.1830**	0.0682	0.0082
lambda	0.0182	0.1802	0.9195	**-0.5595**	0.2294	0.0161	**0.9541**	0.5757	0.0999	-0.0864	0.1922	0.6540	0.3613	0.3675	0.3275
lambda*dum1	**0.4820**	0.1889	0.0119	**1.0138**	0.1718	0.0000	0.1987	0.5532	0.7200	0.0948	0.2347	0.6868	-0.2292	0.3243	0.4809
lambda*dum2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
EU10															
beta	**0.3592**	0.1126	0.0020	**0.6218**	0.1345	0.0000	0.1332	0.0975	0.1754	**0.2271**	0.0447	0.0000	**0.3857**	0.0736	0.0000
lambda	**0.4785**	0.2180	0.0308	-0.1574	0.3066	0.6091	**1.8166**	0.5545	0.0015	0.2640	0.1890	0.1659	**1.4257**	0.4684	0.0031
lambda*dum1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
lambda*dum2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Pollutant growth(t)=Fixed effect-beta*pollutant(t-1)+lambda*gdp growth(t)+(beta*lambda)*gdp(-1)+TEMPORAL DUMMIES, including multiplicative dummies in the EU19 and EU14 regression
See Note of table 3

10 Appendix of Figures

Figure 1.1: NO2 per capita emissions. β-Convergence within European countries

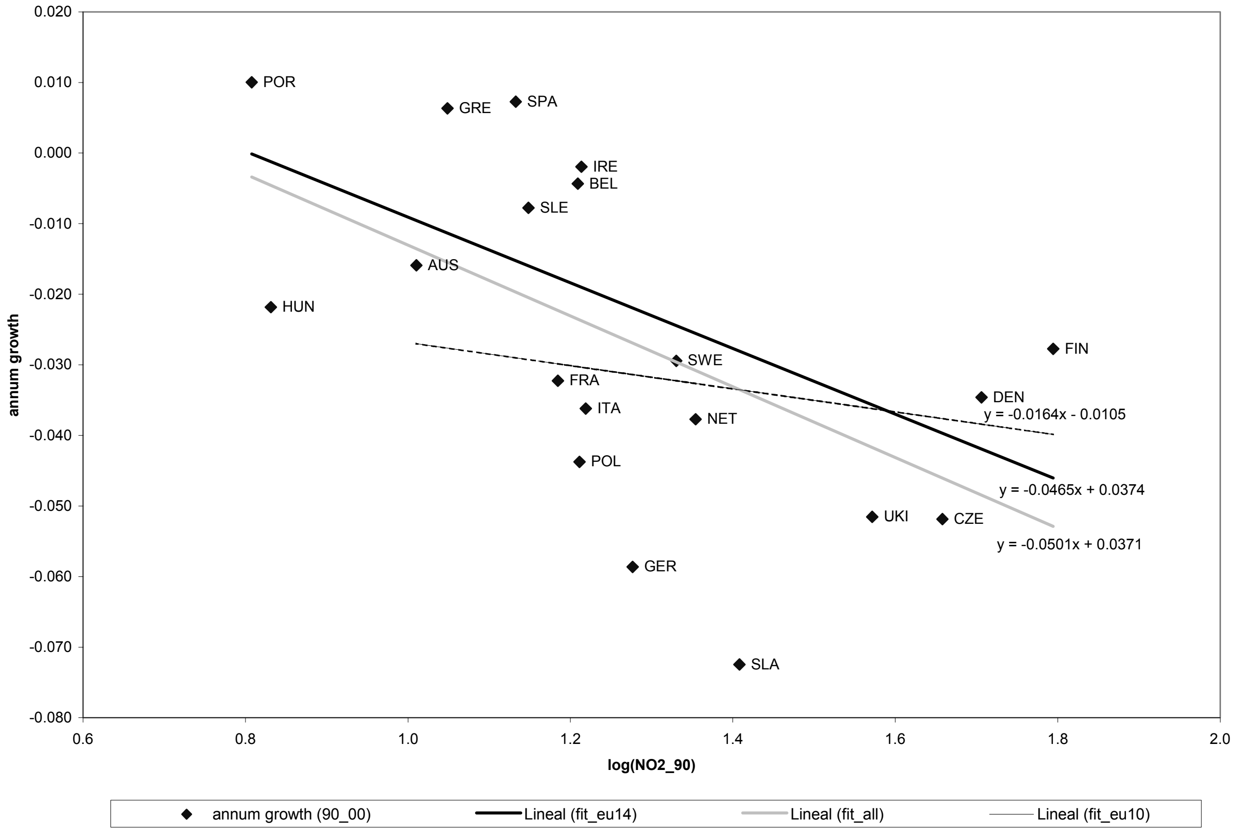

Figure 1.2: CO2 per capita emissions. β-Convergence within European countries

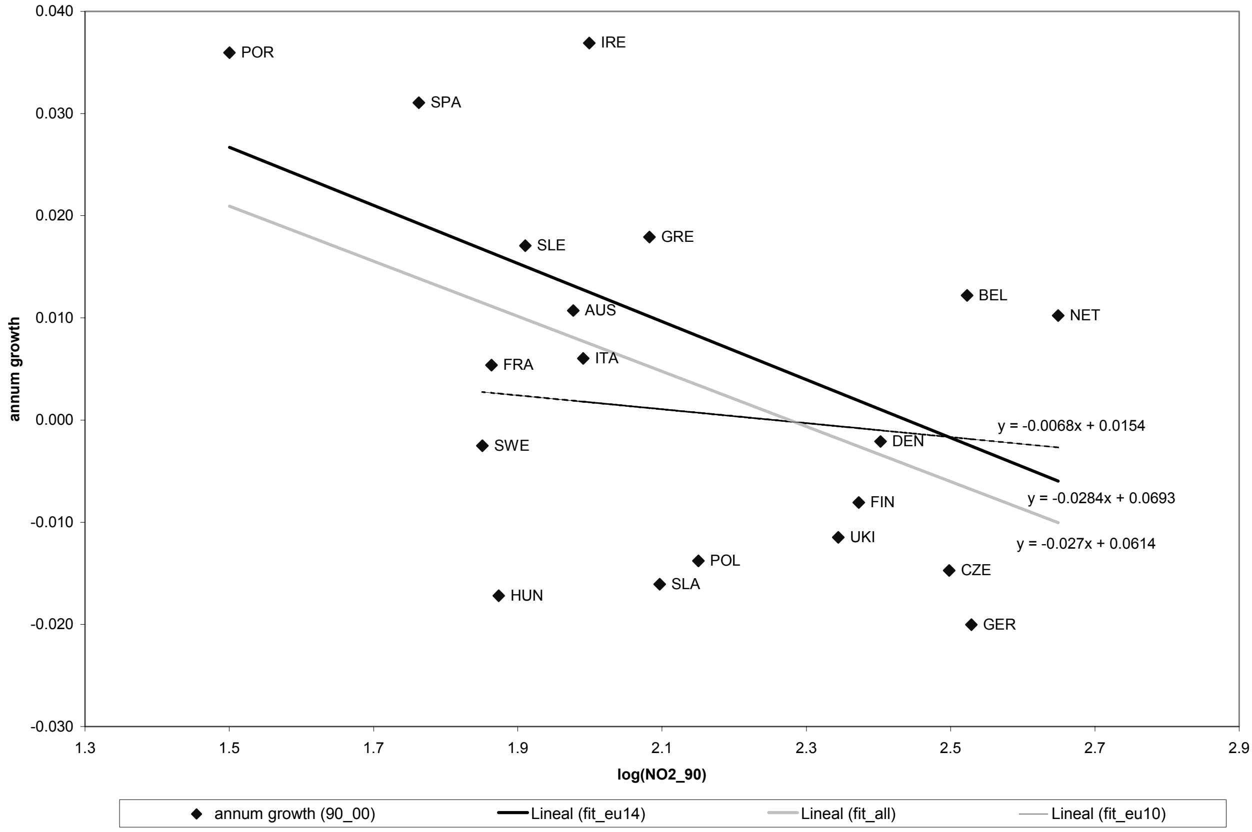

Figure 1.3: SO2 per capita emissions. β-Convergence within European countries

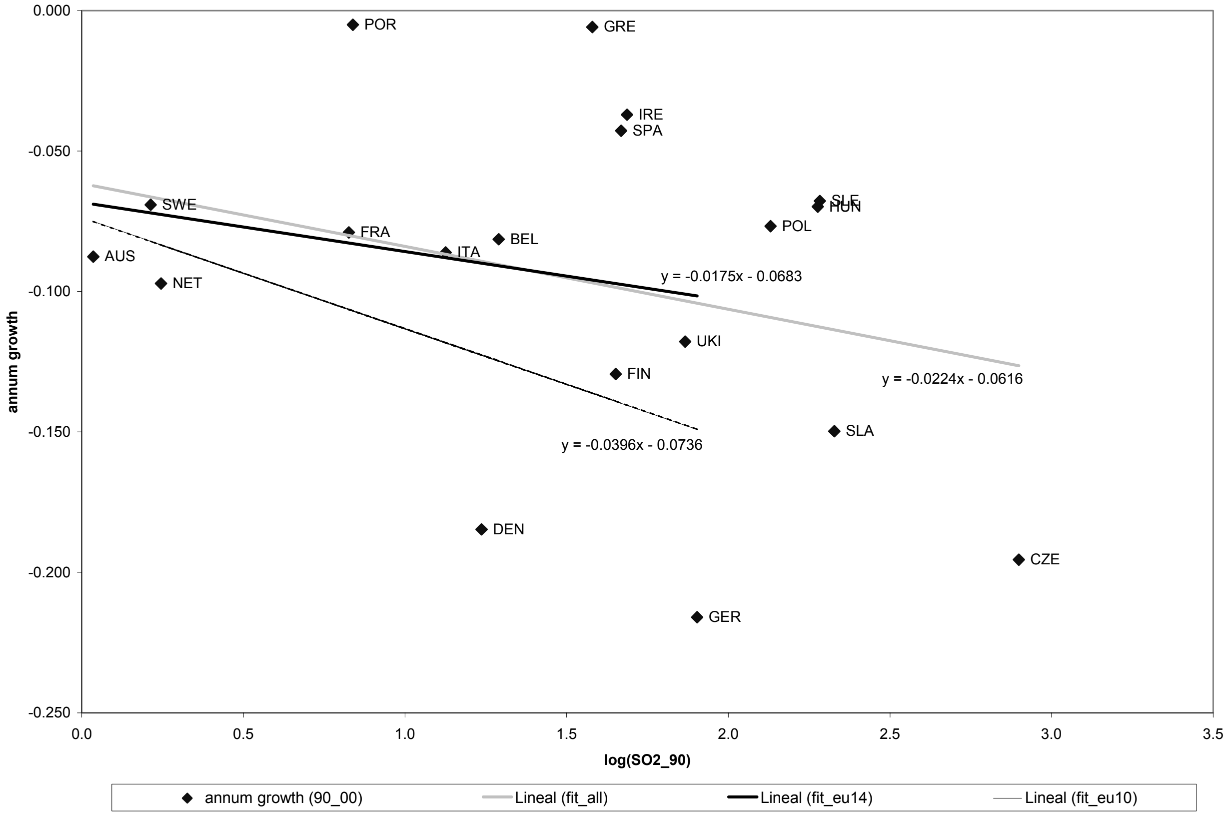

