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A Dynamic Model of the Environmental Kuznets Curve: Turning Point and Public Policy[*]

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We set up a simple dynamic macroeconomic model with (i) polluting consumption and a preference for a clean environment, (ii) increasing returns in abatement giving rise to an EKC and (iii) sustained growth resulting from a linear final-output technology. The model captures two sorts of market failures caused by external effects associated with consumption and environmental effort. This model is employed to investigate the determinants of the turning point and the (relative) effectiveness of different public policy measures aimed at a reduction of the environmental burden. Moreover, the model offers a potential explanation of an N-shaped pollution-income relation. Finally, it is shown that the model is compatible with most empirical regularities on economic growth and the environment.

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1 Introduction

The Environmental Kuznets Curve (EKC) hypothesis states that there is an inverted U-shaped relationship between environmental degradation and the level of income. Starting with Grossman and Krueger (1993) this pattern has been intensively debated in empirical terms; recent reviews are provided by Dasgupta et al. (2002) and Stern (2004). The EKC has also captured considerable attention from policymakers and theorists. This is due to the fact that the EKC hypothesis implies that pollution diminishes once a critical threshold level of income is reached. As a consequence, there is the hope that – loosely speaking – the environmental problem sooner or later peters out as the economy grows.

There are two major strands within the theoretical EKC literature. In the first class of models an EKC arises from shifts in the use of production technologies, which differ in their pollution intensity (Stokey, 1998; Smulders and Bretschger, 2000). The second class focuses on the characteristics of the abatement technology (John and Pecchenino, 1994; Selden and Song, 1995; Andreoni and Levinson, 2001; Chimeli and Braden, 2002; Brock and Taylor, 2004).

The Andreoni and Levinson (2001) (thereafter AL) model has attracted a significant attention. Using a static setup, they show that an EKC can be explained with increasing returns to scale (IRS) in the abatement technology. Moreover, AL claim that by focusing on the degree of returns to scale in abatement, a large part of the literature dealing with very different mechanisms (e.g. a shift in technology or a shift in institutions) can be summarised.

The level of income at which pollution peaks (labelled "the turning point") and the associated level of pollution are of fundamental interest from the perspective of public policy. A sound understanding of the pollution-income relation (PIR) could provide important information for public policies aimed at a reduction of the environmental burden. The empirical EKC literature has accordingly devoted much effort to the determination of this critical threshold. The results show, however, a large dispersion across different studies. For instance, the reported turning points for sulphur dioxide range from $2,900 to $908,200 and for nitrogen oxides from $5,500 to $30,800 (in 1985 PPP$; Lieb, 2003). Given these diverse empirical results, it is clearly desirable to better understand the determinants of the turning point from a theoretical perspective.

In this paper, we set up a simple dynamic EKC model, which has the following characteristics: Pollution is a by-product of consumption activities, it is modelled as flow pollution and it creates disutility. Households can spend resources on abatement to reduce net pollution. Following AL we assume that there are IRS in abatement giving rise to an EKC. There are two market distortions due to external effects associated with consumption and abatement activities. Permanent growth results from an accumulable stock of capital and a linear final-output technology.

The paper at hand focuses on two issues: First, we employ the simple dynamic EKC model to better understand the determinants of the turning point. The factors which are of major interest in this type of models are the preference for a clean environment, the degree of IRS in abatement and the magnitude of external effects. Second, we investigate the effectiveness of public policy measures aimed at a reduction of the environmental burden. In this context, it is important to have a model with multiple market failures so that the question of the relative effectiveness of different environmental policy measures can be answered.

As noted above, pollution is modelled as flow pollution. The reason lies in the fact that an EKC is more likely to arise for flow pollutants than for stock pollutants. This is best illustrated by Lieb (2004, p. 484) who reports that "*almost all studies agree that there is an EKC for sulphur dioxide (SO_2), suspended particulate matter (SPM), oxides of nitrogen (NO_x), carbon monoxide (CO), and for some (but not all) sorts of river pollution (PR)... Although all these pollutants are stock pollutants, they all have short life-times and can therefore be considered as flow pollutants from a long-run point of view.*"

Turning to the related literature, there are a number of theoretical papers on the EKC which consider the determinants of the turning point; some of these papers also investigate the role of public policies. Brock and Taylor (2004) use an augmented Solow model to demonstrate that an EKC arises along the transition to the steady state. Although there is polluting production in this model, there is no market failure. Lieb (2004) uses an overlapping generations model with a stock pollution and a flow pollution. He focuses on the different pollution paths of the stock and the flow pollution. The model captures several external effects associated with production and abatement. However, only the problem of a myopic government is analysed implying that the intragenerational externalities are internalised, while the intergenerational externalities are not. Moreover, the effectiveness of public policy measures is not considered since the unregulated market economy is not investigated. Chimeli and Braden (2002) employ a simple endogenous growth model with environmental quality. The authors show that environmental quality follows a V-shaped pattern, thereby explaining an EKC for a stock pollution. There is single external effect associated with polluting production. Hence, the consequences of multiple external effects cannot be studied. Finally, Anderson and Cavendish (2001) employ a dynamic simulation model to investigate the consequences of public policy measures on the turning point. This computable equilibrium model has the advantage of being able to directly include different aspects of the real world which are important in this context. However, general equilibrium feedback effects are excluded and optimal taxes cannot be derived.

The remainder of this paper is organised as follows: In Section 2, the basic AL model is sketched. In Section 3, a simple dynamic EKC model is set up in general form. The decentralised and the centralised solution are investigated and the optimal tax scheme is determined. In Section 4, a parameterised version of the model is employed to investigate the determinants of the turning point and the relative effectiveness of different public policies. In Section 5, it is shown that an N-shaped PIR can potentially be explained from the interaction of public policy and the intrinsic properties of the model. Section 6 demonstrates concisely that the model is compatible with most sets of stylised facts on economic growth and the environment. Finally, Section 7 summarises the main results and concludes.

2 The Andreoni and Levinson EKC model

In an important paper, AL (2001) set up a simple static model to derive sufficient conditions for an EKC. The AL model is sketched below to provide a reference point for the following discussion.

