Exploring the Carbon Kuznets Hypothesis

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CONTENTS

TABLES

FIGURES

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Abstract

The Carbon Kuznets hypothesis conjectures an inverse U–shape relation between GDP and carbon dioxide emissions. We investigate a number of empirical problems with this hypothesis by way of both econometric analysis and CGE modelling. The econometric analysis takes into account the possibility of unit root non–stationary regressors. On a panel of 107 countries covering the years from 1986 to 1998 we find evidence for unit root non–stationarity in log GDP and log emissions. Our discussion therefore focusses of potential pitfalls in estimating the Carbon Kuznets curve in the context of non–stationary panels context. We conclude that current practice in the literature fails to take these potential problems adequately into account.

The second conceptual problem considered in the paper is the question of how to interpret an observed inverse U–shaped relationship. With the help of a small GCE model, we illustrate the danger of using observed GDP–emission patterns directly as a policy guide. Our model economy, where decarbonization is exogenous, demonstrates in particular that a carbon policy relating to income levels may not be appropriate even in the face of an observed inverse U–pattern between income and emissions.

JEL Classification: Q20, C12, C13
Keywords: Carbon Kuznets curve, non–stationary panel, regressions with integrated variables, CGE modelling

1 Introduction

Eighty percent of the world's primary energy demand is currently met by fossil fuels. Unfortunately, their use yields several undesired joint products, with carbon dioxide – CO_2 – the most prominent among them. Once released into the atmosphere, CO_2 contributes to climate change. This man-made change has negative and potentially irreversible impacts on the world economy and welfare.

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To design and evaluate emission reduction and adaptation policies, projections concerning future CO_2 emissions under no-policy, or 'business as usual' conditions are indispensable. From this point of view, it would be most convenient to have a statistically well specified and robust relationship between GDP and CO_2 emissions. Economic growth scenarios for different regions could then be translated into regional emissions and aggregated into global concentration paths, provided that the estimated relationship is not subject to structural change under the different growth scenarios specified by the researcher (the Lucas critique, Lucas, 1976).

The most widely considered type of relation between environmental pollutants and economic activity, usually measured by GDP, is that of an 'inverse U' or 'Environmental Kuznets Curve' (EKC), after Simon Kuznets who originally postulated this type of relationship between economic development and indices describing income distribution (see Kuznets, 1955).

This paper is an assessment of the econometric approach to testing the Carbon Kuznets hypothesis, which conjectures an inverse U–shape relation between income (measured in GDP per capita) and per capita CO_2 emissions. A review of the literature in Section 2 is organized around a discussion of three important aspects for econometric practice: the focus on parametric regressions, the usual homogeneity assumptions and the failure to appropriately acknowledge the econometric implications of the potential presence of unit root non–stationary regressors. Panel unit root and cointegration tests, as well as their properties and deficiencies, are discussed on a data set covering the years from 1986 to 1998 for a panel of 107 countries.

In the penultimate section the paper highlights another, more general potential problem of an uncritical interpretation of reduced form econometric relationships. The issue at hand is the claim implicit in the Carbon Kuznets hypothesis that income per capita is the driving force behind the inverse U–shape of the GDP–CO_2 relation. In the absence of a structural model explaining all relevant variables, such an interpretation may not be warranted solely based on an observed relation between GDP and CO_2. A simple Computable General Equilibrium model provides a counterexample, showing that an observed inverse U–shape can easily be misinterpreted as a causal relation between income growth and emission patterns. The paper concludes with a chapter summing up the results and indicating possible directions for further research.

2 Econometric Analysis of the Carbon Kuznets Hypothesis

In general, EKC studies test for an inverse U–shape with pollutants like nitrogen oxides (NO_x), sulphur dioxide (SO_2) or CO_2, etc. as undesired by–products of economic activity. We consider CO_2 as the most relevant pollutant on a global scale and therefore exemplify our discussion with carbon dioxide.