Figure 1.4: NMVOC per capita emissions. β-Convergence within European countries

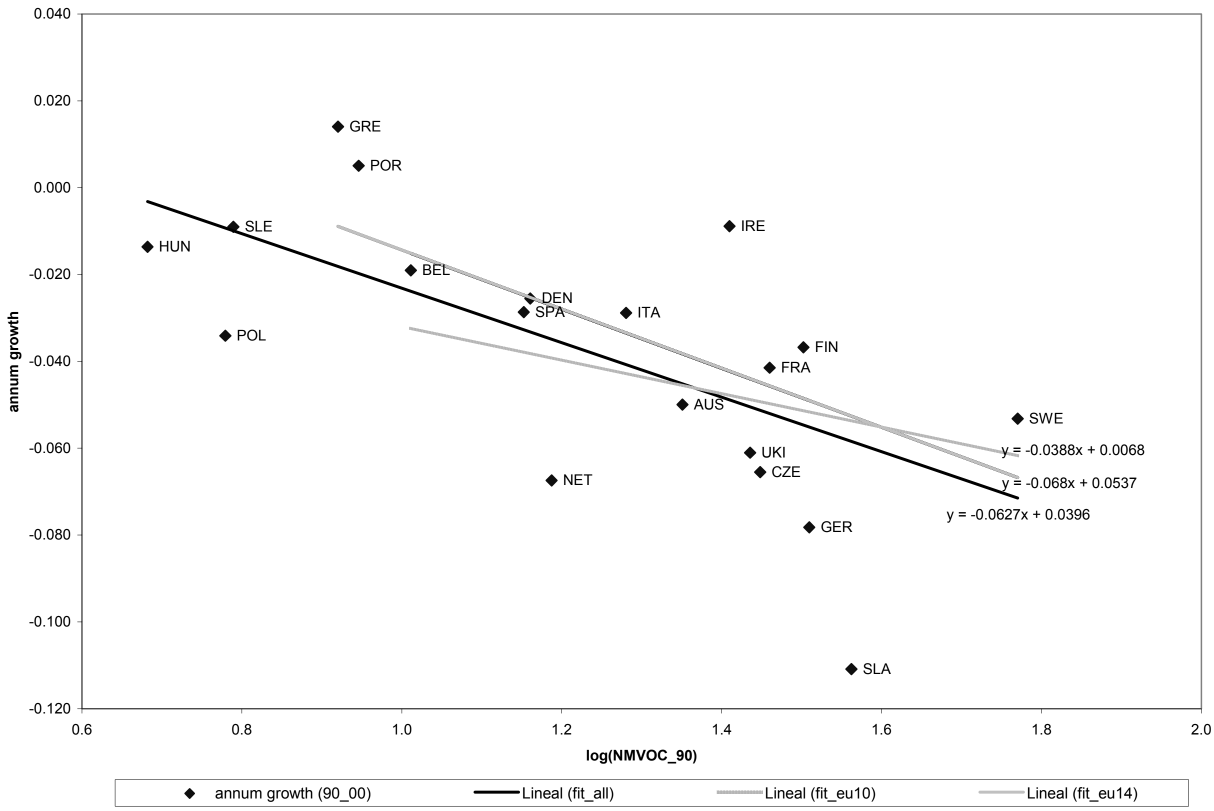

Figure 1.5: CO per capita emissions. β-Convergence within European countries

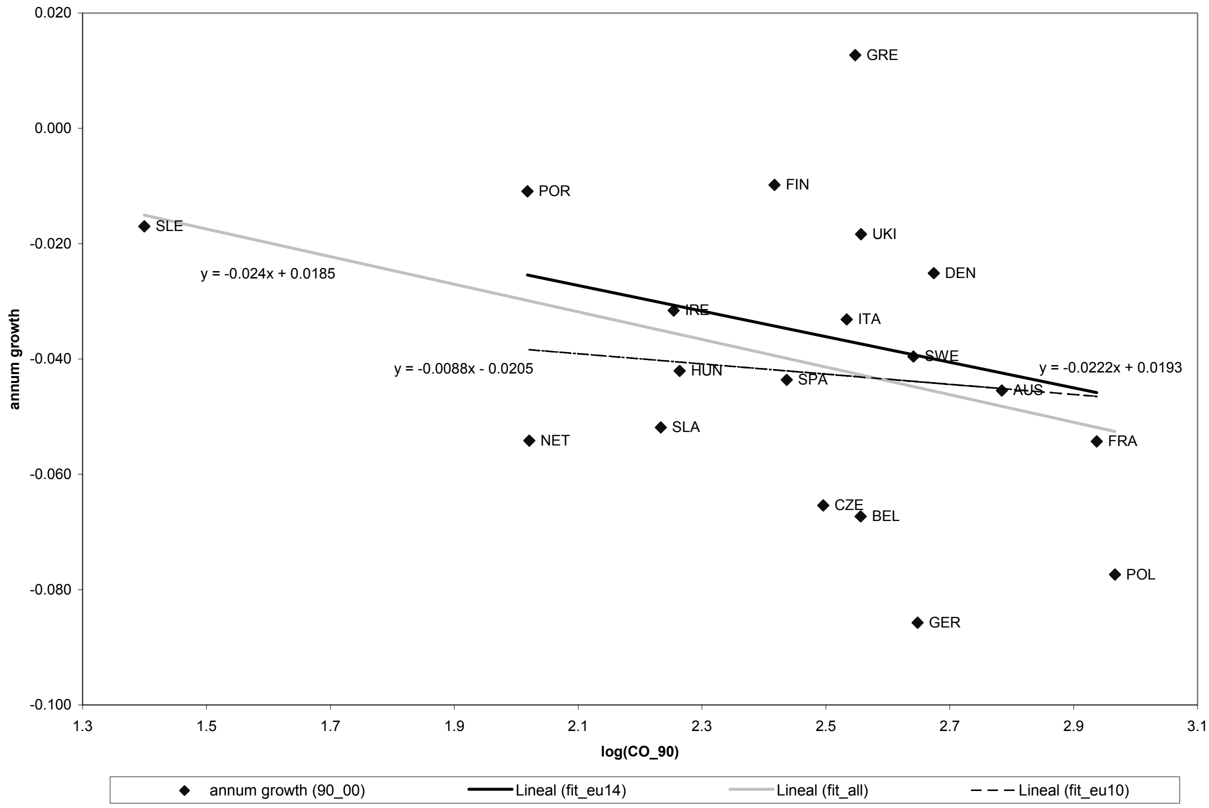

Figure 2.1: Relative Growth of per capita NO2 emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

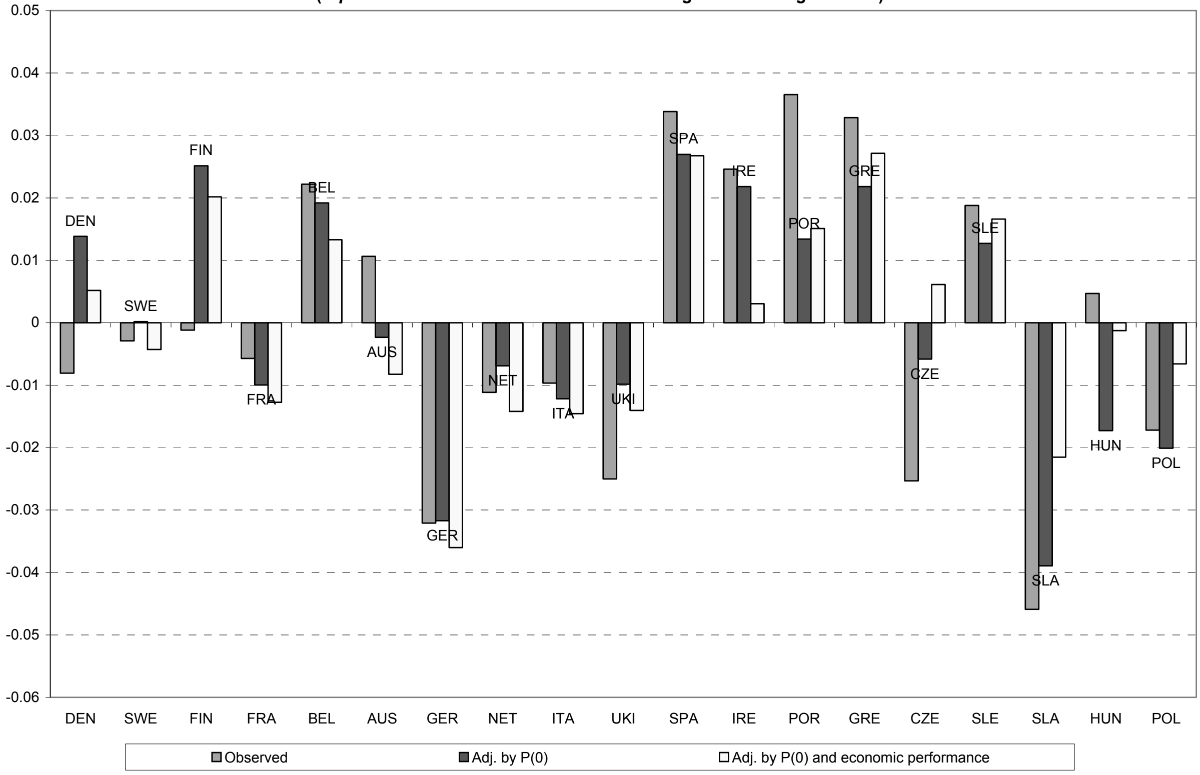

Figure 2.2: Relative Growth of per capita CO2 emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

