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Climbing the electricity ladder generates carbon Kuznets curve downturns*

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This paper examines why some countries have experienced environmental Kuznets curve (EKC)-type reductions in carbon dioxide (CO_2) emissions, while others have not. The hypothesis that climbing to the upper rungs of the electricity ladder (nuclear power and modern renewables) has been the primary mechanism via which countries have achieved substantial reductions in per capita CO_2 emissions is tested using a binomial dependent variable modelling approach for a sample of 105 countries. The findings suggest that electricity mix transitions caused by long-run growth in per capita incomes are indeed the primary determinant of carbon Kuznets curve downturns. The paper explores additional mechanisms via which carbon Kuznets curves may have been generated, but the results indicate that these are of lesser overall importance than the electricity mix effect. The evidence also suggests that countries with larger fossil fuel endowments are less likely to experience carbon Kuznets curve downturns, an additional curse of natural resources.

Key words: carbon dioxide, economic development, electricity ladder, electricity mix, environmental Kuznets curve, resource curse.

1. Introduction

Some countries, such as Sweden, have experienced environmental Kuznets curve (EKC)-type downturns in CO_2 emissions with continued economic growth. Despite passing similar levels of GDP per capita, other countries, such as Australia, have to date had monotonically increasing CO_2 emissions. This paper explores why EKC-type downturns in CO_2 emissions have been observed in some countries, but not others.

The CO_2 emissions-income paths of Sweden and Australia for the period 1851–2006 are presented in Figure 1. In 1970, Sweden and Australia had similar annual GDP per capita and CO_2 emissions per capita. But CO_2 emissions per capita of the two countries diverged from this point: by 2006, Sweden's per capita emissions had fallen by 52 per cent, while Australia's had increased by 70 per cent. Sweden and Australia are not isolated cases of divergent CO_2 emissions-income trajectories. Like Sweden, countries such as France have experienced large reductions in per capita CO_2 emissions, while countries

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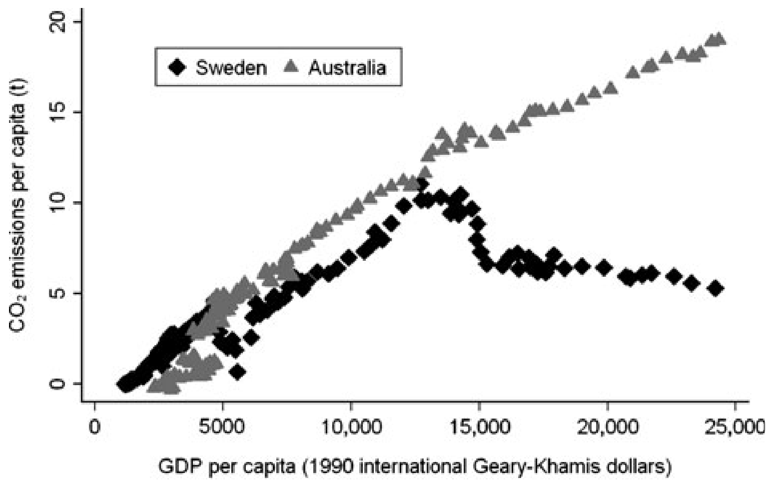

Figure 1 CO_2 emissions-income paths for Sweden and Australia, 1851–2006. Emissions are those from fossil fuel use. Emissions data source: 1851–1959: Boden *et al.* (2009); 1960–2006: International Energy Agency [IEA] (2009a). GDP and population data source: Maddison (2009).

such as Greece have, like Australia, displayed generally increasing per capita CO_2 emissions, despite reaching high-income levels.

There are a number of mechanisms via which long-run economic development may lead to emissions reductions, but which of the mechanisms has been most important for the case of CO_2 is not clear. In this paper, the hypothesis that the extent to which a country climbs to the upper rungs of the electricity ladder (nuclear, modern renewables) is the key determinant of whether that country has experienced an EKC-type downturn in CO_2 emissions is tested using a new estimation approach applied to a sample of 105 countries. The approach involves using a binomial dependent variable model that allows a clear identification of factors affecting long-run emissions-income trajectories.

CO_2 is the main greenhouse gas, and there is compelling evidence that anthropogenic greenhouse gas emissions are changing the Earth's climate. Evidence on the mechanisms via which CO_2 emissions reductions have been achieved historically may have important implications for public policy in the current era of increasingly constrained carbon budgets.

The remainder of this paper is organised as follows. In section 2, a review of recent findings on the electricity ladder and existing knowledge on the carbon Kuznets curve is presented. Section 3 discusses initial evidence on the importance of electricity mix transitions for carbon Kuznets curves. An estimation approach for identifying the importance of electricity mix transitions and other factors for the likelihood of EKC-type downturns is detailed in section 4, and data are discussed. Results are presented in section 5. The final section concludes.

2. Existing knowledge on the electricity ladder and the carbon Kuznets curve

There is recent evidence (Burke 2010) that countries climb an 'electricity ladder' as their per capita incomes increase. This process sees their electricity mixes reorientate away from hydro and oil towards coal and natural gas, and then finally to nuclear power and modern renewables. Burke (2010) also finds that countries with large endowments of fossil fuels are less likely to climb to the low-carbon upper rungs of the electricity ladder (nuclear power and modern renewables) as they reach high income levels than are otherwise similar countries. The implications are that the adoption of low-carbon electricity sources on the upper rungs of the electricity ladder may be an important mechanism via which long-run economic growth has caused an EKC effect for CO_2, and also that fossil fuel endowments may be an important determinant of whether countries experience EKCs for CO_2. Whether this is the case is not examined by Burke (2010).

