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Economic growth and pollution in the long run: the case of carbon dioxide

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Abstract

Does economic growth result in reduced pollution in the long run? In this paper, an extension of Andreoni and Levinson's (2001) theoretical model is presented to demonstrate that an environmental Kuznets curve may be generated by increased ability to adopt low-emission technologies at higher income levels. Evidence on the determinants of carbon dioxide emissions changes for OECD countries over the period 1961-2004 highlights the importance of technology adoption in explaining whether countries have achieved emissions reductions with long-run economic growth. Given that technology adoption is affected by policy decisions and other factors in addition to income level, the environmental Kuznets curve hypothesis is more appropriately framed as a conditional relationship.

1. Introduction

Does economic growth result in reduced pollution in the long run? The potential existence of an environmental Kuznets curve (EKC), whereby environmental damage at first increases and then decreases as a country develops, has captured significant attention since the early 1990s. Evidence on the existence of the EKC remains disputed, and evidence on the mechanisms via which EKCs have emerged remains limited. Significant heterogeneity in the emissions-income paths of different countries indicates that the long-run relationship between pollution and income may be a conditional relationship.

This paper builds on Andreoni and Levinson's (2001) theoretical model to demonstrate that income growth may lead to emissions reductions if there is emissions-reducing technical progress with increasing incomes. A test of whether this mechanism has been relevant in explaining country-specific EKCs is carried out for the case of anthropogenic emissions of carbon dioxide (CO_2). Evidence is presented that the ability to adopt low-carbon electricity generation technologies (specifically, nuclear power and renewable power electricity generation technologies) is a positive function of income. A comparison of the experiences of Sweden and Australia is used to highlight the importance of policies, in addition to income, in explaining technology adoption and emissions-income path trajectories. Using a new estimation approach, evidence indicating that the adoption of low-emission technologies has been an important driver of country-specific EKCs is presented. Estimation is carried out using data for Organisation for Economic Co-operation and Development (OECD) countries for the period 1961-2004.

The use of the term ‘long run’ deserves comment. If pollution were to increase indefinitely with economic growth, in the very long run either pollution or economic growth would need to be curtailed, because there are limits to the world’s capacity to absorb pollution (Lopez 1994). For the purpose of this paper, the long run is considered to be the period from the commencement of global industrialisation to the present.

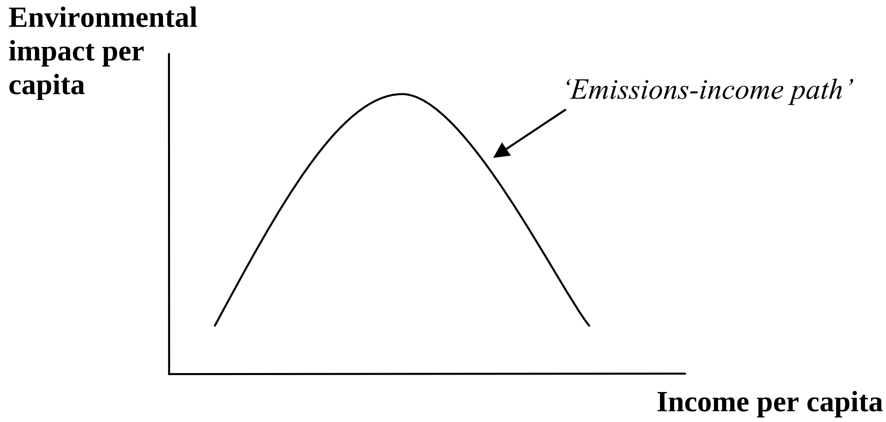
The organisation of this paper is as follows. In section 2, theoretical reasons for why an EKC may emerge are discussed, and the potential for an EKC to be induced by the adoption of emission-reducing technologies at higher income levels is demonstrated. A review of the approach taken in prior studies in the EKC literature is presented in section 3. Section 4 identifies and explores heterogeneity among CO_2 emissions-income paths of OECD countries, and the importance of the adoption of lower-emission technologies in explaining this heterogeneity. In section 5, a new approach to estimating the drivers of emissions changes is detailed, and data are discussed. Estimation results are presented in section 6. Section 7 concludes.

2. Drivers of the EKC

2.1 Six drivers

Pollution, a by-product of economic activity, increases with a country’s income during the initial stage of development. The EKC hypothesis is that, after a point, pollution (and environmental impact, more generally) starts to reduce with continued economic growth. The relationship between per capita pollution and per capita income (termed an ‘emissions-income path’ in this paper) under the EKC hypothesis is presented in Figure 1.

Fig. 1. The EKC hypothesis



There are six potential underlying drivers of a downturn in a country's emissions-income path consistent with the EKC hypothesis:

1. ***Increased ability to develop and adopt lower-emission technologies*** with increasing income;
2. ***Increasing returns to scale in abatement*** (Andreoni and Levinson 2001);
3. ***Income elasticity of demand for environmental quality***;
4. ***Income elasticity of demand for low emissions-intensity products***, such as services;
5. ***The movement of polluting industries overseas*** in search of lower costs as a nation develops, and resultant changes in trade patterns. These lower costs include lower environmental costs (the 'pollution haven hypothesis'); and
6. ***Approaching environmental limits*** as countries develop, whereby a) environmental deterioration caused by economic growth reaches such a high level that a response to reduce pressure on the environment is increasingly imperative; or b) the finite nature of polluting inputs (such as fossil fuels) forces a transition away from the most polluting practices.