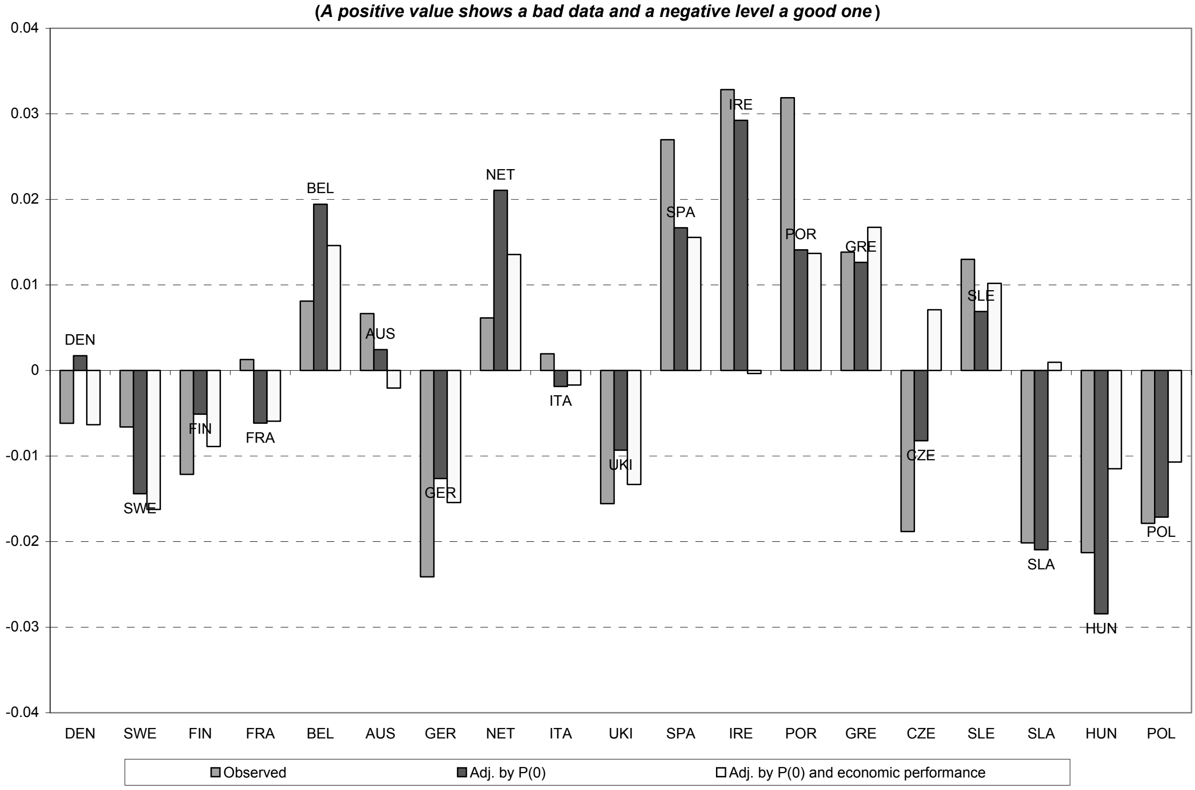

Figure 2.3: Relative Growth of per capita SO2 emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