Utility of the representative agent depends positively on consumption C and negatively on pollution P. The general utility function may be expressed as:

$$U = U(C, P). \tag{1}$$

Pollution is a function of consumption and environmental effort E according to:

$$P = C - B(C, E). \tag{2}$$

Pollution increases one-to-one with consumption (gross pollution) as represented by the first term on the RHS. On the other hand, pollution decreases due to abatement as represented by the second term of the RHS. $B(C, E)$ is the abatement technology, which is increasing in both arguments. Both "inputs" are essential for abatement, i.e. $B(0, E) = B(C, 0) = 0$. The final basic equation is a standard budget constraint given by $M = C + E$, where M denotes the available resources (income).

AL show that there are two conditions which together guarantee the existence of an EKC (AL, 2001, p. 277). The first condition – related to preferences – states that "*the marginal willingness to pay to clean up the last speck of pollution does not go to zero as income approaches infinity*". This is a rather weak condition; it is easily satisfied since pollution abatement can be regarded as a normal good.[1] The second condition – related to the abatement technology – states that there must be IRS in abatement.

Using the following parameterisation $U(C, P) = C - zP$ with $z = 1$ and $B(C, E) = C^{\alpha}E^{\beta}$, AL show that an EKC results provided that $\alpha + \beta > 1$. This can be immediately recognised by inspecting the pollution function in terms of M:

$$P(M) = \frac{\alpha}{\alpha + \beta}M - \left(\frac{\alpha}{\alpha + \beta}\right)^{\alpha}\left(\frac{\beta}{\alpha + \beta}\right)^{\beta} M^{\alpha+\beta}. \tag{3}$$

The preceding equation results from $P = C - C^{\alpha}E^{\beta}$, $C^* = \frac{\alpha}{\alpha+\beta}M$ and $E^* = \frac{\beta}{\alpha+\beta}M$, where C^* and E^* are the optimal level of consumption and environmental effort. Equation (3) implies that $P(M)$ is concave in M provided that $\alpha+\beta > 1$. Hence, IRS in abatement (defined by $\alpha+\beta > 1$) represent a necessary condition for the existence of an EKC.

3 A general dynamic EKC model

In this section, we set up a simple dynamic EKC model, which will be employed in the course of this paper. Pollution results as a by-product of consumption

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[1] Lieb (2002) shows that the normality of environmental quality is a necessary condition for the existence of an EKC.

activities and is modelled as flow pollution. Households can reduce pollution by spending resources on abatement. The abatement technology is characterised by IRS. As AL (2001) have shown, this assumption leads to an EKC. There is a homogeneous final-output good which is produced under constant returns to scale using (physical and human) capital as the sole input factor. Households earn income by renting capital to firms. Output and factor markets are perfectly competitive. We consider two types of externalities and hence the decentralised solution diverges from the centralised solution. At first, the market economy is considered and subsequently the centralised solution is investigated. Finally, the optimal tax scheme is determined.[2]

3.1 The decentralised economy

There is a large number of identical households ordered on the interval $[0, 1]$. The representative household derives utility from consumption C and disutility from net pollution P. The instantaneous utility function is $U(C, P)$ with $U_C > 0$, $U_{CC} < 0$, $U_P < 0$ and $U_{PP} < 0$.[3] The flow of pollution (per period of time) is given by the difference between gross pollution $G(C, \bar{C})$ and abatement $B(C, E, \bar{E})$:

$$P(C, \bar{C}, E, \bar{E}) = G(C, \bar{C}) - B(C, E, \bar{E}), \tag{4}$$

where E is environmental effort and a "bar" above a variable denotes its economywide average. The above-stated pollution function shows that pollution is modelled to result from consumption.[4] Direct examples for polluting consumption activities would be the use of automobiles and central heating. Turning to environmental effort, we can interpret the model in the sense that both households as well as firms conduct abatement. It is plausible and convenient to let the incidence of abatement costs fall on households. To clarify this aspect, consider a real-world example: Abatement in the case of driving automobiles comprises the installation of catalytic converters and strainers. Although the major part of this abatement activity (development and installation) is conducted by firms, households face the decision for, and bear the costs of this environmental effort.

There are two kinds of externalities: First, polluting consumption is only partially taken into account by the representative household, i.e. there is a (negative) pollution externality. Second, environmental effort aimed at reducing (net) pollution affects also the society as a whole, i.e. there is a (positive) externality resulting from environmental effort. As an example, consider again the use of automobiles. It is the household who bears the financial burden but it is society that primarily benefits from the implementation of catalytic converters and strainers. External effects are associated with the economywide

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[2] There are other general growth models with pollution and external effects (e.g. Smulders and Gradus, 1996).

[3] We do not restrict the cross derivatives at this stage.

[4] More frequently, pollution is modelled as a by-product of production (e.g. Xepapadeas, 2004). There are, however, other theoretical studies, beside AL (2001), which assume that consumption generates pollution (e.g. John and Pecchenino, 1994).

averages of consumption $\bar{C}$ and environmental effort $\bar{E}$, which are considered as exogenous from the perspective of the typical household.

As noted above, households earn capital income only. Let r denote the rental price of capital and K the stock of capital owned by households. Then the household's income is simply rK. The household's gross expenditures (including taxes) are given by $(1+\tau_C)C + (1+\tau_E)E$, where τ_C and τ_E represent taxes (or subsidies) on consumption and environmental effort.[5] Overall tax revenues T are redistributed in a lump-sum manner according to a balanced-budget rule, i.e. $T = \tau_C C + \tau_E E$. Households are assumed to maximise the present value of an infinite utility stream. The associated dynamic problem may be expressed as follows (time index suppressed):

$$\max_{\{C,E\}} \int_0^\infty U(C,P)e^{-\rho t}\,dt \tag{5}$$

$$\begin{aligned} s.t.\quad P(C,\bar{C},E,\bar{E}) &= G(C,\bar{C}) - B(C,E,\bar{E}) && (6)\\ \dot{K} &= rK - (1+\tau_C)C - (1+\tau_E)E + T && (7)\\ K(0) &= K_0, && (8) \end{aligned}$$

where ρ denotes the time preference rate, t the time index, $\dot{K}$ the rate of change of K per period of time and K_0 is the initial stock of capital, respectively. Notice that equation (7) shows the flow budget constraint of the typical household.