The EKC hypothesis posits that environmental damage first increases and then decreases as a country develops. In theory, an EKC-type downturn in emissions can occur for a number of reasons, including emissions-reducing changes in the output composition of an economy as it develops, emissions-reducing changes in the inputs used in an economy as it develops, emissions-reducing changes in technology as an economy develops, or the existence of increasing returns to abatement (Stern 2004). Less proximate causes of an EKC downturn include a positive income elasticity of demand for environmental quality and the implementation of tighter environmental regulations in more developed economies. These causes are less proximate because they must affect inputs, outputs or technology to affect emissions. Graduations to electricity sources at the upper rungs of the electricity ladder could be classed as either a change in inputs (e.g. coal to uranium or wind) or a change in technology (e.g. coal-fired generation technology to nuclear power or wind generation).

There is a large literature looking at whether there is a nonlinear relationship between CO_2 emissions and development level, as measured by GDP per capita. The literature indicates that the carbon Kuznets curve is not an unconditional, generalisable phenomenon common to all countries, but provides little indication of why and how some countries have achieved EKC-type downturns in per capita CO_2 emissions (Dijkgraaf and Vollebergh 2005; Galeotti *et al.* 2009; Musolesi *et al.* 2010). Why and how some countries have achieved carbon Kuznets curve downturns is the focus of the current paper.

Some EKC studies – such as Auci and Becchetti (2006), Richmond and Kaufmann (2006a,b) and Tsurumi and Managi (2010) – control for aspects of the energy mix. But these papers do not consider that the long-run impact of economic development on emissions may emerge via changes in energy mix as incomes increase. Studies on countries such as France note that nuclear power has played a role in reducing CO_2 emissions (e.g. Iwata *et al.* 2010). Neumayer (2002) finds that fossil fuel endowments are associated with higher CO_2 emissions. The general importance of electricity mix transitions and fossil fuel endowments for the likelihood of EKC downturns in CO_2 emissions has yet to be examined.

3. The electricity ladder and carbon Kuznets curves: Initial evidence

Many countries that have experienced EKC-type downturns in CO_2 emissions have also seen substantial decarbonisation of their electricity sectors, often because of the adoption of nuclear power or modern renewables. Consider Sweden: between 1970 and 2006, the share of electricity in Sweden generated by nuclear power and modern renewables increased by 54 percentage points, and the share generated by fossil fuel combustion fell by 28 percentage points. Or consider France, where CO_2 emissions fell from a peak of 9 tonnes (t) per capita in 1973 to 6 t per capita in 2006. This reduction was associated with a large expansion of nuclear power in France: 78 per cent of France's electricity generation was from nuclear power in 2006, up from 8 per cent in 1973 and close to 0 per cent in 1960 (IEA 2009b). Finally, consider Denmark, where by 2006 per capita CO_2 emissions had fallen by 24 per cent from a 1996 high of 13 t, and where modern renewables (primarily wind, but also biomass and waste) contributed 22 per cent of electricity generation in 2006 (up from 4 per cent in 1996 and 0 per cent in 1977). In fossil fuel-rich countries, graduations up the electricity ladder have been less frequent and substantial: Australia, for instance, has not adopted nuclear power, and by 2006, non-hydro renewable sources accounted for only 1 per cent of Australia's electricity.

Figure 2 presents emissions-income paths for the period 1839–2006 for Sweden and France, as well as paths for a counterfactual in which, instead of generating electricity from nuclear power and modern renewables, the two countries generated the same amount of electricity using coal. The counterfactual reveals that if Sweden and France had substituted to coal-fired electricity rather than nuclear and renewables, they would not have achieved the EKC-type reductions in CO_2 emissions that were observed from the 1970s. This provides initial evidence on the importance of the adoption of low-carbon electricity technologies for the ability of Sweden and France to achieve carbon Kuznets curve downturns.

4. Estimation approach and data

To explore the determinants of whether countries experience an EKC-type downturn in CO_2 emissions, the following model is estimated:

$$\Pr(K_c = 1|\mathbf{x}_c) = f(\mathbf{x}_c'\boldsymbol{\alpha}) \tag{1}$$

where $K = 1$ if a country (c) experienced an EKC-type downturn in CO_2 emissions during 1960–2006 and 0 otherwise, f is a distribution function, $\mathbf{x}_c$