The econometric approach to the Carbon Kuznets hypothesis is to estimate a relation between per capita GDP and per capita CO_2 emissions on cross-section, time series or panel data sets.

2.1 Brief review of the Literature

The econometric approach to the EKC hypothesis dates back at least to the seminal work of Grossman and Krueger (1991,1993,1995). They find evidence for an inverse U–shaped relationship between measures of several pollutants and per capita GDP.[1] Yandle, Bjattarai and Vijayaraghavan (2004) report more than 100 refereed publications of this type. Summary discussions of this empirical literature are given by Stern (2004) and Yandle, Bjattarai and Vijayaraghavan (2004). The standard parametric EKC regression model is given by

$$\ln(e_{it}) = \alpha_i + \theta_t + \beta_1 \ln(y_{it}) + \beta_2 (\ln(y_{it}))^2 + u_{it} \tag{1}$$

where e_{it} and y_{it} denote per capita emissions and GDP in region i and period t, respectively and u_{it} denotes a stochastic error term. The error terms are in general allowed to be serially correlated. Time series like GDP are often modelled as so–called integrated processes. A stochastic process is called integrated (or 'has a unit root'), if it is not stationary itself but its first difference is. An important assumption necessary for many methods for panels containing integrated variables is that both the errors u_{it} and the regressor $\ln y_{it}$ are cross-sectionally independent. This implies that also the e_{it} are cross-sectionally independent. These independence assumptions, needed for so–called first generation panel unit root and cointegration analysis, are rather strong, and it is not granted at all that they hold in practice. In an increasingly integrated world with large trade volumes it is e.g. not clear why the individual countries' GDP series should be independent.

The general formulation as displayed in (1) includes also country specific effects, α_i, and

[1] To be precise, Grossman and Krueger actually use a third order polynomial in GDP, whereas the quadratic specification seems to have been initiated by Holtz-Eakin and Selden (1995).

time effects, θ_t.[2] We model the country and time effects as fixed effects in this paper, whereas of course also random effects specifications are prominent in the literature. The shape of the functional relation is determined by β_1 and β_2, which depend neither on a specific region nor date. This homogeneity assumption is central to the standard panel analysis of the EKC: apart from the fixed effects α_i, and a stochastic error term u_{it}, all regions exhibit the same GDP–emission pattern.[3] In particular, they all share the same GDP turning point (if $\beta_2 < 0$), though the peak emission levels may differ across countries (see Figure 1) via different country specific effects α_i. The turning point is located at $y^* = \exp(-\frac{\beta_1}{2\beta_2})$. The first econometric

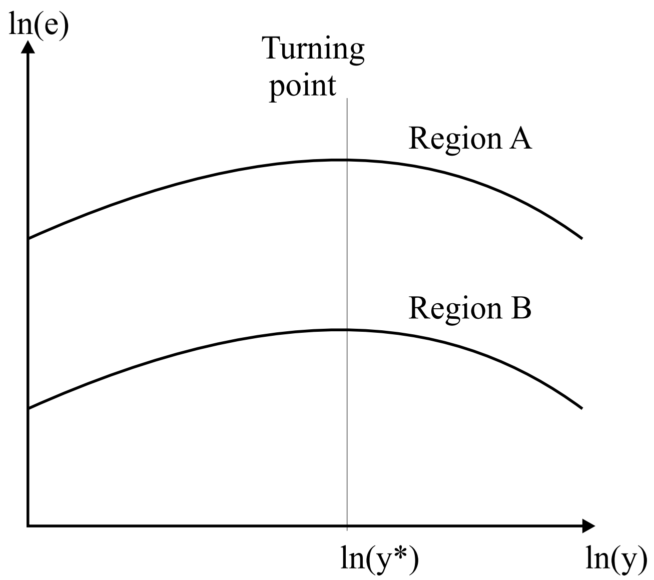

Figure 1: An EKC for two regions A and B. Though emission levels can differ among regions (via different country effects α_i), turning point income $y^* = \exp(-\frac{\beta_1}{2\beta_2})$ is equal among all regions.

