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POLLUTING TECHNOLOGIES AND SUSTAINABLE ECONOMIC DEVELOPMENT

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Abstract

We study how the import of older and more polluting technologies alters the relationship between output and environmental quality in developing countries within a vintage capital framework. Our results show that old technologies prolong the period until which pollution may eventually decrease and cause this turning point to be reached at a higher level of pollution. An empirical analysis using export data of vintage technologies from the US and Europe to developing countries supports our theoretical findings.

Keywords: Environmental quality, sustainable development, vintage technologies
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1 Introduction

In 2002 the city of Dortmund, located in the western part of Germany, was faced with one of the largest dismantling operations ever. Over a thousand Chinese workers, accompanied by engineers, started to cut up a huge iron and steel factory into millions of pieces. About 250,000 tons of iron, steel, electrical devices, and engines were then numbered, packed into boxes, and sent 9000 kilometers away to China, where the factory, piece by piece, was reassembled, intended to produce about 5 million tons of steel annually (Dohmen and Schmid, 'China-Town in Westfalen', *Der Spiegel*; April 8, 2002). While this particular example of the international movement of second hand capital goods is probably one of the more extreme ones, it is nevertheless demonstrative of how, while the market for used machinery and equipment is as old as that for new ones, it has only recently really boomed. For example, its growth rate has been characterized by double-digit figures in recent years, standing now at more then 150 billion Euros annually. Additionally, a simple search on the internet reveals the existence of dozens of auction houses, where objects sold range from simple tools to whole factories. Moreover, many more deals are not made directly at auction houses, but settled over the internet (Janischewski et al., 2003).

The bulk of the transfer of used machinery and equipment flows from the developed to the developing world and arguably has been an important impetus to economic growth in the latter (James (1974) and Schwartz (1973)). More precisely, lacking capital, many less developed countries can, via imported used capital goods, gain access to better means of production and thus avail of a low cost alternative to finance their growth. Additionally, it should be noted that older technologies are more labour intensive because they are less automated and often require greater maintenance. Coupled with the fact that absorptive capacities of new technologies depend on the skill availability of a country and that skilled labour is typically scarce in the developing world, developing countries thus make natural candidates for adopting these older types of machinery and equipment. In recognition of all of these factors, it has often been suggested that developing countries should reduce their barriers to trade on used machines and equipment, which often tend to be more stringent than for new ones.[1]

Nevertheless, there are potentially also drawbacks to importing used rather new capital goods. Specifically, the question has been raised whether the transfer of vintage technologies to developing countries, particularly with

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[1] See, for instance, Czaga and Fliess (2005) and Navaretti et al. (2000).

respect to energy intensive capital goods, will promote sustainable development. Or, as put by Metz et al. (2005, p.15): “Economic development is most rapid in developing countries, but it will not be sustainable if these countries simply follow the historic greenhouse gas emission trends of developed countries. Development with modern knowledge offers many opportunities to avoid past unsustainable practices and move rapidly towards better technologies, techniques and associated institutions.” In other words, if older technologies are, as is likely, more environmental unfriendly, then their advantages in terms lower capital costs and greater labour suitability may in the long term be more than counterbalanced by higher energy costs and pollutant emissions (Janischewski et al., 2003). Indeed, there is now clear evidence that carbon dioxide emissions have been steadily increasing in essentially all developing countries since the last century, and in some cases, such as China and India, have literally skyrocketed.[2] Moreover, developing countries’ continuing reliance on thermal energy and dirtier technologies to support economic growth is likely to further increase their pollutant emissions. In this regard, Janischewski et al. (2003) provide several real-world examples of environmental damages due to the use of older machinery and equipment. For instance, a 23 gigawatts fossil power station will cause about 2.2 billion tons of supplementary emissions of carbon dioxide compared to modern power stations. Similarly, a fleet of 300,000 used cars will cause additional 6,000 tons of nitrogen oxide and 70,000 tons of carbon monoxide compared to new ones.

Despite the potentially important role of the import of used machinery and equipment in the economic pollution-output relationship, there are virtually no studies in the academic literature that have examined this issue. In an early contribution, Sen (1962) developed a small model where used goods move from developed to developing economies not only due to higher maintenance cost and falling productivity with age, but also when wages are lower and when unemployment is higher in the latter. Smith (1974) comes to a similar conclusion, namely that a positive wage gap between developed and developing economies will favor the transfer of second-hand machines in the latter group of countries. More recently, Navaretti et al. (2000) provide theoretical and empirical support for the fact that developing countries have a higher share of imported second-hand equipment goods. The authors argue that this arises because of skill constraints, lower wages, and lack of

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[2] For instance, the growth of carbon dioxide emissions between 1990 and 1996 has been 2.4 per cent in France, 9.9 per cent in the US, compared to 40 and 47.7 per cent in China respectively India (Marland et al., 2000).

absorptive capacity of higher technology. Clerides (2004) and Pelletiere and Reinert (2004) study the impact of trade restrictions for the automobile market using Cyprus' imports and US exports of used cars, respectively. Both come to the conclusion that these restrictions have significant negative effects on trade flows, and point towards potentially important gains from lifting these. It is noteworthy, however, that none the studies above explicitly refer to the pollution issue of imported used machinery and equipment.

In the current paper we set forth to model how the decision to adopt older and dirtier technologies affects the relationship between economic development and pollution. In order to do so we build on the Schumpeterian framework of Aghion and Howitt (1998) by introducing a vintage capital structure, where the law of motion of environmental quality will depend on the pollution flow and some upper limit on environmental quality that takes into account the exhaustibility of resources. Importantly, and contrary to existing models, our vintage capital structure considers the decision of when to replace obsolete with newer technologies and how this may affect the pollution output relationship. If one assumes, as will be the case in our model, that older technologies are more environmentally unfriendly, then the decision of when to scrap these and what type of technology (i.e., used or new) to adopt is likely to be an important determinant of the extent of pollution generation.