As mentioned above, the focus here is on flow pollution. Because a pure flow pollution (i.e. there is no pollution stock) cannot become negative, the technical restriction $P \geq 0$ must be taken into account (see also Lieb, 2004, p. 488). Moreover, since we are interested in an inverted U-shaped PIR, attention is restricted to interior solutions. The dynamic problem above can be easily extended to allow for border solutions with $P = 0$.

The (current-value) Hamiltonian for the above-stated problem reads as follows:

$$H = U[C, P(C,\bar{C},E,\bar{E})] + \lambda[rK - (1+\tau_C)C - (1+\tau_E)E + T], \tag{9}$$

where λ denotes the shadow price of capital. The necessary first-order conditions are given by:[6]

$$\frac{U_C + U_P P_C}{1+\tau_C} = \lambda \tag{10}$$

$$\frac{U_P P_E}{1+\tau_E} = \lambda \tag{11}$$

$$\dot{\lambda} = -\lambda(r-\rho), \tag{12}$$

where U_x and P_x denote the partial derivatives of U and P with respect to $x \in \{C,E\}$, respectively. For ease of interpretation, assume for the moment

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[5] Optimal tax rates are determined below.

[6] In addition, the transversality condition $\lim_{t\to\infty} e^{-\rho t}\lambda K = 0$ must hold. Moreover, we assume that the necessary conditions are also sufficient for a maximum of the utility functional.

that $\tau_C = \tau_E = 0$. Equation (10) then shows that along the optimal growth path the (private) marginal utility of consumption must equal the shadow price of capital λ. The marginal utility of consumption comprises two components: (i) the direct utility from consumption U_C and (ii) the disutility from pollution $U_P P_C$. Moreover, it should be remembered that P_C captures a gross pollution effect G_C and an abatement effect B_C. Similarly, equation (11) indicates that marginal utility from environmental effort $U_P P_E$ must equal the shadow price of capital. Equation (12) shows that if the growth condition holds (i.e. $r - \rho > 0$), the shadow price of capital vanishes at the rate $r - \rho$.

Turning to the firm side of the economy, there is a large number of final-output firms. The representative final-output firm produces a homogeneous good using capital as the sole input factor.[7] The constant returns to scale technology is $Y = AK$, where Y is final output, K the stock of capital and A a constant technology parameter. Capital depreciates at constant rate $\delta \geqslant 0$. From the solution to the firm's static optimisation problem one gets:

$$r = A - \delta.$$

3.2 The centralised economy

The social planner maximises the welfare of the representative individual. This requires, of course, that the external effects are taken into account. The social planner's problem may be expressed as follows:

$$\max_{\{C,\bar{C},E,\bar{E}\}} \int_0^\infty U(C,P)e^{-\rho t}\,dt \tag{13}$$

$$\begin{aligned} s.t.\ \ P(C,\bar{C},E,\bar{E}) &= G(C,\bar{C}) - B(C,E,\bar{E}) && (14)\\ \dot{K} &= F(K) - \delta K - C - E && (15)\\ K(0) &= K_0. && (16) \end{aligned}$$

The (current-value) Hamiltonian reads as follows:

$$H = U[C, P(C,\bar{C},E,\bar{E})] + \lambda[F(K) - \delta K - C - E] \tag{17}$$

and the necessary first-order conditions are given by:[8]

$$U_C + U_P(P_C + P_{\bar{C}}) = \lambda \tag{18}$$

$$U_P(P_E + P_{\bar{E}}) = \lambda \tag{19}$$

$$\dot{\lambda} = -\lambda(F_K - \delta - \rho). \tag{20}$$

Comparing the first-order conditions (18) and (19) to the first-order conditions (10) and (11) shows the differences between the centralised solution and the decentralised solution. When deciding on the optimal levels of C and E the

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[7] As noted above, capital should be interpreted broadly to comprise human as well as physical capital.

[8] Once again, the transversality condition $\lim_{t\to\infty} e^{-\rho t}\lambda K = 0$ must hold and we assume that the necessary conditions are also sufficient.

social planner, in contrast to the private agent, takes the external consequences associated with average consumption $\bar{C}$ and average environmental effort $\bar{E}$ into account. Specifically, the social planner considers also the effects of average consumption on gross pollution ($U_P P_{\bar{C}} = U_P G_{\bar{C}}$) as well as the consequences of average environmental effort on abatement ($U_P P_{\bar{E}} = -U_P B_{\bar{E}}$).

3.3 Optimal tax scheme

Optimal taxes τ_C^* and τ_E^* result from the comparison between the first-order conditions of the social planner's solution [(18) and (19)] and the first-order conditions of the decentralised solution [(10) and (11)]. It can be readily shown that an optimal tax scheme is given by:

$$\tau_C^* = -\frac{U_P P_{\bar{C}}}{U_C + U_P(P_C + P_{\bar{C}})} > 0 \tag{21}$$

$$\tau_E^* = -\frac{P_{\bar{E}}}{P_E + P_{\bar{E}}} < 0. \tag{22}$$

Let us start with the interpretation of τ_E^*, which is straightforward. Equation (22) shows that the optimal subsidy on environmental effort equals the ratio of the external marginal effect of environmental effort on pollution $P_{\bar{E}} < 0$ and the overall (i.e. private and external) marginal effect of environmental effort on pollution $P_E + P_{\bar{E}} < 0$. Similarly, the optimal consumption tax τ_C^* is the ratio of the external marginal consumption effect on utility $U_P P_{\bar{C}} < 0$ and the overall marginal effect of consumption on utility given by $U_C + U_P(P_C + P_{\bar{C}}) > 0$.[9]

Consider finally the consequences of a tax on consumption $\tau_C > 0$ on the decisions of the representative household. A consumption tax $\tau_C > 0$ reduces the LHS of equation (10). Holding the shadow price of capital constant, equation (10) then requires that the marginal utility of consumption must increase. This can be accomplished by reducing the level of consumption. An analogous interpretation (with $\tau_E < 0$) applies to equation (11).

4 A specific dynamic EKC model

In this section, a parameterised version of the model is employed to investigate the determinants of the turning point and the effectiveness of public policy. At first, we consider the centralised solution with $z = 1$. Subsequently, we turn to the more relevant case of an unregulated / imperfectly regulated economy with $z < 1$.