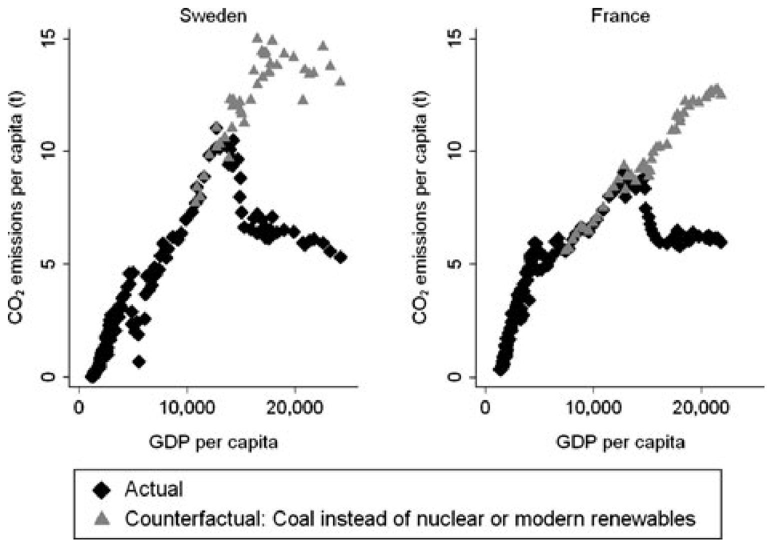

Figure 2 Actual and 'coal instead of nuclear or modern renewables' counterfactual CO_2 emissions-income paths for Sweden and France, 1839–2006. Emissions are those from fossil fuel use. GDP per capita is in 1990 international Geary-Khamis dollars. The counterfactual is constructed assuming that electricity generated from nuclear power and modern renewables was instead generated from coal sources that produce 0.90372 kg of CO_2 per kilowatt hour of electricity (the OECD average for the period 1992–2006; source: IEA 2009c). Emissions data source: 1851–1959: Boden *et al.* (2009); 1960–2006: IEA (2009a). GDP and population data source: Maddison (2009). Electricity data source: IEA (2009b).

is a vector of explanatory variables, and $\boldsymbol{\alpha}$ is a vector of parameters to be estimated. The dependent variable reflects the long-run shape of the CO_2 per capita-GDP per capita relationship and is set equal to 1 if a country meets the following criteria (and zero otherwise): (i) CO_2 emissions per capita reduced by more than 10 per cent from peak level by 2006; (ii) GDP per capita increased by more than 10 per cent from the CO_2 emissions per capita peak year by 2006 and (iii) in the years after the CO_2 emissions per capita peak year, GDP per capita is never 10 per cent below the maximum level reached at or before the CO_2 emissions per capita peak year.

The above criteria, which to my knowledge have not been applied previously, ensure that countries are only classed as having achieved carbon Kuznets curve downturns if their CO_2 per capita-GDP per capita plots display an inverse-U EKC shape. The underlying philosophy for the approach is that whether a country has achieved an EKC downturn for a given pollutant can be observed directly and does not require sophisticated statistical techniques (Levinson 2002). The approach allows flexibility in terms of the level of GDP per capita at which any turning point is achieved, consistent with evidence of turning point heterogeneity in the literature (Dijkgraaf and Vollebergh 2005). The first criterion requires per capita emissions reductions to be of reasonable size and to be sustained to 2006. The second and third criteria rule out cases where emissions reductions were associated with stagnant or falling GDP per capita (such as Zimbabwe).

The advantage of the above estimation approach is that it allows for a direct exploration of the most important long-run determinants of within-country carbon Kuznets curve downturns. The strategy has the further advantage of avoiding the modelling of time-series dynamics. The approach shares similarities with that of Verbeke and De Clercq (2006), whose primary specification uses a dependent variable equal to 1 for 5-year periods in which income growth and reductions in sulphur emissions are simultaneously achieved, and 0 otherwise. The approach here focuses on the long-run relationship between emissions and the explanatory variables rather than the reduced-form relationship between income and emissions over 5-year periods. While the estimation approach is suited to identifying the factors that on average have made countries more likely to experience EKC downturns, it is not able to identify all contributors to emissions reductions for each individual country.

Equation (1) is estimated using both a linear probability model (LPM) and nonlinear specifications (logit and probit). The LPM specification is:

$$K_c = \alpha + \beta \Delta M_c + \gamma F_c + \delta \ln Y_c + \mathbf{w}_c' \zeta + \varepsilon_c \tag{2}$$

where ΔM is the change in the share of nuclear and modern renewables (geothermal, solar, tide, wave, ocean, wind, biomass and waste) in the electricity mix over the period 1971–2006, F denotes fossil fuel endowments, Y is initial real GDP per capita in PPP terms, and $\mathbf{w}$ is a vector of additional explanatory variables, including additional potential underlying determinants of whether a country will experience an EKC (such as the natural logarithms of the 1971 population and land area, and a transition economy dummy), and additional potential mechanisms via which EKCs may emerge (such as measures of structural change, growth in per capita energy use, changes in the carbon intensity of energy use outside the electricity sector and a measure of awareness of human-induced climate change). Estimations of Equation (2) with the three listed explanatory variables considered separately (rather than each included in the equation together) are also explored. Given the objective of examining the implications of the results of Burke (2010) for the likelihood of countries achieving carbon Kuznets curve downturns, the coefficients of primary interest are those for the ΔM and F variables. The natural logarithm of initial income is included primarily as a control. The standard regression assumptions, including $E(\varepsilon_c) = 0$, are applied. Estimation standard errors are robust to heteroscedasticity.

Presenting estimates of the exact curvature of CO_2 emissions-income paths is outside the scope of this paper. For detailed panel estimates on the CO_2 emissions-income relationship, the reader is referred to other papers in the EKC literature, such as Musolesi *et al.* (2010). The inclusion of a term measuring the share of nuclear and modern renewables in the electricity mix in standard EKC specifications (with or without allowing for heterogeneous turning points) indicates that the adoption of nuclear and modern renewables power reduces CO_2 emissions per capita, all else equal.

Data on CO_2 emissions are sourced from the IEA (2009a) and are for emissions from all fossil fuel use. (Emissions data are not just for electricity sector emissions, but total emissions from the electricity sector and other sectors.) GDP data are from the Penn World Table (Heston *et al.* 2009). Electricity mix data are from the IEA. The primary specifications are estimated for as big a sample as data allow (105 countries). This is a larger sample of countries than has been used in most prior contributions. Because the dependent variable is a measure of an aspect of the long-run evolution of CO_2 emissions and GDP per capita in each country, the number of observations included in the sample is equal to the number of countries. A full list of variable definitions and data sources is provided in the Appendix.