All else equal, and with abatement technology that has constant returns to scale, economic growth results in an increase in the scale of economic activity and the pollution that is associated with economic activity (this is known as the 'scale effect'). If increasing returns to scale in abatement technology exist (potential driver 2), the scale effect would diminish with continued growth. The other potential underlying drivers (1, 3-6) can counteract and potentially exceed the scale effect, in one of two ways (Grossman 1995, Stern 2004). First, they may alter the composition of economic output toward activities that are less emission-intensive (the 'composition effect') (drivers 3-6). Second, they may reduce the emissions intensity of any given output, via either the 'input effect' (the substitution of black coal for brown coal in electricity generation results in reduced CO_2 emissions, for example; drivers 3 and 6) or the 'technique effect' (the adoption of lower-emission technologies or practices; driver 1). Policies are an important channel via which the six underlying factors may result in emissions reductions via the composition, input or technique effects. There is not yet clear evidence on which of these effects have been important in explaining observed reductions in CO_2 emissions in certain OECD countries.

2.2 The Andreoni-Levinson model

A number of economic models of how an EKC may emerge have been presented. Among the most influential of these is a model presented by Andreoni and Levinson [AL] (2001). In the AL (2001) model, increasing returns to scale in pollution abatement can produce an emissions-income path in the shape of an EKC. The model is a seminal contribution and dominates other models in terms of parsimony; it generates an EKC without requiring "dynamics, predetermined patterns of economic growth, multiple equilibria, released constraints, political institutions, bundled commodities, irreversible pollution, or even externalities" (AL 2001, p. 271).

The AL (2001) model features a representative agent who attains utility (*U*) from consumption of a private good (*C*) and a 'bad', pollution (*P*). The agent's preferences are represented by:

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

where $U_C > 0$, $U_P < 0$ and *U* is quasiconcave in *C* and *-P*. Pollution is produced jointly with consumption. The agent can alleviate pollution via environmental effort, *E*. Pollution is given by:

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

where $P_C > 0$, $P_E < 0$. The agent has an endowment, *M*, that can be spent on (price-normalized) *C* and *E*. The budget constraint is thus $M = C + E$.

AL (2001) adopted the following functional forms in their exposition:

$$U = C - zP \tag{3}$$

$$P = C - C^{\alpha} E^{\beta} \tag{4}$$

where utility is linear and additive in *C* and *P*, with constant marginal utility of consumption (=1), marginal disutility of pollution (=*z*), and parameters $\alpha, \beta > 0$.

The C term in the pollution equation represents gross pollution before abatement (with constant pollution intensity of consumption), and the Cobb-Douglas component is an abatement function. To simplify the algebra, AL (2001) assume $z = 1$ and show that the agent maximizes utility by setting:

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

(5)

The first and second differentials of (5) are:

$$\frac{\partial P^*(M)}{\partial M} = \frac{\alpha}{\alpha+\beta} - (\alpha+\beta)^{1-\alpha-\beta}\alpha^{\alpha}\beta^{\beta}M^{\alpha+\beta-1}$$

(6)

$$\frac{\partial^2 P^*(M)}{\partial M^2} = -(\alpha+\beta-1)(\alpha+\beta)^{1-\alpha-\beta}\alpha^{\alpha}\beta^{\beta}M^{\alpha+\beta-2}$$

(7)

If there are increasing returns to scale in abatement ($\alpha+\beta>1$), Eq. (5) is strictly concave and the emissions-income path can resemble an EKC. If there are decreasing returns to scale in abatement ($\alpha+\beta<1$), the emissions-income path is strictly convex. If constant returns to scale exist ($\alpha+\beta=1$), the emissions-income path is linear. AL (2001) thus concluded that if increasing returns to scale to an abatement technology exists, a country's emissions-income path may take the shape of an EKC.

The AL (2001) model provides a valuable and clear framework via which to examine the relationship between pollution and income. Attention to further features of the model appears deserved.

2.3 An EKC due to technical progress in abatement

Technical progress in abatement with increasing incomes may also produce an EKC-style downturn in emissions in the AL (2001) model. To see this, I add an abatement productivity term, *A(M)*, with $A'(M) > 0$, to Eq. (4).[1] The pollution function becomes:

$$P = C - A(M)C^{\alpha}E^{\beta} \tag{8}$$

where $A(M)C^{\alpha}E^{\beta}$ is the abatement term. The optimum levels of *C* and *E* remain unchanged in this new specification, and the optimum level of pollution becomes:

$$P^{*}(M) = \left(\frac{\alpha}{\alpha+\beta}\right)M - A(M)\left(\frac{\alpha}{\alpha+\beta}\right)^{\alpha}\left(\frac{\beta}{\alpha+\beta}\right)^{\beta}M^{\alpha+\beta} \tag{9}$$

Adopting the functional form $A(M) = aM \;\; (a > 0)$, the first and second differentials of Eq. (9) are:

[1] In the empirical sections to follow, the adoption of emissions-reducing technology is considered to be equivalent to abatement productivity improvements. Evidence is provided that emissions-reducing technology adoption is indeed a positive function of income, but recognition is also given to the fact that technology adoption is also a function of other variables, such as policy settings.

$$\frac{\partial P^*(M)}{\partial M} = \frac{\alpha}{\alpha+\beta} - a(\alpha+\beta+1)\left(\frac{\alpha}{\alpha+\beta}\right)^{\alpha}\left(\frac{\beta}{\alpha+\beta}\right)^{\beta} M^{\alpha+\beta}$$

(10)

$$\frac{\partial^2 P^*(M)}{\partial M^2} = -a(\alpha+\beta)(\alpha+\beta+1)\left(\frac{\alpha}{\alpha+\beta}\right)^{\alpha}\left(\frac{\beta}{\alpha+\beta}\right)^{\beta} M^{\alpha+\beta-1} < 0$$

(11)

Eq. (9) is thus a strictly concave function, irrespective of whether $\alpha+\beta>1$. Abatement technology that is endogenous to income (or, equivalently, increased adoption of emission-reducing technologies at higher incomes) is consequently a means via which the technique effect can come to dominate the scale effect, and the emissions-income path in the AL (2001) model can take the shape of an EKC. This can occur even without increasing returns to scale to abatement. Whether this mechanism has been important in explaining how some countries have achieved EKC-style reductions in CO_2 emissions will be explored in the empirical sections of this paper.