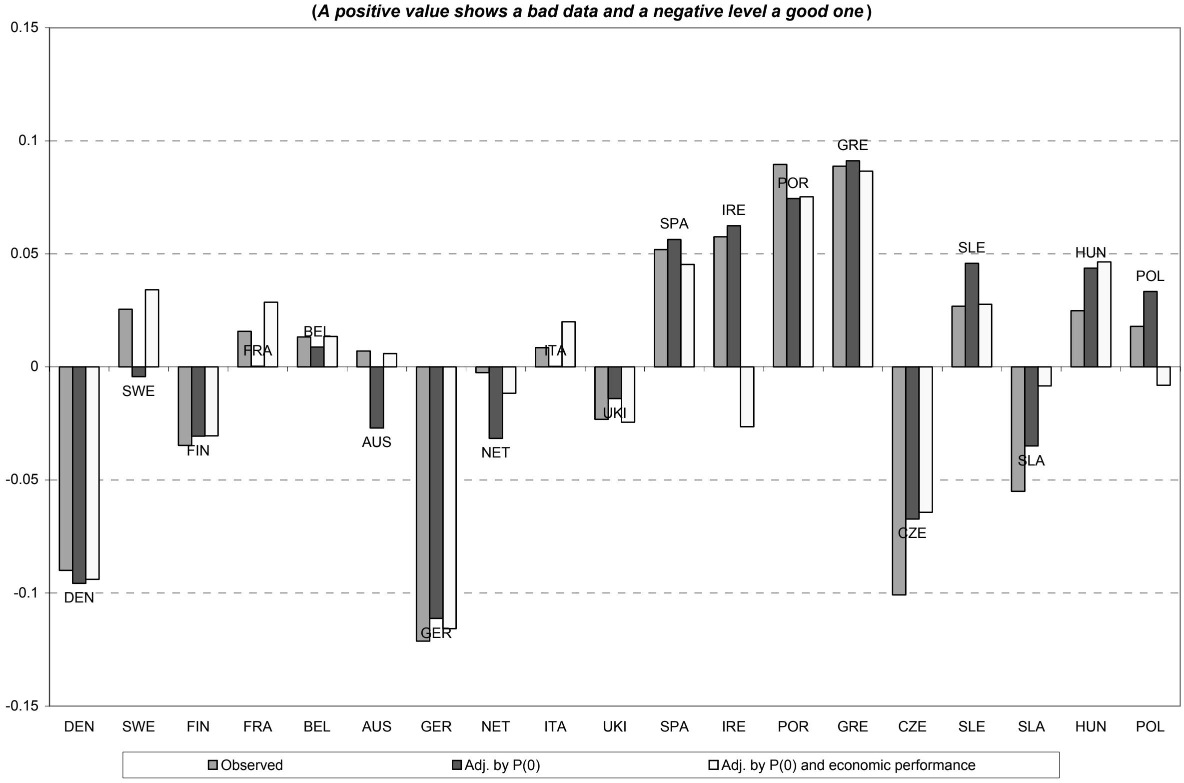

Figure 2.4: Relative Growth of per capita NMVOC emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

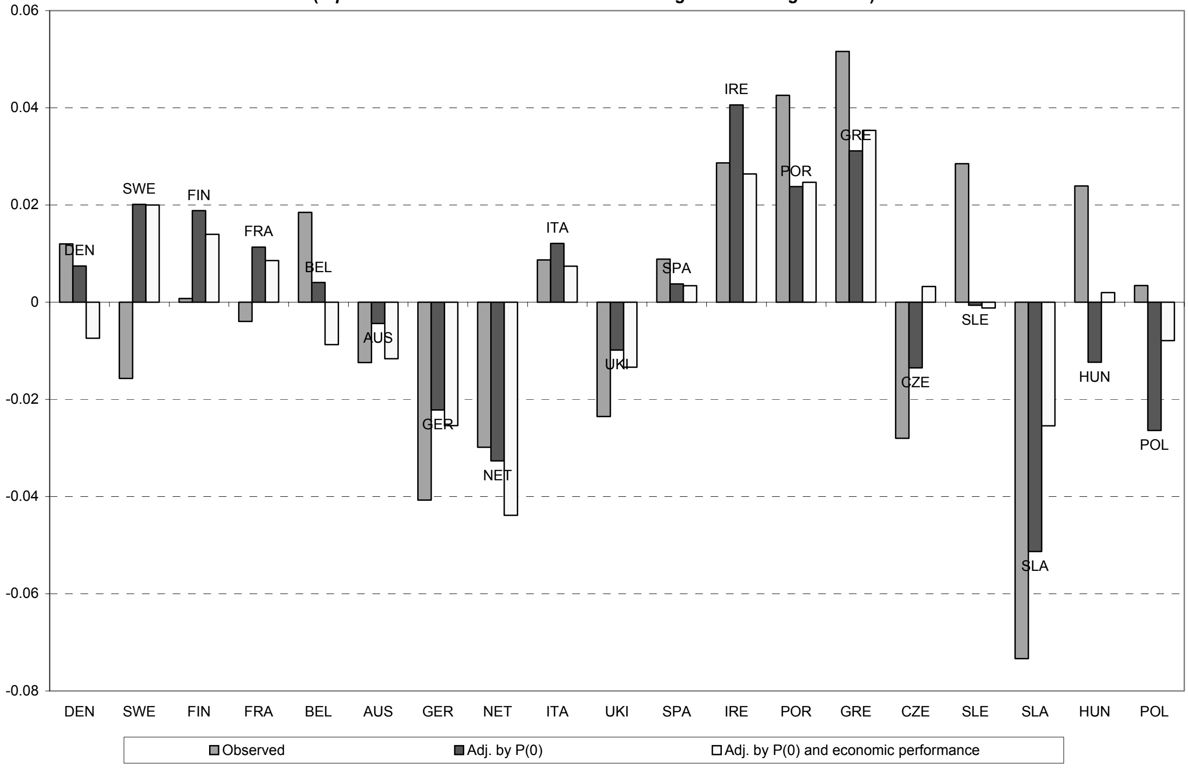

Figure 2.5: Relative Growth of per capita CO emissions (1990-2000), observed rate and adjusted values for initial conditions and economic performance
(*A positive value shows a bad data and a negative level a good one*)