The countries that meet the carbon Kuznets curve criteria (and for which $K = 1$) are listed in Table 1, together with descriptive statistics. Eleven OECD countries meet the criteria (in order of occurrence: Luxembourg, Sweden, Belgium, Switzerland, France, the United Kingdom, the United States, Hungary, Germany, Denmark and Iceland). Carbon Kuznets curve downturns are relatively rare in non-OECD countries, with only seven meeting the criteria (South Africa, Bulgaria, Hong Kong, Malta, Singapore, the Philippines and Sri Lanka). Half of the carbon Kuznets curve downturns occurred during the 1970s. While the oil price rises of this decade had important implications for carbon trajectories (Unruh and Moomaw 1998), they were common to all countries. The 1970s also saw transitions to nuclear power in many of these countries, the commencement of which predates the oil price rises.

On average, the 18 countries classed as having achieved carbon Kuznets curve downturns reduced their per capita CO_2 emissions by 24 per cent from peak levels by 2006. These countries are heterogeneous in terms of the per capita CO_2 emissions and GDP levels at which they experienced their EKC downturns. EKC-type downturns in per capita CO_2 emissions have occurred at per capita GDP levels as high as \$29,726 (Hong Kong, 1993) and as low as \$3640 (the Philippines, 1997). The countries that have experienced EKC-type reductions in per capita CO_2 emissions have each achieved reductions in the carbon intensity of electricity generation (column 7 of Table 1), frequently as a result of substitution towards nuclear and/or modern renewable energy (column 8).

Additional summary statistics for the 105 countries included in the estimations are provided in Table 2. The 18 countries that experienced carbon Kuznets curves have on average been larger adopters of nuclear and modern renewables electricity generation than other countries. They also on average have smaller fossil fuel endowments and larger initial GDP per capita levels than other countries. Further, the carbon Kuznets curve-achieving countries have on average seen faster structural change towards the services sector, have populations that are better informed about climate change, are more

Table 1 Countries exhibiting carbon Kuznets curves turning points, 1960–2006

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Country	Peak year	CO_2 emissions per capita (t)		GDP per capita (international $, 2005 prices)		Δ Carbon intensity of electricity generation (grams CO_2 per kilowatt hour)	Δ Nuclear and modern renewables (per cent share of electricity mix)*
		Environmental Kuznets curve (EKC) peak year	2006	EKC peak year	2006	EKC peak year-2006	EKC peak year-2006
Luxembourg	1960	54.91	23.64	17,479	74,366	−3163.9	3.9
Sweden	1970	11.05	5.32	17,003	31,979	−163.7	53.6
Belgium	1973	13.65	11.12	17,041	32,844	−520.8	58.1
France	1973	9.10	5.97	16,904	29,238	−459.1	71.2
Switzerland	1973	6.67	5.83	26,660	36,510	−12.0	30.5
United Kingdom	1973	11.32	8.86	15,831	31,142	−351.9	13.0
United States	1973	22.17	19.00	22,324	42,683	–†	17.0
South Africa	1976	8.78	7.22	7570	9979	–†	4.1
Hungary	1978	8.20	5.60	10,295	16,876	−348.6	41.6
Germany	1979	14.13	10.00	19,904	30,496	−301.5	22.8
Bulgaria	1980	9.46	6.18	4902	9149	–†	25.2
Hong Kong	1993	7.23	6.11	29,726	40,593	−7.4	0.0
Malta	1993	7.49	6.15	14,856	20,094	−553.7	0.0
Singapore	1994	11.17	9.62	27,555	41,151	−440.6	0.0
Denmark	1996	13.43	10.15	27,127	33,608	−125.3	17.4
Iceland	1996	8.20	7.18	26,277	39,203	−0.7	19.8
Philippines	1997	0.95	0.77	3640	4391	−134.9	0.3
Sri Lanka	2004	0.64	0.57	5056	5787	−115.0	0.0
Average	1982	12.14	8.29	17,231	29,449	−446.6	21.0

Countries are classed as having achieved a carbon Kuznets curve downturn if: (i) CO_2 emissions per capita reduced by more than 10 per cent from peak level by 2006; (ii) GDP per capita increased by more than 10 per cent from the CO_2 emissions per capita peak year by 2006 and (iii) in the years after the CO_2 emissions per capita peak year, GDP per capita is never 10 per cent below the maximum level reached at or before the CO_2 emissions per capita peak year. Sources: IEA (2009a, 2009b, 2009c, 2009d).
*Modern renewables include geothermal, solar, tide, wave, ocean, wind, biomass and waste.
†Data on the carbon intensity of electricity generation are not available for the emissions peak year.

likely to have been early-ratifiers of the Kyoto Protocol, have seen slower (but still positive) growth in per capita energy use and are more likely to have seen decarbonisation of energy use in the industrial sector.