Theoretical results of the model show that a reduction in environmental pollution during the industrialization process is only possible when the optimal rate of technological adoption has been reached. More importantly, the dirtier the adopted technology, the later a hypothetical reduction of the pollution-output ratio will occur. These theoretical predictions have potentially important empirical implications. In particular, there is no guarantee that countries will ever decrease their pollution-output ratio. But even in the particular cases when they will, this turning point will be postponed the older the adopted technology. Using data on output, carbon dioxide emissions, and US and EU exports of used machinery and equipment to a set of developing countries, we show that developing countries importing relatively more vintage technologies tend to reduce their pollution-output ratio at higher levels of output. Given that pollutants in general, and carbon dioxide emissions in particular, have very long lasting environmental effects, supporting the adoption of vintage technologies in developing countries today will arguably have repercussions in the very long run.

The rest of the paper is organized as follows. In Section 2 we present a vintage capital model, where the planner sets the optimal age of the technology according to the stage of development. In Section 3, we analyze the impact of these on the pollution-output relationship for a set of developing countries empirically. Section 4 concludes.

2 A Vintage Capital Structure

We consider a continuous time framework where the economy's population level is constant, and the labor market is perfectly competitive. The production sector produces only one final good, which can be assigned to consumption or net investment and plays the role of the numeraire. Moreover, we assume that in this economy there is no innovation. Technological change is due to adoption, which is costly.

2.1 General model

Production Sector As argued by Feichtinger et al. (2004) and Mulder et al. (2003), amongst others, there may be delays in the diffusion of new technologies due to financial constraints, lack of access, or lack of absorptive capacity. Therefore we will assume that at time $t > 0$, not the newest technology is necessarily adopted, but that imported and less efficient technologies can be used. Following Boucekkine and Martinez (2003), per capita output $y(t)$ is assumed to be

$$y(t) = (1 - \alpha) \int_{t-T(t)}^{t} i(z)dz, \tag{1}$$

where $0 < T(t) < \infty$ represents the vintage of the oldest machine in use (which is endogenously determined), $i(z)$ is investment in a machine of age z, and $\alpha \in (0, 1)$ is a measure of the vintage of the adopted technology. Life expectancy of a machine is defined as $J(t) = T(t + J(t))$, i.e., the expected life of a machine at time t is equal to the scrapping time $T(\cdot)$, evaluated at $t + J(t)$, which corresponds to the time when this new machine will be scrapped in the future.

The central feature of the output function is the way older technologies are at work compared to new ones. In equation (1), we normalize $\alpha = 0$ for the newest technology. The older the adopted technology, the higher α. Stated differently, $\int_{t-T(t)}^{t} i(z)dz$ is total output from investment $i(t)$. However, this investment is not free, rather the fixed fraction α represents its cost of inefficiency, which is measured as lost output during the producing process. Adopting newer technologies will produce more output per unit of investment. The reason why countries may have recourse to older, more inefficient technologies, can be manyfold. It is a well recognized fact that technology diffusion is neither smooth across space nor instantaneous in time. Mansfield (1968) estimated the diffusion time anywhere between five and fifty years, depending on the innovation and its scope. Impediments to diffusion may range from high adoption costs to institutional barriers. In particular, developing economies have been demonstrated to be particularly affected by such barriers (Parente and Prescott, 1994). This may be so for several reasons, including lack of human and physical capital compatible with the newest technologies, institutional barriers, training costs among others.

One should note from (1) that we, in contrast to Stokey (1998), do not consider the level of pollution as an input in the production sector, but rather allow pollution to enter consumers' utility functions. This will allow us to draw conclusions on the perception of the trade off between consumption goods and environmental quality.

Environment Sector As alluded to above, in this economy household agents care not only about their per capita consumption level $c(t) > 0$, but also pay attention to environmental quality. Following Aghion and Howitt (1998, Chap.5), we assume that there is an upper limit to environmental quality, denoted by $\overline{E}$. We measure $E(t)$ as the difference between the actual quality and this upper limit. Thus, environmental quality will always be negative. The equation of motion of environmental quality is given by

$$\dot{E}(t) = -qE(t) - \int_{t-T(t)}^{t} i(z)e^{-\gamma z}dz, \tag{2}$$

where $\gamma > 0$ is the constant rate at which the pollution due to investment of vintage z declines and $q > 0$ is the maximum potential rate of recovery of environment.[3] Pollution is measured by

$$P(t) = \int_{t-T(t)}^{t} i(z)e^{-\gamma z}dz. \tag{3}$$

From (2), pollution is a side-product of investment, $i(z)$, in the production sector. Implicit in (2) is the assumption that new machines are less polluting than older ones. Using a newer vintage leads henceforth to reduced pollution per input. Finally it is worth remarking that pollution is the opposite of

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[3] The notion of sustainable development is intimately linked to the one of nature's *self-regeneration* capacity, as noted by the World Bank (1991a and 1991b).

environmental quality, up to the first term on the RHS of expression (2), which denotes the self-regeneration capacity of nature.

Per capita output $y(t)$ can be consumed, $c(t)$, or invested in a vintage capital good, $i(t) \geq 0$,

$$y(t) = c(t) + i(t). \tag{4}$$

Central Planner The central planner's objective function will entail per capita consumption and environmental quality. More particularly, the planner will choose the paths of consumption and environmental quality in order to maximize the instantaneous utility of the infinitely lived representative household,

$$\max_{c} \int_0^\infty U(c, E)\, e^{-\rho t} dt = \max_{c} \int_0^\infty [\beta c(t) + (1-\beta)E(t)] e^{-\rho t} dt, \tag{5}$$

subject to (2), (4), and

$$J(t) = T(t + J(t)), \tag{6}$$

where $\rho > 0$ is the constant time preference, $0 < \beta < 1$ is a weight parameter between consumption goods and environmental quality, and $i(z)$, $z \leq 0$ and $E(0)$ are given functions.[4]

2.2 Optimal Solution Path

After rearranging the terms and changing the order of integrals, the optimal control problem amounts to determining $i(t)$, $J(t)$, with regard the state variable $E(t)$, as shown in the Appendix.

The first order condition with respect to $E(t)$ leads to

$$\left\{ \begin{array}{l} \dot{\mu}(t) = (\rho + q)\mu(t) + (1-\beta), \\ \lim\limits_{t \to \infty} E(t)\mu(t)e^{-\rho t} = 0. \end{array} \right. \tag{7}$$

The expressions in (7) combined with the transversality condition provide Tobin's q in terms of environmental quality, which is the shadow value of environmental quality. As in the optimal investment profile, this shadow value determines the optimal scrapping rule (8), and the optimal investment strategy (9) below.