2.4 Likely heterogeneity in emissions-income paths

An additional observation to be made with reference to the AL model, and one that is relevant in considering the standard empirical approach taken in the EKC literature of attempting to identify a common emissions-income turning point, is that emissions-income paths for any pollutant are likely to vary across countries. The shape of the emissions-income path, and the income level at which any EKC turning point occurs, depends on structural parameters $\alpha, \beta,$ and a. Cross-country differences in structural parameters would mean that countries do not share a common emissions-income path (see also Brock and Taylor 2004). Countries that do experience EKCs need not share the same emissions-income turning point.

3. Prior empirical studies

The primary methodology employed in EKC studies has been econometric estimation of emissions-income equations of the form:

$$P_{c,t} = \gamma_0 + \gamma_1 Y_{c,t} + \gamma_2 Y_{c,t}^2 + \mathbf{x}_{c,t} + \varepsilon_{c,t} \tag{12}$$

where *P* is usually emissions per capita of some pollutant in country *c* in year *t*, *Y* is gross domestic product (GDP) per capita, $\mathbf{x}$ is a vector of control variables and ε is an error term. Researchers have often included country and time fixed effects in estimations of Eq. (12), and have used a variety of estimation techniques (ordinary least squares, two-stage least squares, cointegration), functional forms (some have, for instance, included a cubic term, or used $Y^{0.5}$ instead of Y^2), and data sets (cross-sectional, panel and time-series). Empirical research has generally found evidence of an EKC for local and regional pollutants, such as sulfur, but generally failed to find conclusive evidence of a common EKC for CO_2, a global pollutant.[2] The robustness of prior empirical findings in the search for a globally-common EKC has, however, been strongly challenged (see Stern 2004).

[2] See Grossman and Krueger (1995), Panayotou (1993, 1997), Selden and Song (1994), Shafik (1994), Cole et al. (1997), Kaufmann et al. (1998), Torras and Boyce (1998), List and Gallet (1999), and Markandya et al. (2006) for the case of sulfur, and Stern and Common (2001) for a contrasting result; and Shafik (1994), Holtz-Eakin and Selden (1995), Moomaw and Unruh (1997), Dijkgraaf and Vollebergh (2005), Azomahou et al. (2006), and Wagner (2006) for the case of CO_2, and Schmalensee (1998) for a contrasting result.

In attempting to estimate a globally-common, time-invariant and differentiable emissions-income path (with country fixed level effects), much of the EKC literature has assumed a very aggregate model of homogenous income determinism that appears to be unlikely to hold in reality. Tests of parameter homogeneity have indeed rejected the commonly assumed "isomorphic pattern of countries in terms of their relationship between emissions and income" (Dijkgraaf and Vollebergh 2005, p. 230; see also List and Gallet 1999). Little attention has been paid to explaining the significant heterogeneity of country experiences or the mechanisms via which emissions reductions successes have occurred.[3] As a consequence, much remains to be learnt about the conditions under which the EKC hypothesis is empirically validated.

In the next three sections, an investigation into whether emissions-reducing technical change with increasing incomes has played a role in explaining how CO_2 emissions-income paths can take the shape of an EKC is presented. CO_2, a greenhouse gas for which anthropogenic emissions arise primarily from the combustion of fossil fuels, provides an important case study given the risks associated with human-induced climate change.[4] OECD countries serve as a useful sample of countries for the purposes of this study because the EKC hypothesis can only be tested for countries that have achieved a certain income level (those that

[3] For example, some papers on CO_2 emissions, such as Moomaw and Unruh (1997) and Azomahou et al. (2006), do not mention the words 'nuclear' or 'renewable', despite the fact that the adoption of these low-carbon energy systems has had significant implications for emissions trajectories.

[4] CO_2 is also released from other activities such as agriculture and land-use change. Data to be analysed here do not include emissions from these other sources.

have achieved economic growth over a sustained period). OECD countries contributed 54 percent of global CO_2 emissions from the burning of fossil fuels and the manufacture of cement over the period 1961-2004 (World Bank 2008).

4. Heterogeneous CO_2 emissions-income paths and the role of technology adoption

Global CO_2 emissions are projected to continue to increase over coming decades, driven primarily by increasing emissions in developing countries associated with rapid development and population expansion (Stern 2006). While developing countries maintain an upward-sloping emissions trajectory, a number of OECD countries have achieved emissions reductions in recent decades (and particularly since 1970).

Table 1 presents changes in per capita CO_2 emissions from fuel combustion for OECD countries over the period 1970-2004 and other summary statistics. All 30 current member countries of the OECD have achieved positive real per capita GDP growth over this period. All but three (Mexico, Poland, Turkey) are classified by the World Bank (2008) as high-income economies. Thirteen OECD countries have experienced per capita CO_2 emissions reductions since 1970. These countries are led by Luxembourg and Sweden, which reduced per capita CO_2 emissions by 50 percent and 46 percent, respectively, over the period 1970-2004.