5. Results

5.1. Initial results

Initial results from an estimation of Equation (2) are presented in Table 3. The estimate in column 1 of Table 3 confirms that the adoption of nuclear and

Table 2 Summary statistics

Variable	Countries achieving carbon Kuznets curve downturn		Countries not achieving carbon Kuznets curve downturn	
	Mean	SD	Mean	SD
Δ Nuclear and modern renewables share of electricity mix (percentage points), 1971–2006	25.03	22.82	3.13	8.75
Fossil fuel reserves, thousand tonnes oil equivalent (ttoe) per capita, 2005	0.08	0.18	0.65	3.54
GDP per capita (thousand 2005 constant prices international dollars), 1971	12.28	7.27	9.10	15.00
GDP per capita (thousand 1990 international Geary-Khamis dollars), 1950	4.59	2.99	2.79	4.71
Fossil fuel reserves (million US$ per capita), 1971	0.00	0.01	0.04	0.16
Fossil fuel depletion (per cent of GNI), 1971	0.24	0.39	3.46	9.06
Population (million), 1971	29.18	50.01	32.49	108.40
Land (thousand squared kilometres), 1971	705.86	2130.62	924.99	1841.80
Transition economy dummy	0.11	0.32	0.03	0.18
Δ Services sector share of GDP, 1971–2006 (percentage points)	17.45	6.86	7.21	12.53
Δ Net exports, 1971–2006 (per cent of GDP)	3.26	9.09	2.86	13.06
Knowledge of climate change in 2007–2008 (per cent of population)	83.94	19.21	62.74	21.31
Ratification of the Kyoto Protocol by end 2004 (dummy)	0.83	0.38	0.64	0.48
Δ Log energy use per capita, 1971–2006	0.40	0.48	0.56	0.69
Δ Log carbon intensity of energy use in industry, 1971–2006	−0.33	0.43	−0.16	0.51
Δ Log carbon intensity of energy use in transport, 1971–2006	0.00	0.09	−0.02	0.21
Number of countries in sample	18		87	

Note: Not all variables are available for all countries in sample.

modern renewable power is an important determinant of whether a country experiences a carbon Kuznets curve. The estimate indicates that every additional percentage point share of the electricity mix for nuclear power and modern renewables increased the likelihood of a carbon Kuznets curve downturn over the period 1960–2006 by 1.4 percentage points. This effect is significant at the 1 per cent level. Given that income has a positive causal impact on the likelihood of adopting nuclear and modern renewables power (Burke 2010), this result identifies graduations to the upper rungs of the electricity ladder as an important mechanism via which EKCs for CO_2 emissions have been generated.

The result in column 2 of Table 3 indicates that countries with larger fossil fuel endowments are less likely to experience EKC downturns in CO_2 emissions (significant at the 5 per cent level). This accords with the findings of Burke (2010), as fossil fuel-rich countries are less likely to have transitioned to using nuclear or renewables power. The estimate in column 3 of Table 3 indicates that higher GDP per capita in 1971 significantly increased the

Table 3 Regression estimates

	(1)	(2)	(3)	(4)	(5)	(6)
Δ Nuclear and modern renewables share of electricity mix (percentage points), 1971–2006	0.014			0.013	0.012	0.012
	(0.002)***			(0.002)***	(0.002)***	(0.002)***
Fossil fuel reserves (ttoe per capita), 2005		−0.008		−0.009		
		(0.003)**		(0.005)*		
Log GDP per capita, 1971			0.089	0.045		
			(0.034)***	(0.029)		
Fossil fuel reserves (million US$ per capita), 1971					−0.299	
					(0.141)**	
Fossil fuel depletion (per cent of GNI), 1971						−0.005
						(0.003)*
Log GDP per capita, 1950					0.078	0.081
					(0.041)*	(0.040)**
R^2	0.317	0.004	0.063	0.330	0.370	0.351
Observations	105	105	105	105	96	81
Number of times dependent variable equals 1	18	18	18	18	14	14
Per cent predicted correctly	88	83	83	87	91	89

The dependent variable equals 1 if the country experienced a carbon Kuznets curve during the period 1960–2006, and 0 otherwise. Robust standard errors are in parentheses. Coefficients on constants not reported. ***, ** and * indicate statistical significance at the 1, 5 and 10 per cent levels, respectively.

likelihood that a country experiences an EKC for CO_2 in the subsequent decades. The estimate implies that if country *A* had a per capita GDP in 1971 twice that of country *B*, the likelihood of country *A* achieving a carbon Kuznets curve downturn by 2006 is 9 percentage points higher than that for country *B*. Given that carbon Kuznets curves are relatively rare, this difference is large in magnitude (country *A* is more than 50 per cent more likely to experience a carbon Kuznets curve than country *B*). The estimate in column 4 of Table 3 includes the electricity mix, fossil fuel endowments and income variables and finds similar results to those in columns 1–3 (although 1971 log GDP per capita is statistically insignificant once the adoption of nuclear and modern renewables and fossil fuel reserves is controlled for).

One potential concern with the estimates in columns 1–4 of Table 3 is that year-2005 data for fossil fuel endowments are used and GDP per capita is measured in 1971 (which is subsequent to the EKC turning points of Luxembourg and Sweden). To explore the importance of these issues, columns 5–6 use earlier measures of fossil fuel wealth (using data for the year 1971) and log GDP per capita (using data from Maddison 2009). Similar results are obtained. To allow a parsimonious presentation with as large a sample as possible, subsequent results use the 2005 fossil fuel reserves measure and 1971 GDP per capita data.

Table 4 presents coefficients and marginal effects for logit and probit specifications. The estimates for the change in the nuclear and modern renewables share of the electricity mix are similar to those in Table 3, confirming that the adoption of these low-carbon electricity sources is an important mechanism via which EKC-type downturns in CO_2 emissions have occurred. The fossil fuel endowments variable has a negative coefficient in the logit and probit specifications, although with a *p*-value outside the traditional significance levels. Estimated coefficients for 1971 log GDP per capita are positive and significant in the logit and probit estimates. The LPM, logit and probit models have similar properties in terms of prediction accuracy. For space reasons, subsequent results are for linear models only. (Results for logit or probit estimations are similar.)