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[4] In order to obtain explicit solutions, we avoid more general utility functions. While general utility functions would allow us to write down optimal conditions as in Ramsey type models, the equilibrium conditions for such an economy would give rise to a mixed-delay differential equation system with endogenous leads and lags (see Boucekkine et al., 1997).

The first order condition with respect to $J(t)$ provides

$$\mu(t) = (1-\alpha)\beta e^{\gamma(t-T(t))}. \tag{8}$$

The optimal scrapping rule in (8) means that a machine should be scrapped as soon as its operation cost with respect to consumption no longer covers its market value in terms of environmental quality.

The first order condition with respect to $i(t)$ provides

$$\beta(1-\alpha)\int_t^{t+J(t)} e^{-\rho z}dz - \beta e^{-\rho t} = \int_t^{t+J(t)} e^{-\rho z}\mu(z)e^{-\gamma t}dz, \tag{9}$$

which states that the optimal investment strategy should be such that at time t the discounted marginal productivity during the whole lifetime of the capital acquired in t exactly compensates for both its discounted operation cost and its discounted environmental shadow value, where the first term on the LHS is the discounted marginal productivity during the whole lifetime of the capital acquired at time t, and the second term is the marginal purchase cost at t normalized to one. The RHS expression is the discounted environmental shadow value at time t.

In the following sections we study the dynamics of $T(t)$ since the block recursive structure of our problem allows us to explicitly obtain $T(t)$, $J(t)$, and $\mu(t)$ by solving (9), (8) and (7). In particular, we make a clear distinction between the case where $T(0) \leq T^*$ and $T(0) > T^*$. The first case corresponds to the situation where countries scrap too fast compared to the optimal scrapping rule, whereas in the second case countries use technologies for a period longer than the optimum. In other words, the first situation mainly refers to countries with a high level of physical capital, i.e., essentially developed countries, whereas the second situation describes countries where capital is in shortage and, thus, machines have to be used for longer periods and/or older cheaper technologies have to be adopted (i.e. $\alpha > 0$). This latter case is arguably particularly relevant for developing countries and hence the focus of our analysis.

2.3 Optimal Scrapping Rule

As is standard in the vintage capital literature, we first solve the timing of both $T(t)$ and $J(t)$.

Substituting (8) into (9), it follows

$$\frac{(1-\alpha)}{\rho}\left(1-e^{-\rho J(t)}\right) - 1 = (1-\alpha)e^{(\rho-\gamma)t}\int_t^{t+J(t)} e^{-\rho z}e^{\gamma(z-T(z))}dz. \tag{10}$$

Deriving expression (10) with respect to time and rearranging the terms, we obtain the optimal scrapping rule

$$T(t) = F(J(t)) = -\frac{1}{\gamma}\ln\left(\left(1-\frac{\gamma}{\rho}\right)-(\rho-\gamma)+\frac{\gamma}{\rho}e^{-\rho J(t)}\right), \qquad (11)$$

which provides the expected life time of the youngest machines in use.

Function $F(\cdot) : \mathbb{R}_+ \to \mathbb{R}_+$ is well defined if and only if the following condition holds.

Assumption 1. The parameters and exogenous variables must satisfy the following conditions:

$$0 < \gamma < \rho < 1,$$

which are necessary and sufficient conditions for the existence of a balanced growth path (BGP)[5] in an exogenous growth models.

Proposition 1 *(Proof: see Boucekkine et al. (1997)). Let Assumption 1 hold. Then for $t > t^*$, the unique differential interior solutions of $T(t)$ and $J(t)$ are given by*

$$J(t) = T(t) = T^* = -\frac{1}{\gamma}\ln\left(\left(1-\frac{\gamma}{\rho}\right)-(\rho-\gamma)+\frac{\gamma}{\rho}e^{-\rho T^*}\right),$$

where T^* is the positive fixed-point of function $F(\cdot)$, and t^* will be given in proposition 3.

The optimal scrapping age does not depend on the weight between consumption goods and environmental quality. However, it does depend on consumers' time preference and on the technology program. Thus, different economies may follow different optimal paths! Note moreover that for $t > t^*$ countries are supposed to have reached an advanced level of development, and thus will only adopt new technologies, thus T^* does not depend on α.

It has been shown in Bertinelli et al. (2005) that once T^* has been reached, three possible outcomes can arise: (i) the rate of investment is too high compared to the self-regeneration rate of nature (γ). The economy converges to a catastrophic outcome where environmental quality reaches its lower bound, (ii) output, investment and consumption grow at constant rates, and environmental quality will steadily improve and tend to its upper bound in the long run. This case corresponds to the so-called bell-shaped

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[5] A balanced growth path is defined by a constant optimal scrapping age and constant rates of growth for the other endogenous variables.

Environmental Kuznets Curve (EKC). (iii) Last, we may end up in a situation where pollution stabilizes, environmental quality permanently improves, though never attains its upper bound, and the BGP is reached, where investment, consumption, and output grow at constant rate γ.

2.4 Transition Dynamics

Before reaching T^*, countries' scrapping rate is too low. This situation corresponds to the case where economies have initially a relatively low stock of machines. Henceforth, machines are used for periods longer than the optimal period T^*, which corresponds to the case of developing countries that do not scrap enough. In this section, we will concentrate on the transition period preceding t^*.

Contrary to Aghion and Howitt (1998, Chap.5), we note that not all the initial conditions instantaneously jump to the potential optimal scrapping path. Actually, the following necessary and sufficient conditions need to hold.

Assumption 2. The parameters must check

$$1 - \beta < \beta(1-\alpha)(\rho + q),$$

and the initial scrapping age must satisfy

$$T^* < T(0) < -\frac{1}{\gamma} \ln \left(\frac{1-\beta}{\beta(1-\alpha)(\rho+q)} \right).$$

The first condition in Assumption 2 states that during the transition period, more attention should be paid to consumption, while the second condition implies that not all the initial stock of capital can reach the potential optimal path and only economies equipped with 'sufficient' initial capital stocks have the possibility to attain it.