evidence on the EKC for carbon dioxide emissions, termed in the following Carbon Kuznets curve (CKC), has been provided by Holtz-Eakin and Selden (1995). They estimate the CKC on an unbalanced panel of 130 nations with annual GDP and emissions data in levels from 1951 to 1986. The signs of the estimated parameters support the inverse U–shape hypothesis, i.e. $\beta_1 > 0$ and $\beta_2 < 0$. The far-out-of-sample turning point at eight million dollars per-capita GDP, however, suggests positive emission growth rates for any empirically relevant per-capita GDP levels. Substituting levels of per-capita GDP and emissions for the logs, as in (1), results

[2] In our implementation, as is common in the panel unit root literature we also investigate specifications including individual specific linear time trends.

[3] A fully homogeneous EKC supposes $\alpha_i = \alpha$ and identical distributions of u_{it} for all i.

in a turning point at \$35,428. This is still out-of-sample but clearly more relevant than the levels estimate.

Schmalensee, Stoker and Judson (1998) is in the same vein as Holtz-Eakin and Selden (1995). They improve the data basis and replace the quadratic formulation of (1) by a more flexible 10-segment linear spline specification. The linear segments are chosen to contain all the same number of observations. Their results confirm a systematic and inversely U–shaped GDP–CO_2 relation. Furthermore, the turning point is now within sample at \$9,799. The spline segment for highest incomes, from \$9,799 to \$19,627, has negative slope (-0.30), indicating a negative income elasticity of emissions in that range. Note, however, that the high $R^2 = 0.976$ is mainly driven by country fixed effects α_i which explain 94 % of the observed emission variance (see Schmalensee, Stoker and Judson, 1998). Both of the above-mentioned papers, Holtz-Eakin and Selden (1995) and Schmalensee, Stoker and Judson (1998), confirm the inverse U–shape hypothesis for CO_2.

From a methodological point of view, however, these and similar studies may well suffer from several serious econometric shortcomings that arise in the presence of non–stationarity:[4] First, all panel unit root and panel cointegration techniques applied so far in the EKC literature are based on the assumption of cross-sectional independence. Second, using log GDP and its square (given there is a unit root) in a regression is lacking a sound theoretical econometric basis. This stems from the fact that non–linear transformations of integrated processes exhibit fundamentally different asymptotic behaviour and require different asymptotic theory (see Park and Phillips (1999) or Park and Phillips (2001)), than integrated processes.[5] Third, the finite sample performance of panel unit root and cointegration tests is known to be poor, especially for short panels (see e.g. Hlouskova and Wagner, 2004), even when abstracting from the above mentioned two points. These three issue are discussed in great detail in Wagner and Müller-Fürstenberger (2004). Fourth, the assumption of a parametric and homogenous formulation of the Kuznets curve requires a detailed specification analysis.

2.1.1 Homogeneity among regions

Let us first turn to the homogeneity assumption. This refers to β_1 and β_2 in equation (1). These parameters determine the shape of the EKC irrespective of the country under con-

[4]A detailed discussion of these issues is contained in Wagner and Müller-Fürstenberger (2004).

[5]The implications of this theory for Kuznets curve analysis are a topic of ongoing research of Martin Wagner. In addtion the relaxation of the cross-sectional independence assumption that is necessary for all the panel unit root and panel cointegration techniques used in the EKC literature is investigated by Martin Wagner.