5.2. Exploring competing explanations

Table 5 presents results for specifications that include additional country characteristics and variables representing alternative mechanisms via which carbon Kuznets curve downturns may have been achieved. Column 1 controls for the 1971 logarithms of population and land area, and a transition economy dummy. The estimates on the adoption of nuclear and modern renewables electricity and on fossil fuel endowments remain similar after the addition of these controls. The estimated coefficient for the land area variable is negative and statistically significant at the 5 per cent level, suggesting that smaller countries are more likely to experience EKC-type downturns in CO_2 emissions. This finding has intuitive appeal, as reductions in emissions from

Table 4 Logit and probit estimates

	Logit (columns 1–4)				Probit (columns 5–8)			
Estimation	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δ Nuclear and modern renewables share of electricity mix (percentage points), 1971–2006	0.092 (0.021)** [0.010]			0.074 (0.022)** [0.005]	0.054 (0.011)** [0.012]			0.043 (0.012)** [0.006]
Fossil fuel reserves (ttoe per capita), 2005		−0.944 (0.819) [−0.103]		−1.215 (1.110) [−0.085]		−0.518 (0.439) [−0.106]		−0.664 (0.621) [−0.098]
Log GDP per capita, 1971			0.649 (0.249)** [0.083]	0.767 (0.409)* [0.054]			0.382 (0.140)** [0.090]	0.401 (0.215)* [0.059]
Pseudo-R^2	0.284	0.021	0.069	0.326	0.287	0.022	0.007	0.327
Observations	105	105	105	105	105	105	105	105
Number of times dependent variable equals 1	18	18	18	18	18	18	18	18
Per cent predicted correctly	87	83	81	88	87	83	81	88

The dependent variable equals 1 if the country experienced a carbon Kuznets curve during the period 1960–2006, and 0 otherwise. Robust standard errors are in parentheses. Marginal effects calculated at the means are in square brackets. Coefficients on constants not reported. ** and * indicate statistical significance at the 1, 5 and 10 per cent levels, respectively.

Table 5 Regression estimates with additional controls

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Δ Nuclear and modern renewables share of electricity mix (percentage points), 1971–2006	0.013 (0.002)***	0.011 (0.003)***	0.012 (0.003)***	0.010 (0.003)***	0.013 (0.002)***	0.013 (0.002)***	0.014 (0.002)***	0.013 (0.002)***
Fossil fuel reserves (ttoe per capita), 2005	−0.007 (0.004)*	0.046 (0.205)	−0.064 (0.036)*	−0.010 (0.005)*	−0.009 (0.005)*	−0.008 (0.005)*	−0.007 (0.004)*	−0.005 (0.004)
Log GDP per capita, 1971	0.037 (0.035)	0.044 (0.063)	0.085 (0.048)*	0.069 (0.052)	0.045 (0.029)	0.053 (0.030)*	0.043 (0.028)	0.050 (0.036)
Additional controls								
Log population, 1971	0.042 (0.033)							0.045 (0.036)
Log land, 1971	−0.067 (0.026)**							−0.059 (0.029)**
Transition economy dummy	0.034 (0.123)							0.013 (0.133)
Competing explanations								
Δ Services sector share of GDP, 1971–2006 (percentage points)		0.005 (0.003)*						
Δ Net exports, 1971–2006 (per cent of GDP)			0.000 (0.003)					
Knowledge of climate change in 2007–2008 (per cent of population)				0.001 (0.003)				

Table 5 (*Continued*)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Ratification of the Kyoto Protocol by end 2004 (dummy)					0.002 (0.064)			
Δ Log energy use per capita, 1971–2006						−0.062 (0.045)		−0.082 (0.049)
Δ Log carbon intensity of energy use in industry, 1971–2006							−0.045 (0.061)	−0.035 (0.053)
Δ Log carbon intensity of energy use in transport, 1971–2006							0.070 (0.074)	0.018 (0.071)
R^2	0.409	0.359	0.332	0.283	0.330	0.342	0.362	0.433
Observations	105	60	81	90	105	105	102	102
Number of times dependent variable equals 1	18	12	16	16	18	18	17	17
Per cent predicted correctly	87	85	85	86	87	88	88	89

The dependent variable equals 1 if the country experienced a carbon Kuznets curve during the period 1960–2006, and 0 otherwise. Robust standard errors are in parentheses. Coefficients on constants not reported. Samples are in some instances reduced because of data unavailability or, in the case of columns 7–8, zero use of energy in the industry or transport sector in 1971. ***, ** and * indicate statistical significance at the 1, 5 and 10 per cent levels, respectively.

any one source (e.g. a power plant) may noticeably reduce national emissions in small countries, but have less important implications for national emissions in large countries. The results on the population and transition economy variables are statistically insignificant.

Columns 2–7 of Table 5 include variables representing potentially competing explanations of how carbon Kuznets curve downturns have occurred. Column 2 includes a variable measuring the change in the importance of the services sector in national GDP to test whether transitions to more services-based economies have assisted some countries to achieve EKC-type emissions reductions. The estimate for this variable provides some evidence that structural change towards the services sector has increased the likelihood of carbon Kuznets curve downturns, although the estimate is only significant at the 10 per cent level. Column 3 includes a variable measuring the change in net exports to test whether a trade effect has assisted some countries to achieve carbon Kuznets curve downturns. The estimate on this variable provides no evidence to support the idea that changing trade balances have contributed to per capita CO_2 emissions reductions. Columns 4 and 5 include variables measuring knowledge of climate change and whether a country ratified the Kyoto Protocol by the end of 2004. The estimates provide no significant evidence that either knowledge of climate change or early ratification of the Kyoto Protocol affected countries' likelihoods of achieving EKC downturns for CO_2.