In the appendix, we prove the following results.

Proposition 2 *During the transition dynamics, provided Assumption 2 holds, the scrapping rule is given by*

$$T(t) = t - \frac{\rho+q}{\gamma} t - \frac{1}{\gamma} \ln \left(e^{-\gamma T(0)} - \frac{1-\beta}{\beta(1-\alpha)(\rho+q)} \left(1 - e^{-(\rho+q)t} \right) \right), \quad (12)$$

which is increasing with α and with respect to $T(0)$, but decreasing with β, while increasing with $1-\beta$. Furthermore, there exists a $t^1 \geq 0$, such that, *when $t > t^1$, $T(t)$ is decreasing with time t. The expression of t^1 can be given by*

$$t^1 = -\frac{1}{\rho+q}\ln\left(\frac{\rho+q-\gamma}{\gamma}\right) - \frac{1}{\rho+q}\ln\left(\frac{\beta(1-\alpha)(\rho+q)e^{-\gamma T(0)} - (1-\beta)}{1-\beta}\right), \tag{13}$$

which is increasing with $T(0)$ and α.

Proposition (2) provides a sufficient condition for $T(t)$ to decrease, and eventually converge to the steady state. Moreover, we can see from the previous expressions that $T(t)$ and t^1 are increasing functions of $T(0)$ and α. If the initial lifetime of machines is long and their efficiency is low (i.e. old technologies are used), it is necessary to prolong the period of use of the current machines in order to increase capital to its threshold value for $T(t)$ to decrease. Furthermore, if consumers value environmental quality in their utility function (i.e., $1-\beta$ is high), then the lifetime of machines will increase. This is so because environmentally concerned consumers will have lower investments in order to reduce pollution. By doing so they, however, also reduce output, and thus consumption and investment. Consequently, for consumption and investment to be high enough, the lifetime of machines has to be prolonged, slowing down the time when the steady state will eventually be reached.

A straightforward consequence of the above proposition is

Proposition 3 *Given an investment profile of a country, if $T(0) > T^*$, there exists a time t^0, such that, $0 < t^0 < \infty$ and $T(t^0) = T^*$, in which case $t^* = t^0$.*

For the developing economy case, the instantaneous jump to the optimal path could be impossible (even when starting from a corner solution, i.e., zero consumption and all output invested in physical capital). Instead of an immediate technology adoption, which would compensate the initial low level of vintage physical capital, there are time delays in adoption given that newer technologies are too costly. Thus, for relatively poor economies, older and relatively environmentally unfriendly machines will be employed until the optimal path is reached. One should note that for developing economies t^0 is the time where the interior solution is reached and the optimal scrapping rule starts. Obviously, different economies, endowed with different parameters, face different t^0's.

2.5 The Pollution-Output Relationship During Transition

In the previous section, we have just argued that countries adopting older technologies face delays in the timing when they can potentially reach their BGP and on top of that, their pollution-output ratio tends to be higher. As a matter of fact, our model provides a number of results in terms of the length of time $T(t)$ during which a technology is in use, and the time t^* when the BGP may be reached. In particular, we have shown that both $T(t)$ and t^* will depend on α, which measures the degree of inefficiency of older technologies. In trying to seek empirical support for these predictions, the major issue becomes that these variables of interest are unlikely to be observable or easily measurable. For instance, there are at best very crude measures of the replacement rates of technologies. Moreover, there is certainly no satisfactory measure of $T(t)$ available across time and countries.

In order to find empirical support for our model we must thus first extend our findings in terms of more measurable variables. In this regard, we rewrite our important results in terms of output and pollution. Apart from providing variables for which there are proxies, this also allows us to make our analysis comparable and place it within the now large body of empirical literature on the EKC, where the basic issue has been to determine whether countries, after having reached a 'high enough' level of development become more aware of the environment and consequently reduce pollution. [6]

Given that our main focus is on the impact of older technologies on the development path, we will restrict our empirical analysis to the case of developing countries since it is these that are the main importers of used machinery. In terms of the theoretical model this implies investigating the transition dynamics, if we hypothesize that most developing countries have not reached their BGP yet. As mentioned in the previous section, when $T(0) > T^*$, the economy starts with a relatively low stock of capital. Then, in order to reach the interior solution (and thus, the optimal path, if there is one) as soon as possible, one possibility is to invest all output. In this case, starting from a corner solution, the economy subsequently produces and pollutes according to

$$y(t) = (1-\alpha)\int_{t-T(t)}^{t} y(z)dz, \quad P(t) = \int_{t-T(t)}^{t} y(z)e^{-\gamma z}dz, \qquad (14)$$

when $0 < t < t^*$. Indeed, pollution increases with the accumulation of

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[6] Evidence on the existence of such an EKC is still under debate, as results are mixed notably according to the estimation method, measure of pollution, sample of observation. Insightful references are Dasgupta et al. (2002) and Bradford et al. (2005).

output $y(\cdot)$ during all the periods in which the machine is in use. Moreover, there is also a *delay effect* on pollution arising from output. In equation (12) we demonstrated that the vintage of machines is an increasing function of α. Taking the ratio of the expressions of pollution and output in (14) we are now able to fully characterize how this ratio behaves for different levels of α. Considering time t, the use of older technologies (i.e., with a high α), will positively affect the pollution-output ratio,

$$\frac{\partial\left(\frac{P(t)}{y(t)}\right)}{\partial\alpha}=\frac{1}{(1-\alpha)^2}\frac{P(t)}{\widetilde{y(t)}}+\frac{1}{1-\alpha}\frac{y(t-T(t))T'_{\alpha}(t)\left[\widetilde{y(t)}e^{-\gamma(t-T(t))}-P(t)\right]}{\widetilde{y(t)}^2}>0, \tag{15}$$

where $\widetilde{y(t)}=\int_{t-T(t)}^{t}y(z)dz$, and the inequality comes from the fact that $T'_{\alpha}(t)>0$ (see equation (12)) and $e^{-\gamma(t-T(t))}>e^{-\gamma z}$, $z\in[t-T(t),t]$. Thus, before reaching $t^*=t^0$, the pollution-output relationship, materialized in empirical studies by the EKC, will always be higher for dirtier technologies. Moreover, one finds that after reaching the maximum of $T(t)$ at t^1, the pollution-output ratio is decreasing over time. In fact, the derivative of $\frac{P(t)}{y(t)}$ with respect to t, where $P(t)$ and $y(t)$ are given by (14), is

$$\left(\frac{P(t)}{y(t)}\right)'=\frac{1-\alpha}{y(t)^2}\left[y(t)\int_{t-T(t)}^{t}y(z)\left(e^{-\gamma t}-e^{-\gamma z}\right)dz\right. \tag{16}$$
$$\left.+\left(1+T'(t)\right)y(t-T(t))\int_{t-T(t)}^{t}y(z)\left(e^{-\gamma z}-e^{-\gamma(t-T(t))}\right)dz.\right.$$