4.1 Parameterisation

For further investigations we parameterise instantaneous utility $U(C, P)$, gross pollution $G(C, \bar{C})$ and abatement $B(C, E, \bar{E})$. The following functional forms are assumed:

$$U(C, P) = \log(C - zP) \quad \text{with} \quad z > 0,\, C \geq zP \tag{23}$$

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[9] Notice that $U_C + U_P(P_C + P_{\bar{C}}) = \lambda > 0$.

$$G(C, \bar{C}) = C^{\phi} \bar{C}^{\omega} \quad \text{with} \quad 0 < \phi, \omega, < 1 \tag{24}$$

$$B(C, E, \bar{E}) = C^{\alpha} E^{\beta} \bar{E}^{\eta} \quad \text{with} \quad 0 < \alpha, \beta, \eta < 1, \tag{25}$$

where z reflects the desire for a clean environment. A lower value of z means that a given amount of pollution causes less disutility and individuals will accordingly spend more on consumption and less on environmental effort. Turning to the gross pollution function (24), C^{ϕ} represents the internal effect of consumption on gross pollution and $\bar{C}^{\omega}$ is the corresponding external effect. We assume throughout the paper that $\omega + \phi = 1$, which implies a linear gross pollution function.[10] Similarly, E^{β} is the private and $\bar{E}^{\eta}$ the external effect of environmental effort in abatement.[11]

A short explanation of the instantaneous utility function (23) is indicated. Since $\phi + \omega = 1$ and taking into account $C = \bar{C}$ and $E = \bar{E}$, pollution is given by $P = C - C^{\alpha} E^{\beta+\eta}$. Moreover, assuming $z = 1$ the utility function becomes $U[C, P(C, E)] = \log(C^{\alpha} E^{\beta+\eta})$. This formulation has the advantage that C and E enter utility additively separable, which enables an analytical solution for the social planner's problem. Two issues should be noticed in this respect: First, the preceding utility function requires $C - zP \geq 0$, otherwise utility would not be defined. For $z \leq 1$ this restriction is automatically satisfied since C is gross pollution and P is net pollution (gross pollution minus abatement). Second, the utility function implies $U_{CP} = \frac{1}{(C-zP)^2} > 0$. This property appears counterintuitive at first glance. However, this is due to the fact that a rise in P has the same effect as a reduction in C and hence marginal utility of consumption increases with pollution P.[12]

4.2 Analytical results

The PIR is derived analytically and determinants of the turning point are discussed. Here we focus on the centralised solution and assume that $z = 1$. This allows us to derive analytical results. The decentralised solution with $z < 1$ is investigated in a second step by simulating the transition process (Section 4.3).

4.2.1 The time path of pollution $P(t)$ and the PIR $P(Y)$

From the first-order conditions [(18) to (20)] and the parameterised functions [(23) to (25)], one obtains the following solutions for K and λ:

$$K = K_0 e^{(A-\delta-\rho)t} \tag{26}$$

$$\lambda = \frac{\alpha + \beta + \eta}{K_0 \rho} e^{-(A-\delta-\rho)t}. \tag{27}$$

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[10] In addition, this restriction enables us to solve the differential equation system resulting from the centralised solution analytically.

[11] An appendix available upon request shows that the parameterised Hamiltonian functions are concave, i.e. the necessary conditions are also sufficient for a maximum of the utility functional.

[12] According to Michel and Rotillon (1995) $U_{CP} > 0$ can be interpreted as a compensation effect.

Using equations (18), (19) and (27) and noting equations (23) to (25), one can formulate an analytical expression for the time path of pollution:

$$
\begin{aligned}
P(t) &= \frac{K_0 e^{(A-\delta-\rho)t}\alpha\rho}{\alpha+\beta+\eta} - \left[\left(\frac{K_0 e^{(A-\delta-\rho)t}\alpha\rho}{\alpha+\beta+\eta}\right)^{\alpha}\right. \\
&\qquad \left.\cdot \left(\frac{K_0 e^{(A-\delta-\rho)t}(\beta+\eta)\rho}{\alpha+\beta+\eta}\right)^{\beta+\eta}\right]. \qquad (28)
\end{aligned}
$$

Furthermore, the PIR may be expressed as follows:

$$
P(Y) = cY - (cY)^{\alpha}(hY)^{\beta+\eta}, \qquad (29)
$$

where $c := \frac{C}{Y}$ is the consumption rate and $h := \frac{E}{Y}$ the "environmental effort rate". To determine c and h, we consider the growth rate of capital $\hat{K} := \frac{\dot{K}}{K}$ using equations (15), (25) and (26):

$$
\hat{K} = A - \delta - \rho = A - \delta - \frac{C}{K} - \frac{E}{K}. \qquad (30)
$$

Together with the parameterised versions of (18) and (19) this immediately yields the balanced growth values of c and h to read as follows:

$$
c = \frac{\alpha\rho}{A(\alpha+\beta+\eta)} \qquad \text{and} \qquad h = \frac{(\beta+\eta)\rho}{A(\alpha+\beta+\eta)}. \qquad (31)
$$

The PIR is illustrated in Figure 1 (a) and the time path of pollution in Figure 1 (b). These figures are based on the baseline set of parameters, which is set out in Section 4.3.1 below. As in AL (2001), IRS in abatement is a necessary condition for a hump-shaped PIR.[13] Figure 1 (a) shows that pollution first rises with income, then declines and eventually becomes zero. This EKC represents a balanced growth phenomenon.[14] Although pollution does not grow

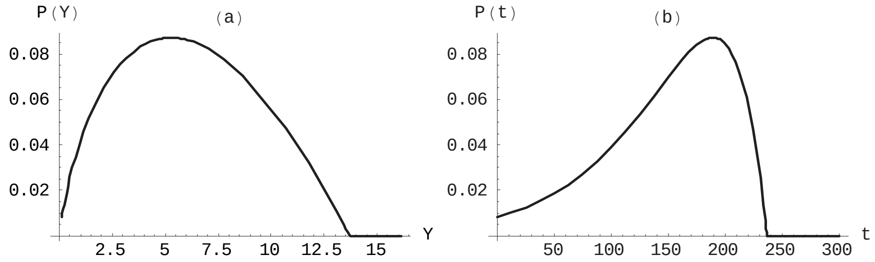

Figure 1: $P(Y)$ and $P(t)$ with IRS in abatement ($\alpha+\beta+\eta > 1$)

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[13] In a more general version of the AL (2001) model Plassmann and Khanna (2004, p. 16) show that "*for non-constant returns to scale in gross pollution, a sufficient condition for pollution to decline is rather that the returns to scale in abatement exceed the returns to scale in gross pollution.*"

[14] Employing a neoclassical growth model, it can be shown that the EKC can also result from transitional dynamics.

at a constant rate (as is required by the definition of a balanced growth path), the illustrated pollution path represents a balanced growth phenomenon since pollution results from two endogenous variables (consumption and environmental effort), which both grow at constant rates. The required time span until pollution reaches its peak and becomes zero is quite long. The whole "EKC story" takes nearly 250 years as is displayed in Figure 1 (b).