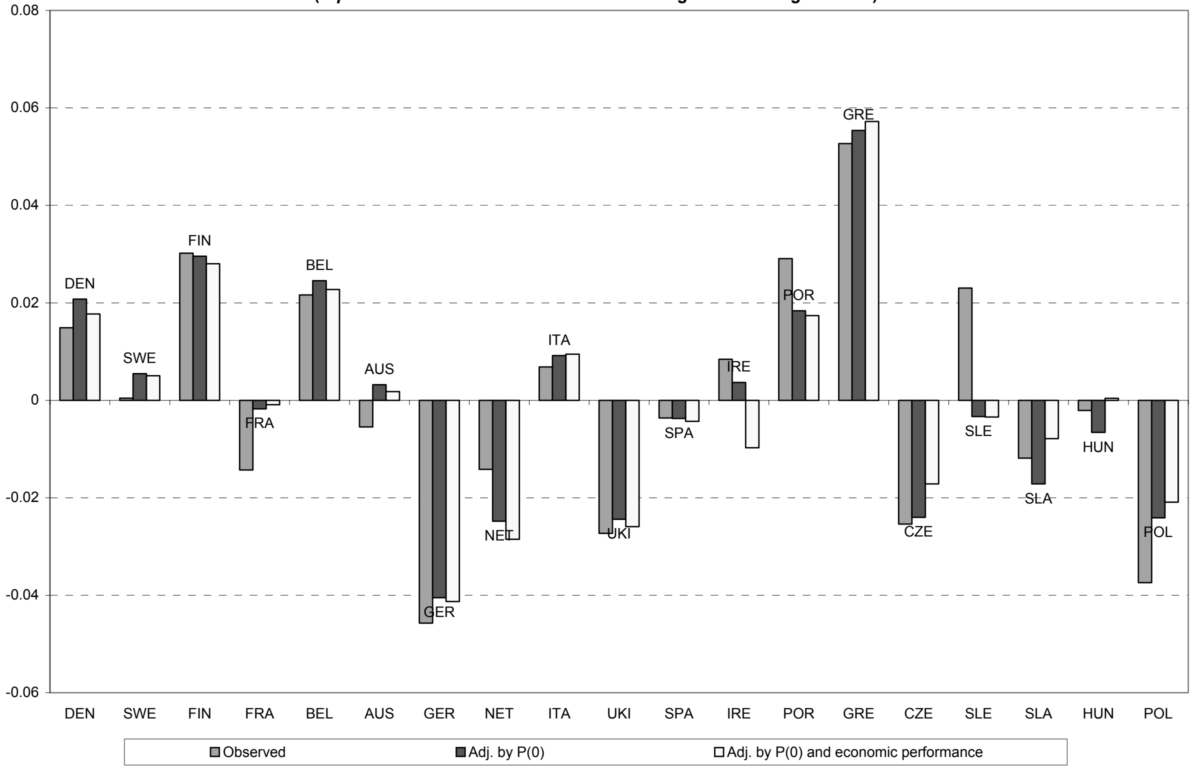

Table 5. 1 - Community Emissions Ceilings

	SO_2	NO_x	NMVOC	CO	CO_2
EU15 (Community's *Fifth Environmental Action Programme* (1993), target for 2000)	12951	9211	11268	--	3320000
EU 15* (Directive 2001/81/EC in the framework of the above programme, target for 2010)	3634	5923	5581	--	--
EU15 1993 levels	12398.51	12287.96	13122.22	44038.51	3222223
EU15 2000 levels	6118.46	10049.9	10049.3	30918.84	3329314

Source: European Environmental Agency (EEA)   Unit: Kilotons (Kt)

* These emission ceilings are designed with the aim of attaining the interim environmental objectives set out in Article 5 for the Community as a whole by 2010.

Table 5.2 SO2: initial levels (1990), current levels (2000), targets and pseudo steady states (% changes)

	The Target: target/1990	*How is doing? 2000/1990*	*What is left? target/2000*	*Target/Pseudo steady-state*
AUS	-50,4	-51,6	2,5	-81,9
BEL	-72,3	-49,4	-45,2	-59,3
CZE		-86,0		
DEN	-69,4	-84,6	98,3	-58,7
FIN	-57,7	-71,7	49,7	-29,2
FRA	-71,7	-50,6	-42,6	-78,1
GER	-90,2	-88,0	-18,5	-63,4
GRE	6,1	-2,0	8,3	73,3
HUN		-51,9		
IRE	-77,4	-29,2	-68,1	-59,3
ITA	-87,3	-26,6	-82,7	-69,0
LAT		-82,5		
NET	-75,2	-54,7	-45,4	-81,2
POL		-52,9		
POR	-44,4	0,0	-44,4	-69,8
SLA		-77,2		
SLE		-51,0		
SPA	-65,8	-30,5	-50,8	-51,6
SWE	-36,6	-45,8	17,1	-77,5
UKI	-84,3	-68,0	-50,8	-59,7

Table 5.3 NOx: initial levels (1990), current levels (2000), targets and pseudo steady states (% changes)