The two integral terms are negative, and after t^1, $1-T'(t)$ is always positive. Therefore $\left(\frac{P(t)}{y(t)}\right)'<0$, for $t^1<t<t^0$. Stated differently, countries that use older technologies will have a pollution-output relationship above countries using the newest technology. Furthermore, countries will converge possibly towards their BGP at a faster pace if α is low. This latter result immediately follows from combining (13) and (16).

From equation (16) we also know that pollution will always be an increasing function of output. As mentioned above, and detailed in Bertinelli et al. (2005), the pollution-output relationship can only decrease once the optimal scrapping age has been reached.

3 Empirical analysis

As stated earlier, we are interested in the case when developing countries use older technologies. Thus, our focus will be on the transition period, where the pollution-output relationship will always be increasing. We can rewrite an empirical version of the pollution-output relationship in a similar manner to the other empirical studies estimating the EKC

$$P(t) = \Gamma(y(t), \alpha) + \Psi(u) \tag{17}$$

where $\Gamma_y > 0$ and $\Gamma_\alpha < 0$. We allow for possible non-linearities in the pollution-output relationship by adding both a level and a squared $y(t)$ term. Also, importantly in our model $\Gamma_{y\alpha} \neq 0$ and thus one has to take account of the marginal impact of α on $y(t)$. We do so in our empirical specification by interacting α with our output measures. The final term of the RHS of (17),$\Psi(u)$, consists of unobserved factors that may be common and/or different across countries, as well as idiosyncratic shocks.

3.1 Data

In order to model the pollution-output relationship, we, as is standard in EKC studies, resort to a measure of carbon dioxide emissions as a proxy of pollutants. Specifically, the data is taken from the Carbon Dioxide Information Analysis Center compiled by Marland et al. (2003), where the earliest available data goes as far back as 1751, and extends up until 2000. Figures for total national carbon dioxide emissions from fossil-fuel burning, cement manufacture, and gas flaring are expressed in thousands of metric tons. In order to get per capita figures we divided carbon dioxide emissions by population data from Maddison (2001, 2003). It is important to note that emissions of carbon dioxide result from the combustion of organic matter. As such, potentially any activity involving combustion may produce carbon dioxide, while our data almost exclusively captures emissions from fossil fuel energy and not that due to non-fossil fuel energy, such as wood, waste, and so forth. However, despite this drawback one should note that non-fossil fuel energy generally tends to release substantially less carbon dioxide than fossil fuel. Moreover, it is widely accepted that since at least the early 19th century fossil fuels have been critical to economic growth, and have also been recognized as major contributors to environmental degradation by generating greenhouse gazes.[7]

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[7] Apart from carbon dioxide, methane and nitrous oxide are the other two important greenhouse effect gazes.

We measure output by GDP per capita in thousands of dollars. Data for this stems from Maddison (2001, 2003) and is appropriately adjusted for purchasing power parity (and expressed in 1990 International Geary-Khamis dollars).

An important aspect in finding support for our theoretical results is the use of an appropriate proxy for α, the inefficiency rate of the older vintage technology. Not surprisingly, it is be difficult to find a direct measure of this at the aggregate level, across countries, and over time. We thus resort to using a proxy, namely a country's share of used to total imported machinery and equipment goods from developed countries. One should note that Navaretti and al. (2000) use a similar measure as a proxy for vintage technology use in developing countries, although in a different context. The underlying hypothesis is that technology is embodied in the machines and equipment goods that are imported, and that older machines and equipment are characterized by more outdated technologies.

To construct such a measure we use trade data from the Eurostat Comext database for European exports and from USA Trade Online for US exports. Although we do not take account of other exporters of machinery and equipment to the developing world, one can arguably be quite confident that EU and US exports represent a substantial amount of imports into the developing world, since it is four European countries and the US which are amongst the six major worldwide exporters of machinery.[8] Comext data was available from 1988 to 1998 at the 8-digit CN (combined nomenclature) classification, where the CN classification is the common nomenclature used in export declarations in the European Community.[9] The 6 first digits of the CN are in common with the HS (Harmonized System) classification, which is the classification for which US data was available. Data on exports from the US stem from STAT-USA (USA trade online), which is part of the US Department of Commerce. US trade data was available from 1992 up until 2000 at the 10-digit HS classification. For both US and EU data we have restricted our data collection to sectors that explicitly make the distinction between used and new goods. This was the case for two-digit export groups 84 (machinery and mechanical appliances, electrical equip-

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[8] Germany, France, Italy, the UK and the US represented more than 50 per cent of machinery exports in 2003. Source: http://www.vdma.org/wps/portal/Home/en/VDMAThemen/Wirtschaft_und_Recht/VwS_20040924_Kbs_Artikel_DerdtMaBauengl?New_WCM_Context=http://www.vdma.org/ilwwcm/connect/Home/en/VDMAThemen/Wirtschaft_und_Recht/VwS_20040924_Kbs_Artikel_DerdtMaBauengl

[9] One should note that there are changes to the nomenclature every year. For the present study, we have used the classification of the latest available year.

ment, parts thereof, sound recorders and reproducers, television image and sound recorders and reproducers, and parts and accessories of such articles) and 87 (vehicles other than railway or tramway rolling-stock, and parts and accessories thereof) of the HS classification. In order to get a measure of the importance of used goods imports in our set of developing countries, we computed the aggregate share of used relative to total imports of machinery and equipment by importing country.[10]

One should note that, while we ideally would have liked to study the role of technology imports on the pollution-output relationship over a long time period so as to capture a substantial proportion of the long run within country growth paths, combining our individual variables left us with a common time span covering only seven years (1992-1998) for about 104 developing countries. Thus, much of our data variability is likely to stem from cross-country variation.