The EKC pattern displayed in Figure 1 (a) is in line with empirical evidence as reported by Grossman and Krueger (1995) according to which the PIR is asymmetric with an upper tail that declines relatively gradually.

4.2.2 The turning point

As has been noted above, the level of income at which pollution peaks and the associated level of pollution is of outstanding interest from the perspective of public policy. We employ the model set up above to investigate the factors which determine this turning point. Unfortunately, closed-form solutions can only be obtained for the centralised economy with $z = 1$. Under these restrictions we can investigate the impact of basic technology and preference parameters on the turning point analytically. This represents an interesting limiting case which is relevant in the sense that the qualitative results largely hold true also for the decentralised economy with $z < 1$. In Section 4.3 we turn to the empirically more plausible case of an imperfectly regulated economy with $z < 1$.

First, consider the point in time at which pollution reaches its maximum. From the analytical expression for the time path of pollution [equation (28)], one can determine this time threshold (denoted as t^*) to read as follows:

$$t^* = -\frac{\log[K_0^{\alpha+\beta+\eta-1}\alpha^{\alpha-1}(\beta+\eta)^{\beta+\eta}(\alpha+\beta+\eta)^{2-\alpha-\beta-\eta}\rho^{\alpha+\beta+\eta-1}]}{(\alpha+\beta+\eta-1)(A-\delta-\rho)}. \quad (32)$$

It should be noticed that z, ϕ and ω do not appear on the RHS, which is due to the restrictions imposed (i.e. $z = 1$ and $\phi + \omega = 1$). Below we will investigate the impact of these parameters numerically. Inserting the preceding expression for t^* into the time path of income $[Y(t) = AK(t)]$ and using equation (26) yields the turning point (denoted as Y^*):[15]

$$Y^* = \frac{A\alpha^{\frac{1-\alpha}{\alpha+\beta+\eta-1}}(\beta+\eta)^{-\frac{\beta+\eta}{\alpha+\beta+\eta-1}}(\alpha+\beta+\eta)^{1-\frac{1}{\alpha+\beta+\eta-1}}}{\rho}. \quad (33)$$

This critical income level is determined by the marginal product of capital A, the rate of time preference ρ, the elasticity of consumption in abatement α as well as the elasticities of environmental effort in abatement β and η. It is independent of the depreciation rate δ and the initial capital stock K_0.

From the preceding solution for Y^* we obtain the comparative static results shown in Table 1.[16] The first row shows that Y^* increases with A. For ease

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[15] This is basically the solution for the turning point one would obtain from the static AL (2001) model.

[16] To simplify notation, we define $\gamma = \alpha + \beta + \eta$.

Table 1: Comparative static results for Y^*

	$\frac{\partial Y^*}{\partial x}$ for $x \in \{A, \rho, \alpha, \beta\}$	
A	$Y^* \frac{1}{A}$	> 0
ρ	$Y^* \frac{-1}{\rho}$	< 0
α	$Y^* \frac{(\gamma-1)(-\alpha+\beta+\eta)+\alpha\gamma(\log[\gamma]+(\beta+\eta)(\log[\beta+\eta]-\log[\alpha])}{\alpha\gamma(\gamma-1)^2}$	?
β	$Y^* \frac{2+\gamma(\log[\gamma]-2)+\gamma(\alpha-1)(\log[\alpha]-\log[\beta+\eta])}{\gamma(\gamma-1)^2}$	?

of interpretation, let us assume that $\alpha = \beta + \eta$ such that $C = E$.[17] In this case, the level of pollution depends only on consumption. Since an increase in A reduces the consumption rate [equation (31)], the required level of income for pollution to reach its maximum increases. The second row indicates that Y^* falls as ρ rises. An analogous reasoning is applicable here. The rate of consumption rises with ρ [equation (31)] and hence the required level of income for pollution to reach its maximum falls. The signs of the partial derivatives of Y^* with respect to α and β are indetermined.[18] In most instances, the derivatives with respect to α and β are negative. An increase in the degree of IRS in abatement leads, ceteris paribus, to a higher abatement output for each level of income and hence to a lower turning point. However, a positive sign can not be excluded in general; for instance, under the restrictions $\alpha = \beta + \eta$ and $z = 1$ the derivative with respect to α is positive.[19]

4.3 Numerical analysis

The preceding analysis focused on the centralised solution with $z = 1$ implying that consumption and pollution have the same weight in the utility function. We now investigate the importance of external effects, the effectiveness of public policies and the implications of different environmental preferences. To accomplish this task, the transition process of the model under study must be simulated. We apply the backward integration procedure (e.g. Brunner and Strulik, 2002) to solve for the time paths of the endogenous variables.

4.3.1 Calibration

Table 2 shows the baseline set of parameters which underlies the numerical investigations. The time preference rate ρ and the depreciation rate δ are similar to the parameter values used in previous exercises (e.g. Ortigueira and

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[17] A similar reasoning would apply to the case $\alpha \neq \beta + \eta$.

[18] Since we are considering the centralised solution with $z = 1$, $\frac{\partial Y^*}{\partial \eta} = \frac{\partial Y^*}{\partial \beta}$.

[19] In this case, the relevant range of consumption is $0 < C < 1$. Within this range an increase in α lowers, ceteris paribus, the abatement output. As a result, the maximum level of pollution occurs at a higher C-level. With $\alpha = \beta + \eta$ the rate of consumption is independent of α and hence a higher C-level implies a higher Y^*.