The electricity sector is just one sector of the economy. It may be that carbon Kuznets curve downturns have been generated by CO_2 emissions reductions in other sectors. The change in total CO_2 emissions per capita can be decomposed as follows:

$$\begin{aligned}\Delta C &= \Delta C_{\text{Electricity sector}} + \Delta C_{\text{Other sectors}} \\ &= \frac{\Delta C_{\text{Electricity sector}}}{\Delta E_{\text{Electricity sector}}}\Delta E_{\text{Electricity sector}} + \frac{\Delta C_{\text{Other sectors}}}{\Delta E_{\text{Other sectors}}}\Delta E_{\text{Other sectors}}\end{aligned} \tag{3}$$

where C and E are CO_2 emissions and energy use per capita. Equation (3) indicates that changes in per capita CO_2 emissions are a product of changes in the carbon intensity of energy use and in energy use per capita, summed by sector. The focus to this point has been on the role of one factor (adopting nuclear and renewable electricity) causing the first term in Equation (3) to fall. The decomposition illustrates that changes in per capita energy use and in the carbon intensity of other sectors may also contribute to emissions reductions.

Column 6 of Table 5 includes the change in the logarithm of total energy use per capita over the period 1971–2006 to investigate whether changes in energy use can explain why some countries have achieved EKC downturns for CO_2 and others have not. The estimate for this variable is negative, indicating that faster energy use growth reduces the likelihood of carbon Kuznets curve downturns. This estimate is insignificant at the standard levels, however.

Column 7 includes variables measuring the 1971–2006 change in the logarithm of the carbon intensity of energy use in the industry and transport sectors (the largest sectoral contributors to global CO_2 emissions from fossil fuel use outside the electricity sector). The estimates for these variables are also statistically insignificant. These variables are also statistically insignificant in the column 8 estimate that includes all of the variables used in Table 5 (except those for which there are many missing observations). This suggests that reductions in the carbon intensity of energy use in industry and transport have on average not played large roles in carbon Kuznets curve downturns. The estimate for the primary explanatory variable, the change in the nuclear and modern renewables share of the electricity mix, remains positive and strongly significant in each of these additional specifications. This indicates that the extent to which countries climb to the upper rungs of the electricity ladder is the strongest and most important explanator of whether they achieved EKC-type downturns in per capita CO_2 emissions over the period 1960–2006.

It is important to consider robustness issues. Results using alternative definitions of the dependent variable, such as definitions that require a 20 per cent reduction in CO_2 emissions per capita before a country is classed as having experienced an EKC downturn, continue to suggest that the adoption of low-carbon electricity sources on the upper rungs of the electricity ladder is the most important mechanism via which EKC downturns have been achieved. Similar results are also obtained using an alternative data source for CO_2 emissions (Boden *et al*. 2009). Results are also similar for a subsample of OECD countries, indicating that the findings are not driven solely by relatively recent per capita CO_2 emissions reductions in countries like the Philippines and Sri Lanka. In specifications in which changes in the nuclear and modern renewables shares of the electricity mix are separated from one another, the estimated impacts of the adoption of both nuclear power and of modern renewables on the likelihood of carbon Kuznets curve downturns are similar. Results for these additional specifications are available from the author on request.

The estimate from column 4 of Table 3 predicts that, on the basis of the adoption of nuclear power and modern renewables, fossil fuel endowments, and 1971 income levels, ten countries would experience carbon Kuznets curves during the period 1960–2006. In decreasing order of likelihood, these are France, Belgium, Sweden, Switzerland, Finland, Hungary, Bulgaria, Germany, South Korea and Japan. Seven of these ten countries are classed as having actually achieved a carbon Kuznets curve peak during the period. (By 2006, Finland, South Korea and Japan had achieved some reductions in per capita CO_2 emissions, but these were smaller than 10 per cent.) These ten countries are also the ten largest adopters of electricity generation using nuclear and modern renewables in the sample (although they are not ranked in the same order). The estimates imply that, on the basis of differences in fossil fuel reserves and in take-up of nuclear and modern renewables power alone, Sweden is 72 percentage points more likely to have experienced a carbon Kuznets curve downturn over the period 1960–2006 than is Australia.

6. Conclusion

This paper began with the observation that CO_2-income paths differ substantially among countries and has sought to explain these differences in long-run development experiences. There are many potential ways in which CO_2 emission reductions may have occurred, but prior studies have not identified the most important mechanisms for the EKC-type reductions in CO_2 emissions that have been observed in some (but not all) countries. The evidence in this paper indicates that graduation to the upper rungs of the electricity ladder (nuclear power, modern renewables) is the most important overall mechanism via which downturns in long-run per capita CO_2-income paths have been generated. The ability of countries such as Sweden, France, Belgium and Denmark to achieve sizeable reductions in per capita CO_2 emissions is principally a product of the large transitions to nuclear and/or modern renewables power in these countries. Because the adoption of nuclear power and modern renewables is a positive function of income (Burke 2010), the results here provide evidence of an important avenue via which long-run income growth can eventually lead to CO_2 emissions reductions.