sideration; the potential turning point of the EKC is not country specific. Dijkgraaf and Vollebergh (2001) test this assumption with reference to the results by Schmalensee, Stoker and Judson (1998). They restrict their panel to only 24 OECD countries from 1960–1997 with GDP measured in \$(1995) purchasing power parities. Even a cursory comparison of GDP-CO_2 plots for Japan and the USA, they argue, casts serious doubts on the homogeneity assumption. They use a cubic extension of (1) and test the null hypothesis that the linear and quadratic coefficients are the same for all countries, i.e. $\beta_{ik} = \beta_k$, for $k = 1, 2$ and for all i. Like Schmalensee, Stoker and Judson (1998) they find within-sample turning points for all nations in their panel. An F–test, however, rejects the null hypothesis of equal coefficients at a 99% level of significance. This holds true even for most sub-panels. (They checked 380,000 combinations). The homogeneity assumption is decisively rejected, raising doubts on both the homogenous polynomial (1) and the spline version. The conclusion of their work is that homogenous panel estimates of the CKC may be inappropriate. However, when estimating the CKC for each country separately, they find support for the CKC hypothesis for 11 out of the 24 countries in their sample. This shows that a careful composition of the panel and a careful investigation of the homogeneity assumption by means of a specification search analysis are both important.

2.1.2 Non-parametric approaches

The second, 'lesser' methodological critique of the EKC concerns the parametric approach. Millimet, List and Stengos (2003) compare several modelling strategies, including semi-parametric techniques. In particular, they contrast the standard parametric framework with the more flexible semi-parametric approach for EKCs of nitrogen oxide and sulphur dioxide emissions in the United States. Millimet, List and Stengos (2003) clearly reject the parametric EKC approach for both pollutants. Especially in the case of sulphur dioxide, they find significant differences between parametric and semi-parametric estimates. Bertinelli and Stroble (2004) employ a semi-parametric estimator in a cross-country analysis for sulphur dioxide and CO_2 emissions. Their panel comprises 108 countries over the period 1950–1990 on an annual basis. They show that emissions increase monotonically at low levels of per capita GDP. On higher levels, the relation is almost flat, i.e. it does not exhibit a turning point. They contrast their results with a parametric regression based on (1), which indicates for their sample again an inverse U–shape. This result, however, is mainly driven by data for the very poorest countries. Hence they conclude that historical evidence about an inverse-U shaped EKC is not robust.

2.1.3 Testing for unit root non–stationarity and cointegration

The main methodological problems with the EKC and CKC literature are, as indicated above, related to the inappropriate treatment of non-stationary, or, to be precise, integrated regressors.[6] Although Stern (2004) in his survey paper notes that it is very easy to do bad econometrics, unfortunately his co-authored Perman and Stern (2003) paper is itself a prime example of doing just that and we will therefore refer to it throughout our discussion.

If variables are integrated but stochastically independent, the so–called 'spurious regression problem' occurs, when they are regressed on each other. Seemingly significant (with respect to standard t-statistics) coefficients may emerge from a regression of stochastically independent variables, hence the name 'spurious'. This phenomenon was first observed by Yule (1926), and analyzed analytically in Phillips (1986). In order to obtain meaningful regression results from a regression containing integrated variables, it is necessary that these variables be *cointegrated*, i.e. share a common stochastic trend. Thus, the first step in the analysis is to test for unit root type non–stationarity and, if this is confirmed, a cointegration test will be the second step.

Thus, let us exemplify this analysis for a panel of 107 countries (see the country list in the Appendix) with annual data over the years 1986 to 1998. We start with the panel unit root tests. Let x_{it} denote the variable we want to test for a unit root, i.e. in our case this will be the logarithm of per capita emissions or of per capita GDP

$$x_{it} = \rho_i x_{it-1} + \alpha_i + \gamma_i t + u_{it}, \tag{2}$$

where u_{it} is a stationary process.[7] All so–called 'first generation tests' used in the EKC literature up to now assume cross-sectional independence of u_{it}. This is an unrealistic assumption, given the large degree of economic interactions across countries.[8] The null hypothesis of the panel unit root tests is given by $H_0 : \rho_i = 1$ for all i, against the *homogenous* alternative

[6] Wagner and Müller-Fürstenberger (2004) contains a detailed discussion of the issues discussed only briefly here.