Table 1. Per capita CO_2 emissions (from fuel combustion) changes in OECD countries, 1970-2004

Country	% change in emissions per capita	Year of highest per capita emissions	Per capita emissions, 2004 (tons per capita)	Average real per capita GDP growth rate (per cent per annum)
Luxembourg	-49.9	1970	24.5	3.1
Sweden	-46.1	1970	6.0	1.7
Czech Republic*	-24.3	1987	11.6	..
France	-23.4	1973	6.2	2.0
Denmark	-21.9	1996	9.4	1.9
United Kingdom	-19.8	1973	9.0	2.1
Germany	-18.8	1979	10.3	2.0
Slovak Republic*	-18.5	1980	7.0	..
Poland	-13.0	1987	7.8	..
Belgium	-11.3	1973	11.0	2.2
United States (US)	-4.6	1973	19.7	2.1
Hungary	-2.6	1978	5.7	2.6
Switzerland	-0.5	1973	6.0	0.9
Canada	10.5	2003	17.2	1.9
Netherlands	15.3	1979	11.4	1.9
Iceland	18.4	1996	7.7	2.7
Norway	23.4	1999	7.9	2.9
Japan	36.2	2003	9.4	2.4
Finland	46.6	2003	12.9	2.5
Austria	47.6	2003	9.2	2.3
Italy	48.6	2003	7.7	2.2
Ireland	55.3	2001	10.4	4.2
Australia	57.1	2000	17.6	1.8
New Zealand	69.1	2003	8.4	1.2
Mexico*	84.1	1998	3.6	1.6
Spain	136.8	2004	7.7	2.4
Turkey	172.9	2000	2.9	2.1
Greece	246.5	2003	8.5	2.1
Portugal	287.8	2002	5.7	2.8
Korea, Rep.*	522.6	2004	9.7	5.7

Source: International Energy Agency (IEA) (2007a), World Bank (2008). Ordered by column 2. Four countries marked with a *: % change in CO_2 emissions per capita are for 1971-2004.

The 13 OECD countries that achieved reductions in per capita CO_2 emissions over the period 1970-2004 did so primarily as a result of reductions in the carbon intensity of energy use. [5] These reductions were achieved in large part via the adoption of low-

[5] All 13 countries experienced reductions in the carbon intensity of energy use over the period 1970-2004. Sweden, for example, reduced its carbon intensity of energy use by 57 per cent. Only four OECD countries (the Czech Republic, Denmark, Luxembourg and Poland) had lower energy use per capita in 2004 than in 1970. A decomposition of CO_2 emissions indicate that even in these four countries, the reduction in the carbon intensity of energy use exceeded the reduction in energy use per capita over the

carbon energy generation technologies. Ten of the 13 countries substituted heavily toward nuclear power (Sweden, the Czech Republic, France, the United Kingdom, Germany, the Slovak Republic, Belgium, the US, Hungary, and Switzerland). These substitutions to nuclear power mostly predated heightened concerns about the effects of global warming, but had important implications for emissions of pollutants from fossil fuels, including CO_2. One of the 13 countries substituted significantly toward wind power (Denmark). Luxembourg's significant emissions reductions were achieved in large part via a restructuring of the iron and steel industry, and the phasing out of the use of coal allowed by the replacement of blast furnaces with electric arc furnace technology (IEA 2005).

Globally, high-income countries have been at the forefront of the uptake of nuclear and non-hydro renewable generation technologies (primarily, wind; see Table 2).[6] There thus appears to be evidence that lower-emissions technology adoption is indeed endogenous to income level, as modeled in the AL (2001) model extension here. This evidence supports findings elsewhere that per capita income is an important determinant of technology development and adoption for a range of technologies, from telephones to passenger cars (see Comin and Hobijn 2004). The high costs associated with research and development and the size of capital investments in the energy sector are reasons for technology adoption in the energy sector being a particularly strong positive function of income level. (Both nuclear and wind technology are characterised by high capital costs relative to operating costs; nuclear

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period. This indicates that the composition effect may be of less importance in explaining CO_2 emissions reductions than the technique and/or input effects.

[6] Unreported regression results indicate that the *change* in the nuclear and the wind shares of electricity production is also a positive function of per capita income.

technology, in particular, requires significant capital investment and a highly skilled workforce.) The greater ability and propensity of countries that have achieved significant economic growth to develop and adopt modern and low-emission technologies thus appears to be a crucial explanator of any EKC effect for carbon.

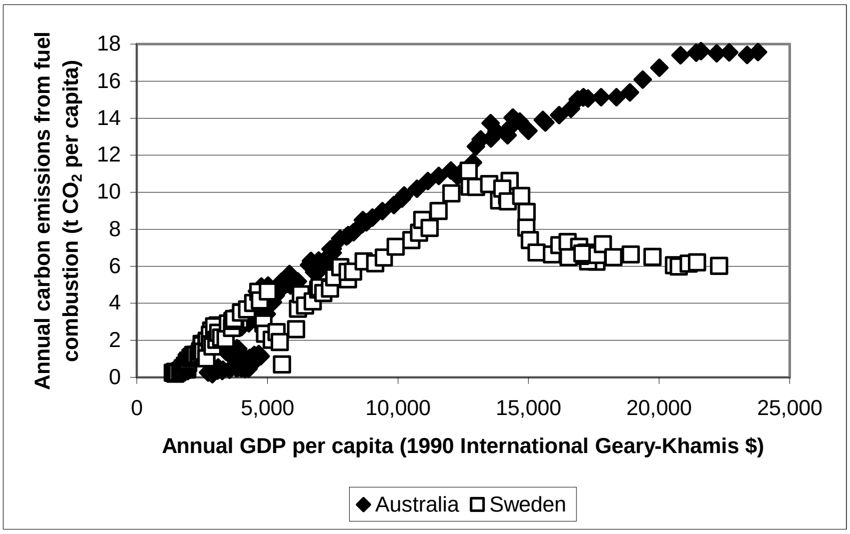
Table 2. Adoption of nuclear and wind energy technologies, 1960-2004

	Nuclear		**Wind**	
	Share of electricity generation (%)			
	1960	2004	1960	2004
High-income countries	0.2	22.9	0.0	0.8
Middle-income countries	0.0	5.6	0.0	0.1
Low-income countries	0.0	0.8	0.0	0.0

Source: World Bank (2008), IEA (2007b, 2007c)

While higher incomes have facilitated the adoption of low-emission technologies, policy differences and differences in natural endowments have meant that individual countries at similar levels of income per capita have differed significantly in terms of their technology uptake. Iceland, for example, is particularly well suited to geothermal technologies, and has come to have the highest share of electricity generation from geothermal sources among OECD countries. In Denmark, government policy from the 1970s onwards played a crucial role in the development of wind power technologies and capacity (Meyer 2006). Governments have also played leading roles in the adoption of nuclear power. The cases of Australia and Sweden, two countries that have followed different policy paths with respect to energy technologies, provide evidence on the role of policies in affecting the adoption of low-emission technologies and the shape of emissions-income paths. Scatterplots of CO_2 emissions-income paths for these two countries using long time-series (145 years of data, from 1860 to 2004) are presented in Figure 2.