Santos, 1997; Eicher and Turnovsky, 2001). Given these values A is chosen such that the implied net rate of return on capital $(A-\delta)$ and the growth rate of per capita income $(A-\delta-\rho)$ are in line with empirically plausible numbers (6% and 2%). The parameter ω determines the strength of the external pollution effect of consumption, while η captures the external effect of environmental effort in abatement. We choose ω and η such that the relative external effect of consumption in (gross) pollution $(\frac{\omega}{\phi+\omega})$ and the relative external effect of environmental effort in abatement $(\frac{\eta}{\beta+\eta})$ are both 10%, implying fairly moderate external effects. As noted above, we assume that the gross pollution function is linear (i.e. $\phi+\omega=1$).[20]

Table 2: Baseline Set of Parameters

Final output technology	$A=0.12$; $\delta=0.06$
Preferences	$\rho=0.04$
Abatement technology	$\alpha=0.6$; $\beta=0.45$; $\eta=0.05$
Gross pollution	$\phi=0.9$; $\omega=0.1$

Turning to the abatement technology parameters (α, β and η), there are two points to be noticed: First, we assume that there are IRS in abatement, i.e. $\alpha+\beta+\eta>1$. As in AL (2001), IRS in abatement are necessary for an EKC. This is in line with Xepapadeas (1994), where IRS in the pollution abatement sector (due to knowledge spillovers) is a necessary condition for unbounded growth without excess pollution (similar results are given in Michel 1993). Another way to justify IRS in abatement is due to technological progress in the abatement technology (Anderson and Cavendish, 2001). There is also empirical evidence for the existence of IRS in pollution abatement. For instance, AL (2001, p. 281) argue that "*at the level of US states, average pollution abatement costs per dollar of GSP [gross state product] decline with industry size, across states and industries, and over time.*" Moreover, Maradan and Vassiliev (2005) report that the marginal opportunity costs of carbon dioxide abatement, measured as forgone production of output, are negatively associated with income. Second, the parameters β and η crucially determine the ratio of abatement expenditures and income. This ratio ranges from about 3% for $z=0.5$ to 15% for $z=1$. These values are in line with the empirical figures reported by Brock and Taylor (2004, p. 6).

4.3.2 The turning point

The dependence of Y^* on the different model parameters is investigated numerically. On this occasion, we consider three different values of z. In addition, the unregulated economy (Table 3) is distinguished from an imperfectly regu-

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[20] The alternatives of a concave or convex gross pollution function $G(C)$ appear clearly less plausible.

lated economy (Table 4).[21] We focus on these two cases since we believe that the real world is best represented by an unregulated or imperfectly regulated economy. The basic assumption here is that politicians know the optimal taxes but due to imperfections in the political process do not fully implement this optimal tax scheme. The numbers reported in Tables 3 and 4 show the elasticities of Y^* with respect to different model parameters, i.e. $\frac{\Delta Y^*/Y^*}{\Delta x/x}$ with $x \in \{\omega, \eta, A, \rho, \alpha, \beta, z\}$.[22]

Table 3: Elasticities of Y^* with respect to model parameters;
unregulated economy ($\theta = 0$)

	ω ($\phi + \omega = 1$)	η	A	ρ	α	β	z
Y^* $z = 1$	0.67	-0.79	0.97	-0.90	-4.41	-5.74	-4.70
Y^* $z = 0.75$	0.46	-1.45	0.98	-0.90	-7.48	-7.40	-4.42
Y^* $z = 0.5$	0.28	-2.22	0.99	-0.91	-9.06	-8.61	-4.19

Three points should be noticed: First, the case of $z = 1$ is qualitatively identical to the cases of $z < 1$. By lowering z, the results change only gradually. Furthermore, the respective elasticities show the same sign for the unregulated economy (Table 3) and for the imperfectly regulated economy (Table 4). Second, the analytical results from Table 1 are confirmed and the ambiguous effects of α and β are determined, at least numerically. Third, compared to the case investigated above (centralised solution with $z = 1$) the impact of additional model parameters (i.e. ω and η) can now be assessed.

The first column of Table 3 shows the elasticity of Y^* with respect to ω. At the outset, it should be noticed that the restriction for the gross pollution function to be linear ($\phi + \omega = 1$) remains valid, i.e. increasing ω requires a reduction of ϕ. The positive impact of ω on Y^* can be explained as follows: Since $\phi + \omega$ is held constant, the level of consumption resulting from the centralised solution remains constant. Increasing ω leads to a larger gap between the centralised and the decentralised allocation. This implies that decentralised consumption rises, which, holding other things constant, causes a higher level of pollution at each level of income. Graphically speaking, the EKC is expanded outwards and the turning point increases. Moreover, this column also shows that the impact of ω on Y^* increases with z. A higher value of z (i.e. greener preferences) leads to a larger gap between the centralised and the decentralised solution, as can be

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[21] The tax rates imposed are specified as $\tau_C = \theta_C \tau_C^*$ and $\tau_E = \theta_E \tau_E^*$, where $\tau_C^* > 0$ and $\tau_E^* < 0$ are optimal taxes (defined in Section 3.3); $\theta_C \geq 0$ and $\theta_E \geq 0$ indicate the extent of tax implementation. A policy programme which diminishes both market distortions simultaneously is described by $\theta = \theta_C = \theta_E$.

[22] The elasticities are based on an 10% increase of the parameter under consideration.

seen by inspecting the first-order condition (18). This implies that the strength of the mechanism described above is reinforced. Finally, the effect of ω on Y^* is smaller for the imperfectly regulated economy (Table 4).

Table 4: Elasticities of Y^* with respect to model parameters; imperfectly regulated economy ($\theta = 0.5$)

	ω $(\phi + \omega = 1)$	η	A	ρ	α	β	z
Y^* $z = 1$	0.30	-0.75	0.99	-0.90	-2.71	-4.87	-4.98
Y^* $z = 0.75$	0.21	-1.46	1.00	-0.91	-6.92	-7.00	-4.60
Y^* $z = 0.5$	0.14	-2.27	1.00	-0.91	-8.90	-8.43	-4.29

The second column of Table 3 gives the impact of a variation in η on Y^*, which is negative. An increase in η has two separate effects: First, environmental effort falls. To understand this effect, consider the case of a variation in η assuming that $\beta + \eta =$ constant. This implies that E resulting from the centralised solution remains constant. Since the magnitude of the distortion increases, the gap between the centralised and the decentralised solution gets larger. Hence, E must decrease implying that pollution rises at each level of income and that the turning point increases as well. Second, by holding β fixed (which is assumed in Table 3 and 4), an increase in η leads to a higher degree of IRS, which means that pollution at each level of income falls. This implies that the turning point decreases. The second effect dominates the first and hence the sign of this elasticity is negative.[23]

The third column (A) and the fourth column (ρ) are in line with the analytical results obtained from the special case investigated in Section 4.2. The fifth column (α) and sixth (β) column contain negative values. Increasing either α or β increases the degree of IRS in abatement, which has a strong negative impact on the turning point.[24] Finally, the last column (z) shows that an increase in z has a substantially negative impact on Y^*. This observation is in line with Figure 2 below.