	The Target: target/1990	*How is doing? 2000/1990*	*What is left? target/2000*	*Target/Pseudo steady-state*
AUS	-49,5	-3,7	-47,6	-45,1
BEL	-45,1	-5,1	-42,1	-41,7
CZE		-41,0		
DEN	-53,4	-24,1	-38,5	-40,2
FIN	-43,3	-21,3	-28,0	-22,3
FRA	-57,3	-24,1	-43,8	-40,4
GER	-61,5	-41,9	-33,6	-17,6
GRE	18,6	10,7	7,2	5,5
HUN		-22,3		
IRE	-44,9	5,9	-48,0	-47,4
ITA	-48,5	-29,1	-27,3	-24,6
LAT		-56,5		
NET	-54,4	-27,5	-37,0	-30,6
POL		-34,5		
POR	-12,6	41,6	-38,3	-43,4
SLA		-53,0		
SLE		-7,9		
SPA	-33,4	12,8	-41,0	-42,6
SWE	-55,7	-24,4	-41,4	-36,5
UKI	-57,7	-37,0	-32,8	-22,6

Table 5.4 NMVOC: initial levels (1990), current levels (2000), targets and pseudo steady states (% changes)

	The Target: target/1990	*How is doing? 2000/1990*	*What is left? target/2000*	*Target/Pseudo steady-state*
AUS	-53,9	-32,8	-31,5	-26,1
BEL	-49,3	-15,0	-40,3	-42,8
CZE		-48,5		
DEN	-47,5	-20,4	-34,1	-36,1
FIN	-42,0	-28,1	-19,3	-16,3
FRA	-57,5	-30,0	-39,3	-38,7
GER	-69,1	-50,0	-38,2	-29,9
GRE	2,4	19,6	-14,4	-13,5
HUN		-15,6		
IRE	-53,0	-17,5	-43,0	-46,7
ITA	-43,2	-23,5	-25,7	-24,4
LAT		-51,5		
NET	-62,4	-43,5	-33,5	-30,6
POL		-27,9		
POR	-53,8	25,1	-63,1	-66,0
SLA		-66,0		
SLE		-9,1		
SPA	-59,4	-4,9	-57,3	-57,0
SWE	-51,6	-39,0	-20,7	-19,0
UKI	-50,4	-41,3	-15,5	-17,4

Table 5.5 CO2: initial levels (1990), current levels (2000), targets and pseudo steady states (% changes)

	The Target: target/1990	*How is doing? 2000/1990*	*What is left? target/2000*	*Target/Pseudo steady-state*
AUS	-13,0	8,0	-19,5	-18,9
BEL	-7,5	7,3	-13,8	-15,4
CZE				
DEN	-21,0	0,2	-21,2	-32,6
FIN	0,0	-0,3	0,3	-1,2
FRA	0,0	3,0	-2,9	-4,1
GER	-21,0	-15,4	-6,6	-5,8
GRE	25,0			
HUN				
IRE	13,0	38,7	-18,5	-13,1
ITA	-6,5	7,7	-13,2	-10,6
LAT				
NET	-6,0	9,1	-13,9	-15,4
POL	0,0	0,0	0,0	0,0
POR	27,0	44,9	-12,4	-7,4
SLA				
SLE				
SPA	15,0	35,5	-15,1	-8,6
SWE	4,0	-4,8	9,3	3,8
UKI	-12,5	-7,8	-5,1	-5,6

Notes

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

[2]Nitrogenous Dioxide (NO_2), Sulphur Dioxide (SO_2), Carbon Monoxide (CO), Non-Methane Volatile Organic Compounds (NMVOC) and Carbon Dioxide (CO_2). See below for further details on the environmental and macroeconomic data we use.

[3]Among transboundary pollutants, we focus attention on NO_2, CO, NMVOC and SO_2. The most important greenhouse gas is represented by CO_2.

[4]These data can be downloaded from:

http://themes.eea.eu.int/Specific_media/air/data

and http://pwt.econ.upenn.edu/php_site/pwt_index.php

respectively. The sources for all the data used in this study are listed in Appendix A.

[5]With the only exception that data of CO_2 emissions are missing for Greece, Slovenia and Hungary.

[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.

[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.

[8]Our sample does not contain any country showing an inverted U-shaped relationship between pollution emissions and real GDP along the nineties, as the environmental Kuznets

curve literature would suggest.

[9]See the Appendix for a more detailed description of the competitive equilibrium problem.

[10]Notice that with $\varepsilon = 0$ we have the standard condition $\rho > n + (1 - \tilde{\tau})x$.

[11]As in the S-S setup, the time t for which $p(t)$ is halfway between $p(0)$ and p^* must satisfy:

$$0.5 = e^{-\beta_{zz}t} \Leftrightarrow t = \frac{\ln(2)}{\beta_{zz}} = \frac{0.69}{\beta_{zz}}.$$

[12]More precisely, a simple model of environmental pollution dynamics in our framework can be described with

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

[13]We are aware of more than ten years of developments in the convergence and growth literature. In particular, it is well known that part of the drawbacks of the cross-section are overcome by the panel data analysis. We will be more precise on these issues (clarifying what we do not do) below.

[14]As it is pointed out by Selden and Song (1994), emissions are measured imperfectly and errors for a country persists over time, which reinforce the use of panel data techniques to deal with convergence issues in a heterogenous set of countries.

[15]For each pollutant, the estimated β differs slightly from those obtained when controlling for the GDP growth rate. These facts give robustness to the estimations.