[7] Also time effects θ_t as contained in (1) can be included in the test procedure.

[8] Thus, it may be important to study the CKC relationship with methods for non–stationary panels that allow for cross-sectional correlation. A first investigation along these lines is contained in Wagner and Müller-Fürstenberger (2004).

UNIT ROOT TESTING		
Variable	IPS	$IPS - LM$
	Fixed Effects	
CO_2	0.229 (-1.707)	-1.291 (1.096)
GDP	-1.590 (-0.582)	0.070 (1.231)
	Fixed Effects and Trends	
CO_2	**-2.093** (-1.823)	0.259 (0.276)
GDP	**-3.423** (-1.346)	0.456 (0.301)

Table 1: Results of Im, Pesaran and Shin panel unit root tests for the logarithm of CO_2 emissions and the logarithm of per capita GDP including only fixed effects in the upper block-rows and fixed effects and time trends in the lower block-rows. The asymptotic 5 % critical value is given by -1.645 for the IPS test and by 1.645 for the IPS-LM test. In brackets the bootstrap critical values are displayed. Bold indicates rejection based upon the bootstrap critical values.

$H_1^1 : \rho_i = \rho < 1$ for all i, or the *heterogeneous* alternative $H_1^2 : \rho_i < 1, i = 1, \ldots, N_1$ and $\rho_i = 1, i = N_1 + 1, \ldots, N$, for some N_1 such that $\lim_{N\to\infty} N_1/N > 0$.

In a relatively heterogeneous panel as is the case in our example, the heterogeneous alternative H_1^2 may be more relevant, since the homogenous alternative restricts H_1^1 the first order dynamic behaviour to be *identical* across countries. Thus, we believe it to be more appropriate to use tests that allow for the heterogeneous alternative, like the tests developed by Im, Pesaran and Shin (1997,2003). Perman and Stern (2003) apply two tests, the Im, Pesaran and Shin (2003) test with the heterogeneous alternative and the Levin, Lin and Chu (2002) test with the homogenous alternative. Using the latter test with the homogenous alternative may be somewhat questionable in the CKC context with large country data sets.

However, there is another serious problem, namely the fact that the short time dimension of the panels makes asymptotic inference a bad guide for panel unit root testing (see Hlouskova and Wagner (2004) for ample simulation evidence). This stems from the fact that the panel unit root tests, at one step or the other, essentially involve a unit root test on the short individual time series. To overcome this limitation, *bootstrapping* may be an important tool (see Wagner and Müller-Fürstenberger (2004)) for an application in the CKC context. We display the importance of bootstrapping below, by reporting the results for the two tests of Im, Pesaran and Shin (1997,2003) for the so–called parametric bootstrap. One of these tests is given by essentially the group-mean of individual ADF t-statistics (IPS), and the other is a group-mean LM statistic ($IPS - LM$). The results in Table 1 show huge differences

COINTEGRATION TEST		
	PG_ρ	PG_{df}
Linear Specification		
FE	**-1.595** (-0.041)	**-10.956** (-6.949)
FE & Tr.	**1.477** (3.002)	**-14.352** (-9.149)
Quadratic Specification		
FE	**2.335** (2.401)	**-9.718** (-8.927)
FE & Tr.	**4.592** (5.611)	**-14.352** (-10.554)

Table 2: Results of panel cointegration tests, linear specification in the upper block-row and quadratic specification in the lower block-row. The asymptotic 5 % critical value is given by -1.645. In brackets the bootstrap critical values are displayed. Bold indicates rejection based upon the bootstrap critical values.

between the asymptotic and the bootstrap critical values. In the results presented in Table 1, however, basing the test decision on either the asymptotic or bootstrap critical values does not alter the results, despite the large differences.[9] In the specification with intercepts and trends unit root non-stationarity is rejected for both variables by the IPS test, however, not by the IPS-LM test.