Fig. 2. CO_2 emissions-income paths for Sweden and Australia, 1860-2004



Data sources: Marland et al. (2007), IEA (2007a), Maddison (2007) and The Conference Board and Groningen Growth and Development Centre (2008). CO_2 emissions data are for emissions from fuel combustion. The Marland et al. (2007) series was used to 1959 and the IEA (2007a) series henceforth.

CO_2 emissions increased with rising incomes in the initial stages of development in both Sweden and Australia. In 1970, the two countries had similar per capita CO_2 emissions and per capita GDP (in 1990 International Geary-Khamis $ terms, sourced from Maddison 2007). But the two countries diverged sharply from this point: by 2004, Sweden had reduced its per capita CO_2 emissions by 46%; Australia's had increased by 57 percent.

Why was there such a stark divergence in CO_2 emissions-income paths for these two countries? The adoption of low-emission technologies (primarily, nuclear power, but also, more recently, renewable energy technologies) has been a particularly important explanator of Sweden's emissions reductions.[7] After two and a half decades of

[7] Other factors that have contributed to emissions reductions in Sweden include structural change in production, improved energy efficiency, a high "willingness to pay to improve environmental quality", and the effects of specific policies designed to reduce emissions (Kristrom and Lundgren 2005, p. 1226, Lindmark 2002). These policies include a carbon tax, introduced in 1991. (Sweden has continued

government-led research and development, motivated primarily by reasons of energy security, the first commercial nuclear power plant was opened in Sweden in 1972 (Kaijser 1992). In contrast to Sweden, Australia did not adopt nuclear power, in large part due to a reversal of political support for nuclear power in the early 1970s (Cawthe 1992, Holland 2002). More recently, Australia has not adopted renewable energy generation technologies to the same extent as several other developed nations. While the evidence in Table 2 indicates that the adoption of low-emission technologies is, on average, a positive function of income level, the divergent cases of Sweden and Australia provide evidence that policy settings also have important implications for technology adoption decisions. With reference to the extension of the AL (2001) model presented in section 2.1, it appears that the adoption of low-emissions technologies is indeed a positive function of income, but also a function of off-model factors, such as energy sector policies.

To demonstrate the importance of the adoption of low-emission technologies in explaining how (and when) certain countries have achieved ‘country-specific’ EKCs, a counterfactual is informative. If, instead of adopting nuclear power, Sweden has substituted toward coal-fired electricity generation (using a similar mix of coal to that used in Australia, to produce the same quantity of electricity as was produced by nuclear power in Sweden), it is estimated that Sweden’s CO_2 emissions from fuel combustion in 2004 would have been 15 tonnes per capita, rather than the actual level of 6 tonnes per capita (and compared to the 1970 level of 11 tonnes per capita). Sweden’s EKC for CO_2 emissions has thus resulted primarily from its adoption of

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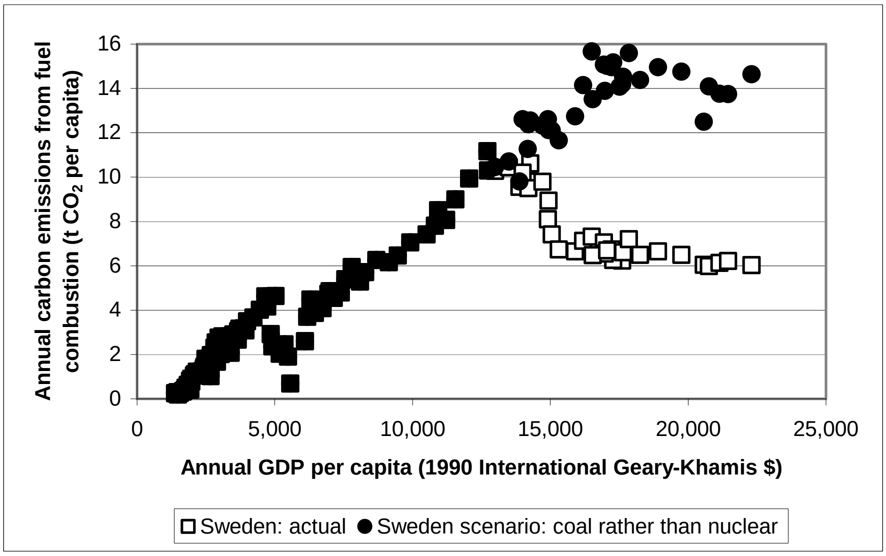
to be a net exporter of energy in goods, indicating that Sweden’s emissions reductions have not been driven by changing trade relationships; see Kander and Lindmark 2006.)

nuclear power technology. (A similar story applies for other countries that have achieved 'country-specific' EKCs, such as France and Belgium.) The actual and counterfactual emissions-income trajectories for Sweden are presented in Figure 3.

Fig. 3. Actual and 'coal rather than nuclear' scenario CO_2 emissions-income paths for Sweden, 1860-2004



Data sources: Marland et al. (2007), IEA (2007a), Maddison (2007) and The Conference Board and Groningen Growth and Development Centre (2008). CO_2 emissions data are for emissions from fuel combustion. The Marland et al. (2007) series was used to 1959 and the IEA (2007a) series henceforth. Scenario constructed assuming that electricity generated from nuclear power was instead generated from coal sources that produce 1 kilogram of CO_2 per kilowatt hour of electricity (a rate similar to that for coal-fired electricity in Australia).