Table 1 provides the means and standard deviations of our variables by developing country groups. As can be seen, GDP per capita is, in accordance with expectations, highest for Eastern European countries. Interestingly, the average GDP per capita in sub-Saharan Africa is higher than in South Asia. This is so because the latter group includes essentially the poorest of the Asian countries, notably Bangladesh, Nepal and Pakistan, which have GDP per capita figures way below average African GDP per capita. Comparing carbon dioxide emissions per capita, one finds that the poorest countries are also those polluting the least. Finally, the share of imported used goods varies between 19 and 44 per cent, thus pointing to substantial dispersion across countries. In this regard, Middle East and Northern Africa import the lowest, while Eastern European import the highest share of used machinery and equipment.

3.2 Econometric Results

In order to econometrically assess our theorectical predictions, we use our pooled cross-country data for the period 1992 to 1998 to estimate specification (17). One important aspect in (17) are the unobserved factors common and/or different across counties. In order to control for the common unobserved possibly time varying factors across countries we included year dummies. Ideally one would also like to explicitly control for unobserved differences across countries. One way to purge these factors, at least the time invariant ones, would be to run a fixed effects estimator. Unfortu-

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[10] A complete list of countries can be retrieved in the appendix.

nately, the short time period for which all our variables were available made this unfeasible since there was only little time variation within countries over our constructed sample period. As a matter of fact, when we did experiment with such a fixed effects estimator, which can capture only the within country variation of our data, the coefficients on all explanatory variables were insignificant. In particular this would have implied that there was no relationship between output and solution, a result that runs contrary essentially to all of the empirical studies of the EKC. We thus, despite its potential drawbacks, used standard OLS to estimate our empirical specification. However, we did include a set of six regional dummies to control for time invariant region specific unobservable effects.[11]

The results of estimating (17) are displayed in Table 2. As expected, the positive and highly significant coefficient of per capita GDP points towards an increasing effect of output on pollution. This comes as no surprise, since it is well known that our measure of pollutant, namely carbon dioxide, crucially depends on energy consumption, which in turn is a major input into production.

Our theoretical model has shown that under some parameter conditions we may end up with a decreasing pollution-output curve on the right hand side, when countries have reached a high enough level of development. This echoes the empirical artifact first described in the seminal paper by Grossman and Kruger (1995), where it was shown, using first and second order terms of GDP per capita, that the link between per capita output and pollution follows a bell-shaped pattern across countries. In Column 2 we allow for such possible non-linearity by introducing the squared value of GDP per capita in our estimated specification. As can be seen from the coefficient on the squared term, this supports the existence of a bell-shaped relationship, which would tend to suggest that lower income regions are 'too poor to be green', and only when these become rich enough will the benefits from a clean environment outweigh its costs. One should note, however, that if one uses the estimated coefficients then the maximum of this bell-shaped curve lies around \$15000, implying that over 95 per cent of the countries in our sample have not yet reached their BGP.[12]

In Column 3 we have added our main variable of interest, namely the share of used imported goods. This turns out to insignificantly impact on carbon dioxide generation. However, as noted above, the cross derivative

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[11] See Table 1 for the regional groupings.

[12] It is important to recall here that according to our theoretical results, if there is a bell-shaped EKC, the maximum can only be attained when countries have reached their optimal scrapping age.

of pollution with respect to output and the share of used imported goods differs from zero in our theoretical model. In order to allow for this we add an interaction term of output with the share variable in the regression in the fourth column, the sign of which turns out to be positive and statistically significant. Thus the marginal impact of GDP per capita on pollution will increase with the share of used in total imported machinery.

In Column 5 we also included an interaction term of the share variable with the squared value of GDP per capita in order to detect whether the use of imported technologies has an impact on the curvature of the relationship. Accordingly, one finds that while this renders the interaction with the level of GDP per capita insignificant, the interaction term between GDP per capita squared and the share variable is positive and statistically significant. Thus, importing older and dirtier technologies changes the curvature of the pollution-output relationship. More precisely, a higher share value will reduce the concavity of the pollution-output relationship.

In order to gauge the economic importance of importing used technologies via the second hand capital goods market and its effect on the pollution-output relationship, we conducted simple graphical simulations with our estimated coefficients. More precisely, we used the significant coefficients of the last column of Table 2 in order to simulate the effect that various degrees of used capital goods import intensity will have on the pollution-output relationship.[13] As shown in Table 1, the share of imported used machinery varied considerably across our six regional groups. We thus experimented with holding fixed different values of the share variable along this range (namely 0, 15, 30, and 45 per cent), while letting GDP per capita levels vary to produce corresponding pollution emission figures using our estimated (significant) coefficients. The results of this exercise are given in Figure 1. As is apparent, the pollution-output relationship will differ widely according to the type of technology that is imported. When holding the share of imported used goods fixed at zero, then the maximum of the pollution-output curve is reached for a GDP per capita range of $10,000-$11,000/. As the import of used machinery increases, the value of the share variable also rises, considerably changing the shape of the curve. Thus, as is apparent, the maximum of the pollution-output curve is an increasing function of the share of used imported goods. As a matter of fact, when we set the share of used imported goods to anything above 63.3 per cent, the relationship becomes monotonically increasing; i.e., an increase in output per

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[13] For convenience's sake we abstracted from any regional and year specific effects, as well as the constant, so that all the curves cross the origin of the x and y-axis.

capita will always induce a more than proportional increase in pollution.

4 Conclusion

The United Nations Framework Convention on Climate Change has stated that developed countries "shall take all practicable steps to promote, facilitate and finance, as appropriate, the transfer of, or access to, environmentally sound technologies and know-how [to developing countries]" (Article 4.5, United Nations Framework Convention on Climate Change, 1992).[14] In the present study we provide evidence on how adoption of old technologies may delay achieving sustainable economic development. Starting from a vintage capital model, we hypothesize that investment in new machines is polluting, but pollution per output decreases with newer technologies. If the share of imported used goods is high, periods of high pollution per output will be prolonged. As a consequence, if countries ever reach a balanced growth path, this will happen later in time. Moreover, the less efficient older technologies are, the longer the period of time during which old technologies will be kept in use. We find econometric support for our theoretical results using data of proxies for pollution generation, output, and vintage capital use for a set of developing countries.