4.3.3 The effectiveness of public policies

The effectiveness of public policies aimed at a reduction of the environmental burden is investigated. On this occasion, we distinguish between the case of highly environmentally sensitive preferences ($z = 1$) and the case of less environmentally sensitive preferences ($z = 0.5$).

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[23] The results are nearly identical for the unregulated and the imperfectly regulated economy. This is due to the fact that the IRS argument does not depend on the degree of regulation.

[24] As for the analytical solution the impact of δ is zero.

The baseline set of parameters implies fairly moderate external effects, i.e. the relative external effect of consumption in gross pollution ($\frac{\omega}{\phi+\omega}$) and the relative external effect of environmental effort in abatement ($\frac{\eta}{\beta+\eta}$) are both 10%. Nevertheless, the impact of the associated market failures on the PIR is substantial, as illustrated in Figure 2. The PIR labelled "social" shows the EKC resulting from the centralised solution, while the PIR labelled "market" shows the EKC resulting from the unregulated market economy (ignore the curves marked by $\theta_C = 1$ and $\theta_E = 1$ for the moment). Moreover, Figure 2 (a) is based on $z = 1$, while Figure 2 (b) assumes $z = 0.5$. In both cases, Y^* and the maximum amount of pollution $P^* = P(Y^*)$ are highly sensitive with respect to external effects, i.e. the market economy shows considerably higher values for Y^* and P^* compared to the centralised solution. This implies that public policy should be highly effective with respect to a reduction of the environmental burden.

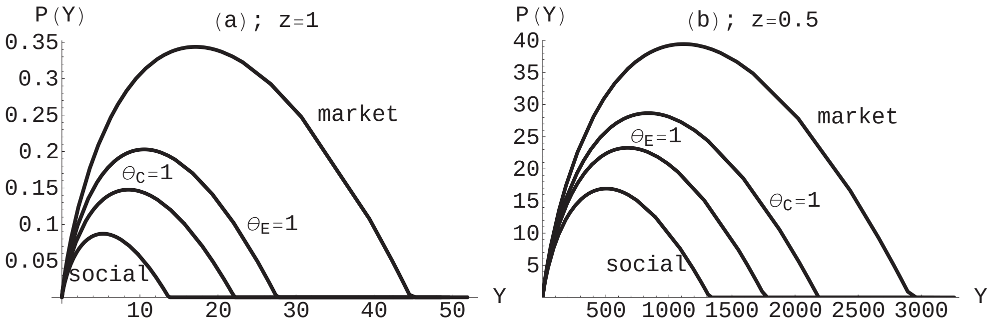

Figure 2: Centralised EKC versus decentralised EKC

By imposing appropriate taxes on consumption and subsidies on environmental effort the government can correct the market failures. The taxes imposed are specified as $\tau_C = \theta_C \tau_C^*$ and $\tau_E = \theta_E \tau_E^*$, where $\tau_C^* > 0$ and $\tau_E^* < 0$ are optimal taxes (determined in Section 3.3) and $\theta_C \geq 0$ and $\theta_E \geq 0$ indicate the extent of tax implementation.

Figure 2 illustrates the effectiveness of the policy instruments under consideration. The curves labelled as $\theta_C = 1$ implies that the external effect of polluting consumption is completely internalised, whereas the external effect of environmental effort is not. The curves labelled as $\theta_E = 1$ shows the reverse situation, i.e. the external effect of environmental effort is completely internalised and the external effect of consumption on gross pollution is not.

We now turn to the relative effectiveness of public policy measures. Figure 2 (a) shows that the consumption tax is more effective than a subsidy on environmental effort provided that preferences are extremely environmentally sensitive ($z = 1$). This can be recognised by the fact that the curve $\theta_C = 1$ lies strictly below the curve $\theta_E = 1$ implying both a lower Y^* and P^*. In contrast, provided that preferences are less environmentally sensitive ($z = 0.5$) the reverse holds true. A subsidy on environmental effort is more effective than a tax on polluting consumption.

The reason for this observation is as follows: The optimal taxes shown in equations (21) and (22), which are Pigouvian taxes, indicate the importance of the respective market failure. The optimal environmental effort subsidy is independent of z. In contrast, the optimal consumption tax depends on z. This can be immediately recognised by inspecting the parameterised versions of τ_C^* and τ_E^*:

$$\tau_C^* = \frac{z\omega C^{\phi+\omega}}{C - z(\phi+\omega)C^{\phi+\omega} + z\alpha C^{\alpha}E^{\beta+\eta}} \tag{34}$$

$$\tau_E^* = -\frac{\eta}{\beta+\eta}. \tag{35}$$

Holding C and E fixed we see that the optimal consumption tax τ_C^* increases with z. For z approaching zero, the representative individual does not care about pollution and hence polluting consumption does not represent a problem. The greener the preferences become (the larger z), the more important is this market failure.[25] For large values of z we find that $|\tau_C^*| > |\tau_E^*|$, which means that the market distortion resulting from polluting consumption is of a higher magnitude than the market distortion associated with environmental effort. Consequently, a consumption tax is more effective than a subsidy on environmental effort. In contrast, provided that z is small enough the reverse holds true, i.e. $|\tau_C^*| < |\tau_E^*|$. In this case, a subsidy on environmental effort is more effective than a consumption tax.

5 N-shaped pollution-income relation

There are a number of empirical studies which argue that the PIR is not inverted U-shaped but instead is N-shaped, at least for some pollutants (Grossman and Krueger, 1995, Section IV; Lieb, 2003). This is important because, in this case, pollution eventually increases with income.