The evidence presented in this section has provided an initial indication that the adoption of low-emission technologies with increasing incomes is an important channel via which certain countries have achieved reductions in carbon emissions with long-run economic growth. A new estimation approach to formally identify the role of technology adoption, and to test for the importance of the other potential drivers of an EKC, is detailed in section 5. Estimation results using this new approach for CO_2 emissions in OECD countries are presented in section 6.

5. Formally identifying drivers of CO_2 emissions changes

To identify the main drivers of emissions changes in OECD countries, a model of the following form is estimated:

$$\mu_\Delta P_{c,t:t-j} = \alpha_0 + \alpha_1 \mu_\Delta Y_{c,t:t-j} + \alpha_2 \mu_\Delta \mathbf{z}_{c,t:t-j} + \alpha_3 \mathbf{x}_{c,t-j} + \alpha_4 I_c + \eta_{t:t-j} + \varepsilon_{c,t:t-j}$$

(13)

where μ_Δ is average change, $P_{c,t:t-j}$ is per capita emissions from year *t-j* to year *t* in country *c*, $Y_{c,t:t-j}$ is real per capita GDP, $\mathbf{z}_{c,t:t-j}$ is a vector of variables representing potential drivers of changes in emissions, $\mathbf{x}_{c,t-j}$ is a vector of control variables, I_c is a vector of country-specific variables, $\eta_{t:t-j}$ is a vector of time-specific effects, and $\varepsilon_{c,t:t-j}$ is an error term with $E(\varepsilon_{c,t:t-j}) = 0$.

The dependent variable and the primary explanatory variable (economic growth) are in growth rates. $\mathbf{z}_{c,t:t-j}$ includes variables to proxy the potential drivers of an EKC listed in section 2.1. These variables are 1) technology adoption (the average annual change in the nuclear and renewable shares of electricity production between years *t-j* and *t*);[8] 2) changes in economic energy efficiency (specifically, the average annual change in GDP per unit energy use (2000 US$/t oil equivalent) between years *t-j* and *t*);[9] 3) structural change (the average annual change in the services sector's share of value added between years *t-j* and *t*); 4) any potential pollution

[8] The measure for renewables includes hydroelectricity.

[9] Economic energy efficiency is the inverse of the more commonly used 'energy intensity'. Changes in economic energy efficiency capture the effect of changes in technology, energy efficiency efforts, and the composition of output.

haven effect (the average annual change in net manufacturing exports as a share of GDP between years *t-j* and *t*); and 5) environmental preferences and policy response (a carbon tax dummy, equal to one for Denmark (from 1992), Finland (1990), Italy (1998), the Netherlands (1990), Norway (1991) and Sweden (1991)).[10] $\mathbf{x}_{t-j}$ includes lagged CO_2 emissions and GDP per capita. Time and country fixed effects are included.[11]

It appears that this is the first paper to estimate a model of the above form. By directly including potential drivers of an EKC, the model allows a more detailed analysis of the mechanisms via which long-run economic growth has affected emissions trajectories. Given that the dependent and primary explanatory variables are in growth rates or differenced form, issues related to unbalanced regressions are not of significant concern (see Wagner 2006 for a discussion of this issue with respect to the nonlinear transformations of GDP per capita used in standard EKC regressions). CO_2 emissions appear to be suitable for use in estimation of Eq. (13) because a country's emissions of CO_2, a global pollutant, should not be expected to have had any short-run impact on that country's rate of economic growth. As such, endogeneity bias is not expected to be an issue.

[10] Carbon taxes varied in coverage and magnitude across countries and over time; the carbon tax dummy serves as a proxy only. A number of other OECD countries had energy or fuel taxes that are not covered by the carbon tax dummy.

[11] Time-specific effects leading to emissions changes include the oil price rises of the 1970s and the fall of communism. Results are robust to the inclusion of a dummy variable for the fall of communism. Country fixed effects are included because the emissions-income trajectory is expected to differ for countries with different structural parameters or initial conditions (Brock and Taylor 2004).

Estimation was carried out using data for all 30 OECD countries for the period 1961-2004. Data were sourced from the International Energy Agency (IEA) (2007a, 2007c), United Nations (2008), and World Bank (2008). Variable definitions and data sources are listed in Appendix A. Summary statistics for explanatory variables included in the estimations are presented in Table 3.

Table 3. Summary statistics for estimation sample

Variable	**Mean (standard deviation)**
Change in per capita carbon dioxide emissions$_t$ (%)	1.67
	(5.54)
Per capita GDP growth rate$_t$ (% real)	2.71
	(2.95)
Change in economic energy efficiency during year *t*	6.88
	(195.38)
Change in nuclear share of electricity production during year *t*	0.41
	(2.13)
Change in renewables share of electricity production during year *t*	-0.49
	(4.14)
Change in services sector share of value added during year *t*	0.48
	(1.15)
Change in net manufacturing exports share of GDP during year *t*	0.07
	(1.52)
Population growth rate$_t$ (%)	0.74
	(0.67)

Source: World Bank (2008), IEA (2007a, 2007c)

In Table 4, correlation coefficients between GDP per capita and the variables included in the estimations (in levels) for 2004 for all available countries (not just the OECD sample) are presented. These cross-country correlations indicate that wealthier countries (those with higher GDP per capita) were more likely to have a higher share of electricity generated by nuclear and non-hydro renewables (as also evidenced in Table 2). Specifically, the correlation coefficients between GDP per capita in US$ and the share of electricity produced by 1) nuclear; and 2) wind generation technologies are around +0.3, confirming that emissions-reducing technology adoption has been a positive function of income level. High-income countries are also more energy efficient, have larger services sectors, and have been more likely to have adopted a carbon tax, than poorer countries. These may be important channels via which economic growth may have led to reduced CO_2 emissions in the long run, and relate back to the potential drivers of an EKC listed in section 2.1. Wealthier countries were also more likely to have a larger share of net manufacturing exports as a share of GDP than poorer countries, a situation which does not indicate the presence of a strong pollution haven effect for CO_2 emissions.