Ignoring the issue of potentially neglected cross-sectional dependence (which may for some cases be mitigated when resorting to bootstrap techniques), we have thus collected some evidence for unit root non–stationarity of log per capita GDP and log emissions, with the exception of the IPS results when trends are included.

We can therefore now proceed to testing for cointegration in equation (1) by panel cointegration tests. These tests are given by unit root tests on the residuals of equation (1) estimated by some appropriate method. If the variables are cointegrated, the residuals are stationary (hence the unit root hypothesis is to be rejected) and if they are not cointegrated the residuals are integrated (hence the unit root hypothesis is not to be rejected).

We perform here two *group-mean* tests of Pedroni (2004). These group-mean tests are preferred to pooled tests since they put less restrictions on the dynamics in the individual countries. Again, we resort to bootstrap techniques and in Table 2 we present the results of the PG_ρ test based on the estimated first-order serial correlation coefficient and the PG_{df} test in which the correction for serial correlation in u_{it} is achieved by a Dickey-Fuller type correction.

[9] In the larger set of results in Wagner and Müller-Fürstenberger (2004), the asymptotic and the bootstrap critical values lead in quite a number of cases to different test decisions.

The results indicate a rejection of the null of *no cointegration* throughout. Thus, there seems to be strong evidence for a Carbon Kuznets curve.

However, there is one problem that has been completely ignored in the time series and panel EKC literature: if log GDP is integrated, then the square of it cannot be. Thus, the results displayed in the lower block-row of Table 2 lack an econometric theoretical basis – if either log per capita GDP or its square is integrated. This fact does not prevent Perman and Stern (2003) from basing subsequent (consequently equally meaningless) estimates on such 'findings of cointegration' in the quadratic formulation.

The problem ignored up to now is that only the recently developed theory of regression with non–linear transformation of integrated variables allows the correct specification of Kuznets curves in the context of integrated variables. While it is essential to test for unit root and cointegration in evaluating Kuznets curve hypotheses based on time-series or panel data, the techniques used so far are – in case of integrated data – flawed and not helpful in these discussions.

3 Reduced Form versus Structural Explanation: A CGE Model Example

The Carbon Kuznets curve, as most other Environmental Kuznets curves, is generally modelled as a polynomial (up to degree 3) or spline relationship between GDP emissions. As such, this relationship is a *reduced form* relationship, to which no structural meaning should be attached directly. In other words, the underlying economic and technological factors that generate this relationship are neither modelled nor investigated in econometric analysis which only include these two variables. Taken at face value, it is tempting to interpret the Carbon Kuznets curve as a causal relationship running from GDP to emissions in the sense that the willingness to pay for environmental quality rises sufficiently with increasing income to reduce emissions. This interpretation, however, can not be based simply on reduced form econometric analysis. The example in this section will show that a CKC relationship can emerge, even though the decarbonization of the model economy is entirely driven by exogenous technological change. Thus, with our example we highlight the caveat that reduced form relationships in general should not be used in a structural context, e.g. for policy analysis. If the CKC relationship is due to other reasons than the standard interpretation outlined above, or is subject to structural instabilities when changing the GDP path, policy conclusions based on a hitherto observed relationship may be highly misleading.

Our example is generated by a small dynamic Computable General Equilibrium (CGE) model. CGE models have a long tradition in climate change economics. They emerged from detailed energy technology assessment models like ETA-Macro (see Manne, 1977). Assigning carbon emission coefficients to different types of fossil fuels allows the tracking of carbon emissions along economic growth paths. The so-called 'Integrated Assessment Models' (IAMs) combine these dynamic general equilibrium models with stylized carbon cycle models from atmospheric physics. A climate change impact model, which reduces to some type sort of 'damage function', translates atmospheric carbon concentrations via changes of mean surface temperatures into economic damages. This type of model was pioneered by Nordhaus (1992) with his DICE model and Manne, Mendelsohn and Richels (1995) with MERGE. Variations and extensions of these models define the current state of research in CGE climate economics.