Arguably our results have important policy implications. More precisely, recourse to older technologies may serve short-term economic goals of developing countries suffering from a lack of capital. However, static gains will be at the expense of long term consequences in terms of higher rates of pollution and time delays in order to possibly reach the balanced growth path. Pressures put on developing countries in order to reduce their barriers to imports of used goods should thus be balanced against the costs of supplementary pollution that the use of older technology will induce. In this regard it is noteworthy that the United Nations have now explicitly recognized the potential importance of this issue and provide support to projects enabling the transfer of 'environmentally sound technologies' to developing countries.[15]

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[14] The full document of the convention can be gathered at http://unfccc.int/resource/docs/convkp/conveng.pdf.

[15] See Metz et al. (2005) for a detailed account.

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5 Appendix

5.1 Optimal control problem is section 2.2

The market clearing condition (4) can be denoted

$$\begin{aligned}\mathcal{L}(i(t),T(t),E(t)) &= \int_0^\infty e^{-\rho t}\left[\beta\left((1-\alpha)\int_{t-T(t)}^{t-D} i(z)dz - i(t)\right) + (1-\beta)E(t)\right]dt \\ &- \int_0^\infty e^{-\rho t}\mu(t)\left[\dot{E}(t) + qE(t) + \int_{t-T(t)}^{t-D} i(z)e^{-\gamma z}dz\right]dt.\end{aligned}$$

Integrating by parts and changing the order of the integrals, it follows

$$\begin{aligned}\mathcal{L} &= \int_0^\infty \int_{t+D}^{t+J(t)} \beta(1-\alpha)i(t)e^{-\rho z}dzdt - \int_0^\infty \beta e^{-\rho t}i(t)dt \\ &+ \int_0^\infty (\dot{\mu}(t) - \rho\mu - q\mu + (1-\beta))E(t)e^{-\rho t}dt \\ &- \int_0^\infty \int_{t+D}^{t+J(t)} i(t)e^{-\gamma t}\mu(z)e^{-\rho z}dzdt + E(0)\mu(0) \\ &+ \int_{-T(0)}^{-D} \int_0^{t+D)} i(t)e^{-\gamma t}\mu(z)e^{-\rho z}dzdt \\ &+ \int_{-T(0)}^{0} \int_{t+D}^{t+J(t)} i(t)e^{-\gamma t}\mu(z)e^{-\rho z}dzdt \\ &+ \int_{-T(0)}^{-D} \int_0^{t+D)} \beta(1-\alpha)i(t)e^{-\rho z}dzdt + \int_{-T(0)}^{0} \int_{t+D}^{t+J(t)} \beta(1-\alpha)i(t)e^{-\rho z}dzdt.\end{aligned}$$

Notice that before $t = 0$, all the endogenous variables are given, so the last 4 terms in $\mathcal{L}$ will have no effect on the first order conditions, except if we provide the initial conditions.

The first order conditions with respect to the control variables $i(t)$, $J(t)$, and the state variable $E(t)$ will be:

$$\frac{\partial \mathcal{L}}{\partial i(t)} = 0, \quad \frac{\partial \mathcal{L}}{\partial J(t)} = 0, \quad \frac{\partial \mathcal{L}}{\partial E(t)} = 0. \quad \spadesuit$$

5.2 Proof of Proposition 2

From (8), we have that $\mu(0) = (1-\alpha)\beta e^{-\gamma T(0)}$. Hence it is easy to get

$$\mu(t) = e^{(\rho+q)t}\left[\beta e^{-\gamma T(0)} - \frac{1-\beta}{(1-\alpha)(\rho+q)}\left(1 - e^{-(\rho+q)t}\right)\right].$$

Combing $\mu(t)$ with (8), we have

$$e^{-\gamma T(t)} = e^{(\rho+q-\gamma)t}\left[e^{-\gamma T(0)} - \frac{1-\beta}{\beta(1-\alpha)(\rho+q)}\left(1-e^{-(\rho+q)t}\right)\right].$$

Hence,

$$T(t) = T(t;T(0)) = t - \frac{\rho+q}{\gamma}t - \frac{1}{\gamma}\ln\left(e^{-\gamma T(0)} - \frac{1-\beta}{\beta(1-\alpha)(\rho+q)}\left(1-e^{-(\rho+q)t}\right)\right).$$

Furthermore,

$$\frac{\partial T(t;T(0))}{\partial T(0)} = \frac{e^{-\gamma T(0)}}{e^{-\gamma T(0)} - \frac{1-\beta}{\beta(1-\alpha)(\rho+q)}\left(1-e^{-(\rho+q)t}\right)} > 0,$$

and

$$T'(t) = 1 - \frac{\rho+q}{\gamma} + \frac{1}{\gamma}\frac{\frac{1-\beta}{\beta(1-\alpha)}e^{-(\rho+q)t}}{e^{-\gamma T(0)} - \frac{1-\beta}{\beta(1-\alpha)(\rho+q)}\left(1-e^{-(\rho+q)t}\right)},$$

where the difference of the first two terms on the right hand side is strictly negative and less than $-\frac{q}{\gamma}$, due to $\rho > \gamma$, but the last term is positive. However,it is easy to check that the last term tends to zero when $t \to \infty$. Therefore, there exists time t^1, such that, $T'(t^1) = 0$, and $T'(t) < 0$ when $t > t^1$. Set $T'(t) = 0$, we have the explicit form of t^1, and the effect of $T(0)$ and α on t^1 are straightforward.