Table 4. Cross-country correlations of potential drivers and GDP per capita, 2004

Potential driver of emissions changes	**Cross-country correlation coefficient with GDP per capita (2000 US$)**	**Number of countries**
Economic energy efficiency (GDP in 2000 US$ / unit energy use in t oil equivalent)	0.73	124
Nuclear share of electricity production	0.29	180
Renewables share of electricity production	-0.19	129
Non-hydro renewables share of electricity production	0.13	129
Wind share of electricity production	0.31	129
Services sector share of value added	0.55	175
Net manufacturing exports share of GDP	0.43	133
Carbon tax dummy	0.40	180

Source: World Bank (2008), IEA (2007b, 2007c). The number of countries varies due to data availability.

6. Empirical results

Results from estimating Eq. (13) using annual data (j = 1) are presented in Table 5. Standard errors are robust for heteroscedasticity and allow for clustering at the country level to account for possible serial correlation (Bertrand et al. 2004). The results indicate that, *ceteris paribus*, faster rates of economic growth have led to faster increases in per capita CO_2 emissions in OECD countries, with a one percentage point increase in the growth rate of GDP per capita leading to an average increase in the CO_2 emissions per capita growth rate of 0.6-0.9 percentage points. The insignificant coefficient estimate on the GDP per capita term indicates that, other things equal, countries were no more likely to achieve emissions reductions at higher income levels. The inclusion of an interaction term between GDP per capita growth and level in the estimate in column 2 is to test for whether the impact of per capita GDP growth on per capita emissions growth differs for countries at different per capita GDP levels. The estimated coefficient for this term does not indicate that there was a diminishing impact of growth on CO_2 emissions at higher income levels. It thus appears that economic growth has not directly led to CO_2 emissions reductions in OECD countries.

Table 5. Estimation results for OECD countries using annual data, 1961-2004

Dependent variable: 1-7: Change in per capita carbon dioxide emissions$_t$ (%); 8: Change in total carbon dioxide emissions$_t$ (%)

	1	2	3	4	5	6	7	8
Per capita GDP growth rate$_t$ (% real)	0.55	0.61	0.82	0.80	0.86	0.77	0.80	0.82
	(0.06)***	(0.07)***	(0.07)***	(0.07)***	(0.07)***	(0.08)***	(0.07)***	(0.07)***
Per capita GDP growth rate$_t$ (%)*GDP per capita$_{t-1}$ (2000 US$ '000)		-0.01						
		(0.01)						
Change in economic energy efficiency during year *t*			-0.02	-0.02	-0.02	-0.01	-0.02	-0.02
			(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***	(0.00)***
Change in nuclear share of electricity production during year *t*				-0.42	-0.41	-0.40	-0.42	-0.43
				(0.05)***	(0.05)***	(0.05)***	(0.05)***	(0.05)***
Change in renewables share of electricity production during year *t*				-0.32	-0.31	-0.33	-0.32	-0.33
				(0.04)***	(0.04)***	(0.05)***	(0.04)***	(0.04)***
Change in services sector share of value added during year *t*					0.17			
					(0.16)			
Change in net manufacturing exports share of GDP during year *t*						-0.13		
						(0.07)*		
Carbon tax dummy$_t$							-0.21	
							(0.35)	
GDP per capita$_{t-1}$ (2000 US$ '000)	0.01	0.02	0.01	0.02	0.05	0.06	0.03	0.03
	(0.07)	(0.07)	(0.05)	(0.05)	(0.06)	(0.06)	(0.05)	(0.05)
CO_2 emissions$_{t-1}$ (tons per capita)	-0.27	-0.28	-0.16	-0.13	-0.23	-0.34	-0.13	-0.13
	(0.10)**	(0.11)**	(0.06)**	(0.05)**	(0.05)***	(0.13)**	(0.05)**	(0.05)**
Population growth rate$_t$ (%)								0.84
								(0.33)**
Time fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country fixed effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.36	0.36	0.64	0.72	0.73	0.73	0.72	0.73
Countries	30	30	30	30	30	30	30	30
Years	1961-2004	1961-2004	1961-2004	1961-2004	1971-2004	1961-2004	1961-2004	1961-2004
Observations	1,190	1,190	1,190	1,190	957	1,045	1,190	1,190

***, ** and * indicate statistical significance at the 1, 5 and 10% significance levels respectively. Robust standard errors clustered by country are in parentheses. Estimated coefficients on country and year fixed effects not reported. Missing data reduces the number of observations used in estimations below 1,320.

The results in Table 5 confirm that the adoption of low-CO_2 energy technologies has had a pivotal impact on CO_2 emissions trajectories in OECD countries. An increase in the proportion of electricity generated by nuclear or renewables energy of one percentage point is estimated to have reduced annual CO_2 emissions growth by 0.3-0.4 percentage points.[12] A country's ability and propensity to adopt nuclear and non-hydro renewable electricity has been a positive function of income level (Tables 2, 4). The adoption of low-emission energy technologies is thus an important mechanism via which an EKC effect has worked.[13]

The Table 5 results also indicate that improvements in economic energy efficiency have had a strong negative impact on CO_2 emissions changes (this reflects energy efficiency improvements and structural change toward less energy-intensive production). The coefficient estimates on the change in the size of the services sector share of value added, the change in net manufacturing exports as a share of GDP and the carbon tax dummy (columns 5-7) do not provide any statistically significant evidence to indicate that emissions reductions were, on average, strongly driven by sectoral change, the pollution haven effect, or the imposition of carbon taxes.[14] The dependent variable in column 8 is the percentage change in total CO_2 emissions. The main findings are robust to this specification (and the importance of population growth in driving CO_2 emission changes is identified).