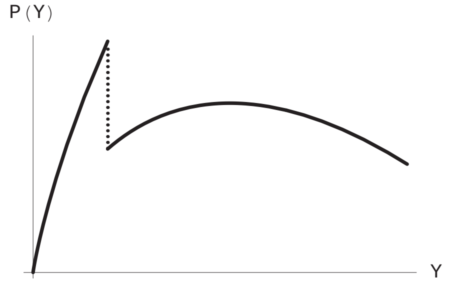

Figure 3: M-shaped PIR

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[25] This argument is based on holding C and E fixed, which is problematic because optimal C and E depend, of course, on z. We checked numerically that $|\tau_C^*| > |\tau_E^*|$ for $z = 1$ and $|\tau_C^*| < |\tau_E^*|$ for $z = 0.5$ indeed holds at each point in time for the simulations underlying Figure 2.

The model under study provides a potential explanation for this phenomenon. Imagine the economy develops at first along the upward sloping branch of the EKC resulting from the market economy as shown in Figure 3. At some point in time, policy instruments are implemented to internalise external effects and pollution accordingly diminishes. In the model, the economy jumps to the centralised EKC; of course, in reality this process is distributed over time. Provided that the economy is still below the critical threshold Y^* of the centralised solution, pollution starts to increase again. As a result, one would observe an N-shaped PIR resulting from the interplay of public policy and the intrinsic properties of the model. It should be noticed that this explanation implies in fact an M-shaped PIR. As soon as the peak of pollution (on the centralised EKC) is reached, pollution starts to decline again.

The mechanism sketched above provides one potential explanation for an N-shaped PIR. We do not consider this to be a general explanation. However, future empirical research aimed at explaining this pattern should take this possibility into account. This kind of reasoning implies that the first downward movement is policy induced, i.e. it should succeed the implementation of environmental regulations aimed at a reduction of pollution. The subsequent increase in pollution is then simply due to the fact that growth might be accompanied by a rise in pollution. Moreover, an N-shaped pattern can result provided that there are less than IRS in abatement. Finally, one should notice that Giles and Mosk (2003) find indeed an M-shaped EKC pattern by using long-run data on methane emissions for New Zealand.

6 Other empirical regularities

A dynamic EKC model should not only be able to reproduce an inverted U-shaped PIR. In addition, it should be compatible with the remaining empirical regularities on economic growth and the environment. These have been reported by Brock and Taylor (2004) based on US data for the period 1950 to 2001: First, the emission intensities (P/Y in our notation) for most pollutants are declining over time. Second, despite the fact that emission intensities decline, the emission levels (P in our notation) continue to increase for a certain period of time. Third, abatement costs relative to GDP (E/Y in our notation) are roughly constant.

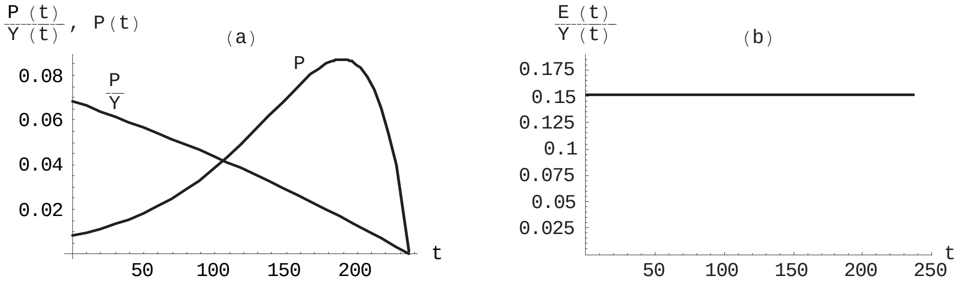

Figure 4: Pollution levels, pollution intensity and abatement expenditures

The EKC model set up above is compatible with these empirical regularities. Figure 4 (a) shows that the model is in line with the first and the second stylised fact.[26] The emission intensity (P/Y) is indeed declining over time and the pollution level (P) continues to increase for a certain period of time although pollution intensity is falling. Figure 4 (b) indicates that the third regularity is also satisfied, i.e. abatement expenditures relative to GDP (E/Y) are indeed constant over time.

In addition, the simple dynamic EKC model (being a standard AK growth model with pollution) is compatible with most of the stylised facts on economic growth, known as the Kaldor (1961) facts: (i) the growth rate of per capita output is constant, (ii) the capital-output ratio is constant and (iii) the real rate of return on capital is constant as well.[27]

7 Summary and conclusions

We have set up a simple dynamic EKC model with multiple market failures resulting from external effects associated with polluting consumption and environmental effort. The model has been used to investigate the determinants of the level of income at which pollution starts to decline (turning point) as well as the relative effectiveness of public policy measures aimed at a reduction of the environmental burden. The main results can be summarised as follows:

(1) The turning point is most strongly affected by the degree of IRS in abatement and the preference for a clean environment. In addition, the magnitude of external effects associated with polluting consumption and environmental effort also has a substantial impact. This aspect points directly to the importance of public policy measures.

(2) Provided that households have a strong preference for a clean environment a consumption tax (i.e. avoiding the problem of pollution) is more effective than a subsidy on environmental effort (i.e. correcting the problem of pollution). In contrast, if households are less environmental sensitive, then a subsidy on environmental effort is more effective in comparison to a consumption tax.

(3) It has been shown that an N-shaped PIR, observable for some specific pollutants, can potentially be explained from the interaction of public policy measures and the intrinsic properties of the model. Although we do not consider this explanation to be valid in general, we think that this kind of reasoning should be taken into account in future empirical research aimed at explaining this pattern.

(4) In addition to the empirical EKC hypothesis, the dynamic EKC model under study is compatible with the remaining empirical regularities associated with economic growth and the environment. Moreover, the model is also compatible with most of the stylised facts on economic growth due to Kaldor (1961).

Finally, the paper points to a number of interesting questions for future research. For instance, an obvious flaw of the AL model, which becomes especially obvious in a dynamic context, lies in the fact that pollution sooner or

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[26] Figure 4 is based on the centralised solution with $z = 1$ and the baseline set of parameters.

[27] The model is silent on the constancy of the capital and labour income shares.

later becomes negative as the economy grows provided that there are IRS in abatement. Finding a plausible mechanism which is able to avoid this problematic implication would represent a valuable contribution to the theoretical EKC discussion.

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