The effect of α can be easily done as following

$$\frac{\partial T(t;T(0),\alpha)}{\partial \alpha} = \frac{1}{\gamma(1-\alpha)^2}\frac{\frac{1-\beta}{\beta(\rho+q)}(1-e^{-(\rho+q)t})}{e^{-\gamma T(0)} - \frac{1-\beta}{\beta(1-\alpha)(\rho+q)}\left(1-e^{-(\rho+q)t}\right)} > 0.$$

The β effect can be done in the same way. ♠

5.3 Country list

Latin America ANTIGUA & BARBUDA, ARGENTINA, BARBADOS, BELIZE, BOLIVIA, BRAZIL, CHILE, COLOMBIA, COSTA RICA, CUBA, DOMINICA, DOMINICAN REPUBLIC, ECUADOR, EL SALVADOR, GRENADA, GUATEMALA, GUYANA, HAITI, HONDURAS, JAMAICA, MEXICO, NICARAGUA, PANAMA, PARAGUAY, PERU, ST. VINCENT & THE GRENADINES, TRINIDAD AND TOBAGO, URUGUAY, VENEZUELA

Middle East and North Africa ALGERIA, EGYPT, IRAN, JORDAN, LEBANON, MOROCCO, OMAN, SAUDI ARABIA, SYRIA, TUNISIA, TURKEY, YEMEN

Eastern Europe and Central Asia ALBANIA, BULGARIA, HUNGARY, POLAND

South Asia BANGLADESH, INDIA, NEPAL, PAKISTAN, SRI LANKA

East Asia and Pacific CAMBODIA, CHINA, FIJI, INDONESIA, LAOS, MALAYSIA, MONGOLIA, PAPUA NEW GUINEA, PHILIPPINES, THAILAND, VIET NAM

Sub-Saharan Africa ANGOLA, BENIN, BOTSWANA, BURKINA FASO, BURUNDI, CAPE VERDE, CENTRAL AFRICA, CHAD, COMOROS, COTE D IVOIRE, DJIBOUTI, EQUATORIAL GUINEA, ERITREA, ETHIOPIA, GABON, GAMBIA, GHANA, GUINEA, KENYA, MADAGASCAR, MALAWI, MALI, MAURITANIA, MAURITIUS, MOZAMBIQUE, NAMIBIA, NIGER, NIGERIA, CAMEROON, RWANDA, SAO TOME & PRINCIPE, SENEGAL, SEYCHELLES, SIERRA LEONE, SOUTH AFRICA, SUDAN, SWAZILAND, TOGO, UGANDA, TANZANIA, ZAIRE, ZAMBIA, ZIMBABWE

Table 1: Descriptive statistics

	# of observations	**CO^2/capita**	**GDP/capita**	**Share of imp. used goods**
Latin America	*199*	*0.697*	*5909.8*	*0.369*
		(0.804)	*(3164.4)*	*(0.203)*
Middle East and North Africa	*72*	*0.809*	*4494.1*	*0.191*
		(0.616)	*(2246.1)*	*(0.152)*
Eastern Europe	*28*	*1.463*	*6239.8*	*0.443*
		(0.852)	*(2342.3)*	*(0.284)*
South Asia	*35*	*0.126*	*1912.8*	*0.249*
		(0.094)	*(0.617)*	*(0.227)*
East Asia and Pacific	*63*	*0.454*	*3958.6*	*0.299*
		(0.434)	*(2274.7)*	*(0.274)*
Sub-Sahara Africa	*267*	*0.232*	*2333.2*	*0.342*
		(0.726)	*(2680.5)*	*(0.301)*

Notes: Standard deviations in parenthesis; averages over 1992-1998 period.

Table 2: Econometric Results

Dependent variable: CO2/capita

	(1)	(2)	(3)	(4)	(5)
GDP/capita	*0.135**** *(0.009)*	*0.218**** *(0.026)*	*0.136**** *(0.009)*	*0.112**** *(0.013)*	*0.255**** *(0.038)*
(GDP/capita)^2		*-0.007**** *(0.002)*			*-0.012**** *(0.003)*
Share imp. used goods			*0.021* *(0.095)*	*-0.269** *(0.144)*	*0.088* *(0.193)*
GDP/capita*Share				*0.087**** *(0.033)*	*-0.134* *(0.092)*
(GDP/capita)^2*Share					*0.020*** *(0.008)*
Time dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Regional dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Observations	*664*	*664*	*664*	*664*	*664*
Adj. R-squared	*0.37*	*0.38*	*0.37*	*0.38*	*0.39*

Notes : dependent variable is CO2/capita growth. Standard errors in parentheses. ***, **, and * indicate 1, 5, and 10 per cent significance levels.

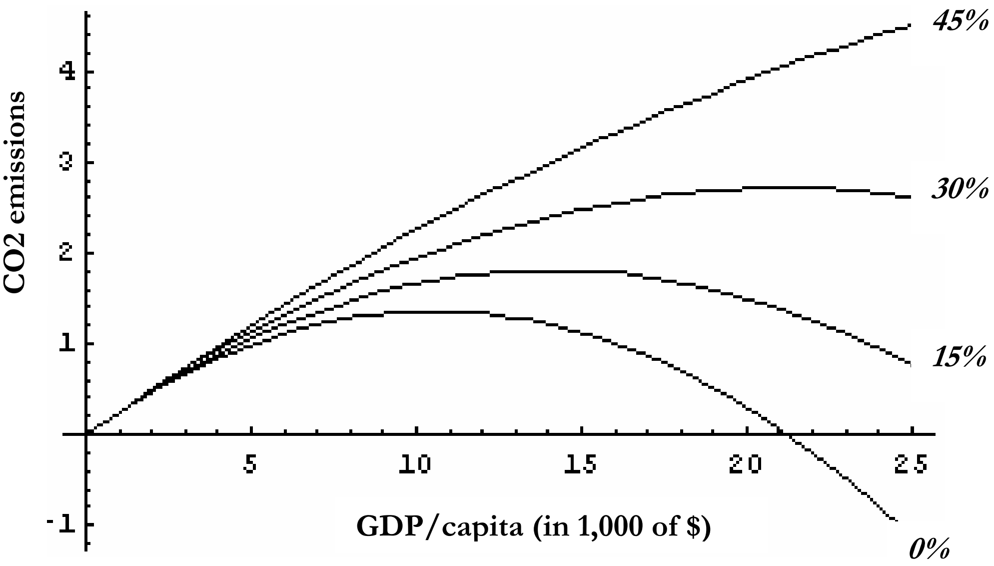

Figure 1: Simulations of the Pollution-Output Relationship for Various Imported Used Machinery Intensities

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