The results provide no significant evidence that decarbonisation in non-electricity sectors or reductions in energy use per capita on average have been important contributors to EKC-type reductions in per capita CO_2 emissions. There is some evidence that structural change towards the services sector has increased the likelihood of EKC-type downturns in per capita CO_2 emissions. The findings do not mean that factors such as energy efficiency improvements have not been important in reducing CO_2 emissions in individual cases. What they do indicate is that transitions to nuclear and modern renewables power have had greater overall importance for the historical cases of carbon Kuznets curve downturns than other mechanisms via which CO_2 emissions may have been reduced.

Evidence on how reductions in CO_2 emissions have been achieved historically has important implications in the current policy context, as many countries have ambitious targets for greenhouse gas emissions reductions. If the historical example is the best guide, the evidence indicates that countries looking to achieve reductions in CO_2 emissions would be well advised to follow the example of countries such as Sweden and Denmark by switching to low-carbon electricity sources on the upper rungs of the electricity ladder. While income levels and fossil fuel endowments affect the viability of switching to nuclear power and modern renewables (and the incentives for seeking to do so; Burke 2010), there remains scope for government intervention to encourage 'leapfrogging' to these low-carbon technologies on the upper rungs of the electricity ladder. Policies to encourage leapfrogging to the upper rungs of the electricity ladder – such as the carbon pricing strategies and renewable energy targets of Australia and New Zealand – would increase the likelihood of EKC-type reductions in CO_2 emissions, and the magnitudes of these reductions. Care needs to be taken to ensure that leapfrogging to low-carbon electricity sources is carried out in the least-cost manner.

The findings also have important implications for fossil fuel-rich countries such as Australia, which are less likely to experience EKC-type reductions in CO_2 emissions with long-run economic growth. The existence of this additional 'curse' of natural resources means that the largest CO_2 reduction successes are likely to occur in fossil fuel-scarce countries. Given the importance of fossil fuel endowments in many countries, the development of affordable lower-carbon fossil fuel energy technologies is likely to be an indispensible part of an optimal climate change mitigation response. Additional attention directed at the best way to convince fossil fuel-rich countries to participate proportionately in global CO_2 emission reduction efforts may also be of substantial benefit.

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Appendix

Variable descriptions

Carbon Kuznets curve dummy: Equals 1 if a country meets the following criteria (zero otherwise): (i) CO_2 emissions per capita reduced by more than 10 per cent from peak level by 2006; (ii) GDP per capita increased by more than 10 per cent from the CO_2 emissions per capita peak year by 2006; and (iii) in the years after the CO_2 emissions per capita peak year, GDP per capita is never 10 per cent below the maximum level reached at or before the CO_2 emissions per capita peak year. Constructed using data from IEA (2009a) and Heston *et al*. (2009). CO_2 emissions are total emissions from all fuel use (in the electricity sector and other sectors).

Δ Nuclear and modern renewables share of electricity mix (percentage points), 1971–2006: Change in the percentage share of electricity generated using nuclear, geothermal, solar, tide, wave, ocean, wind, biomass and waste over 1971–2006 (IEA 2009b,d).

Log GDP per capita, 1971: Natural logarithm of 1971 GDP per capita in 2005 constant prices international dollars (Heston *et al*. 2009).

Fossil fuel reserves (ttoe per capita), 2005: Sum of total recoverable coal and proved reserves of crude oil and natural gas, in thousand tonnes of oil equivalent per capita. Data set equal to zero if listed as 'not applicable' (U.S. Energy Information Administration 2009). Conversion factors from BP (2009). Population data from Heston *et al*. (2009).

Fossil fuel reserves (million US$ per capita), 1971: Sum of natural gas, oil, and coal reserves in 1971 (reverse-constructed) (Norman 2008).

Fossil fuel depletion (percentage of GNI), 1971: The product of unit resource rents and the physical quantities of crude oil, natural gas, and coal extracted (World Bank 2011).

Log GDP per capita, 1950: Natural logarithm of 1950 GDP per capita in 1990 international Geary-Khamis dollars (Maddison 2009).

Log population, 1971: Natural logarithm of the 1971 population (Heston *et al*. 2009).

Log land, 1971: Natural logarithm of the 1971 land area in squared kilometres (World Bank 2011).

Transition country dummy: Equals 1 for countries classed as transition economies, 0 otherwise (Development Research Institute 2008).

Δ Services sector share of GDP, 1971–2006 (percentage points): Change in the percentage share of GDP contributed by the services sector over 1971–2006 (World Bank 2011).

Δ Net exports, 1971–2006 (percentage of GDP): Change in net exports of goods and services as a percentage share of GDP, 1971–2006 (World Bank 2011).

Knowledge of climate change in 2007–2008 (percentage of population): Share of the population that knew about climate change in 2007–2008 (Pugliese and Ray 2009).

Ratification of the Kyoto Protocol by end 2004 (dummy): Equals 1 if country ratified the Kyoto Protocol before 31 December 2004, 0 otherwise.

Δ Log energy use per capita, 1971–2006: Change in the natural logarithm of total primary energy supply per capita (IEA 2009b,d).

Δ Log carbon intensity of energy use in industry, 1971–2006: Change in the natural logarithm of the carbon intensity of energy use in manufacturing and construction (IEA 2009a,b,d).

Δ Log carbon intensity of energy use in transport, 1971–2006: Change in the natural logarithm of the carbon intensity of energy use in the combustion of fuel for all transport activity except international marine bunkers and international aviation (IEA 2009a,b,d).