[12] The magnitude of this estimate is as expected given that electricity generation on average contributed around 30 percent of CO_2 emissions from fuel combustion in OECD countries over the period.

[13] Note that reductions in the share of electricity generated from hydro sources in OECD countries have, *ceteris paribus*, placed upward pressure on CO_2 emissions.

[14] Similar estimates on these variables are obtained if the other control variables are excluded from the estimations; or if alternative variable definitions are used, e.g. the services sector growth rate is used instead of the change in the size of the services sector as a share of value added; or if the dependent variable is respecified as the change in per capita CO_2 emissions rather than the percentage change in per capita CO_2 emissions.

The main variables included in the estimations in Table 5 are in differenced form. A Maddala and Wu (1999) panel unit root test indicated that all variables other than GDP per capita are stationary at the 1% significance level (for at least one of the 30 countries in the sample). Similar results are obtained if lagged GDP per capita is excluded from the estimations (and if the lagged CO_2 emissions per capita control is also excluded).

A number of additional checks were carried out to investigate the sensitivity of the estimation results on the drivers of emissions changes. Similar results are obtained if a time trend is used instead of year fixed effects, or if random effects are used instead of country fixed effects. Results are similar if Luxembourg is excluded from the estimation sample (on the basis of the Cook's distance measure, Luxembourg was identified as the country with the largest number of outliers), or if countries for which the full 44 years of data are not available are excluded from the estimation sample. Results are also robust to the inclusion of additional control variables, including changes in the share of the population living in urban areas, change in POLITY score (a measure of democratic governance, sourced from Marshall and Jaggers 2007), education expenditure (per cent of GNI), electricity production, net exports of electricity, and demographic factors. Similar results are obtained using CO_2 emissions data from the World Resources Institute (2008) or Marland et al. (2007). Similar results (unreported) are also obtained using 4-year or 10-year averaged data (j = 4 or 10).

In summary, the empirical results provide strong evidence that the adoption of low-emission energy technologies (nuclear and renewable energy technologies) has been an important 'countervailing' factor that has worked against the scale effect for CO_2 emissions in OECD countries. Given that low-emission technology adoption is a positive function of income level (see Table 2, 4), this finding provides support to the hypothesis that an important mechanism via which the EKC for CO_2 operates is emissions-reducing technical progress with long-run economic growth.

7. Conclusion

The extension of the AL (2001) model in this paper identifies that if long-run economic growth facilitates emissions-reducing technical progress, the relationship between pollution and income may take the form of an environmental Kuznets curve (i.e. initially increasing, but eventually decreasing). This result has been tested using data on CO_2 emissions in OECD countries.

Countries that have experienced long-run economic growth (high-income countries) have had a greater ability and propensity to adopt low-carbon electricity generation technologies, such as nuclear power and renewable power. The new empirical evidence presented here indicates that the adoption of nuclear and renewable electricity generating technologies has played a vital role in explaining how certain OECD countries (Sweden, France, Belgium, and Denmark, for example) have achieved CO_2 emissions reductions with continued economic growth in the long run. The carbon Kuznets curve, where it has existed, appears to have worked largely via the channel of increased adoption of low-emission technologies with rising incomes.

Technology adoption is in reality not solely a function of income alone; policy settings and other factors (such as natural endowments) play crucial roles in technology adoption decisions. Given the dual importance of policies and income in explaining technology adoption, the EKC for CO_2 is more appropriately considered to be a conditional relationship: whether economic growth leads to emissions reductions in the long run is conditional on whether policy settings are conducive to the adoption of emissions-reducing technologies.

The evidence on CO_2 emissions in this paper indicates that the EKC is not immutable. Sustained economic growth is not sufficient to achieve reductions in CO_2 emissions. An enabling environment for the adoption of low-emission technologies can, however, mean that long-run economic growth eventually results in reductions in pollution. There consequently appears to be a vital role for policies related to technology adoption in enhancing the sustainability of development trajectories.

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Appendix A. Definitions of variables

Variable name	Variable description	Source
CO_2 emissions (tons per capita)	Per capita carbon dioxide emissions from fuel combustion, calculated using the sectoral approach	IEA (2007a)
Change in per capita carbon dioxide emissions (%)	Percentage change in per capita carbon dioxide emissions from fuel combustion, calculated using the sectoral approach	IEA (2007a)
Change in total carbon dioxide emissions (%)	Percentage change in total carbon dioxide emissions from fuel combustion, calculated using the sectoral approach	IEA (2007a)
GDP per capita (2000 US$ '000)	Per capita GDP based on constant 2000 US$ GDP	World Bank (2008)
Per capita GDP growth rate (% real)	Annual percentage growth rate of GDP per capita based on constant local currency	World Bank (2008)
Population growth rate (%)	Annual population growth rate	World Bank (2008)
Economic energy efficiency	GDP (2000 US$) divided by total primary energy supply (t oil equivalent)	World Bank (2008), IEA (2007c)
Change in nuclear share of electricity production during year *t*	Change in the percentage share of electricity output sourced from nuclear power plants	World Bank (2008)
Change in renewables share of electricity production during year *t*	Change in the percentage share of electricity output sourced from hydro, geothermal, solar, tidal, wave, ocean and wind sources	IEA (2007c)
Change in services sector share of value added during year *t*	Change in the percentage share of value added attributed to the services sector, where the services sector covers wholesale, retail trade, restaurants, hotels, financial intermediation and other services (excluding transport services)	United Nations (2008)
Change in net manufacturing exports share of GDP during year *t*	Change in manufacturing exports minus manufacturing imports as a percentage share of GDP	World Bank (2008)
Carbon tax dummy	Equal to 1 for Denmark (from 1992), Finland (1990), Italy (1998), the Netherlands (1990), Norway (1991) and Sweden (1991). Fuel or energy taxes not included	