We use a very simple IAM model to generate artificial GDP and CO_2 time series. These series will be subject to an econometric fitting which, in turn, indicates an inverse U–shape. This shows that there are sufficient degrees of freedom in calibration and scenario design for an inverse U–pattern to occur or not to occur. Thus, the CGE model cannot resolve the issue of whether there is a turning point or not. But it is able to reveal mechanisms that can both generate such inverse U–shaped patterns and provide model based explanations thereof.

To demonstrate this, we consider just two regions, called North and South. North is thought of as comprising all members of the OECD in 1990, and South is thought of as the remaining countries of the 107 countries listed in Table 4 in the Appendix. Production in both regions is described by a nested CES aggregator f_i, with physical capital k_{it}, labour l_{it}, and energy g_{it} as production factors:

$$f_i(k_{it}, l_{it}, g_{it}) = \left(a_i^1 \left(l_{it}^{\vartheta_i} k_{it}^{1-\vartheta_i}\right)^{\tau_i} + a_i^2 g_{it}^{\tau_i}\right)^{\frac{1}{\tau_i}}, \tag{3}$$

where a_i^1 and a_i^2 are factor productivities, ϑ_i is a technical parameter determining the value share of labour in value addition, and τ_i relates to the elasticity of substitution between value added and energy. Production output is spent either on consumption, investment, energy production or to fix climate damages:

$$y_{it} = f_i(k_{it}, l_{it}, g_{it}) = c_{it} + i_{it} + m_{it} g_{it} + \theta_{it}^* y_{it}. \tag{4}$$

We denote gross output by y_{it}, consumption by c_{it} and investments by i_{it}. The marginal costs of energy supply, m_{it} are constant within period t, expected climate damages in terms of per cent losses of gross output are given by θ^*_{it}. We assume discrete time $t = 0, 1, \ldots, \infty$. The regions are indexed by i, with $i =$ North, South. Capital accumulates according to

$$k_{it+1} = \delta k_{it} + \omega i_{it}, \tag{5}$$

with δ as the capital survival rate, i.e. one less deterioration rate, and ω as the linear production coefficient in the investment technology. Atmospheric carbon accumulates according to the Nordhaus equation (see Nordhaus, 1991)

$$S_{t+1} = \phi_1 \sum_i \eta_{it} g_{it} + \phi_2 S_t. \tag{6}$$

where ϕ_1 and ϕ_2 are climate system parameters. The emission coefficient is given by η_{it}. It measures the carbon content of energy. Accumulated carbon S_t induces climate change which translates into economic damages according to a quadratic damage function

$$\theta_{it} = \left(\frac{\Delta S_t}{\Omega_i}\right)^2, \text{ with } \Delta S_t = max(0, S_t - S_0)., \tag{7}$$

where Ω_i is the so–called critical atmospheric carbon level, given by 1979.9 ppmv in North and 1252.2 ppmv in South. Both regions are operated as if independent benevolent policy makers maximize

$$W_i = \sum_{t=0}^{\infty} \beta^t \ln c_{it}, \tag{8}$$

subject to constraints (3), (4) and (5); β is the time discount rate. The decision makers do not take into account that regional fossil fuel use causes an externality. Instead, they anticipate a sequence of future climate damages θ^*_{it}, $t = 0, 1...$

The equilibrium concept is of Nash-type, i.e. both regions correctly anticipate the future climate damage path. In equilibrium, both emission paths must add up to the atmospheric carbon concentration path according to (6) which yields the anticipated path of climate damages, i.e. $\theta^*_{it} = \theta_{it}$ is the main equilibrium condition.

To run computational experiments on this type of model, the production functions are calibrated on a given data set. We use the standard CGE approach (compare Shoven and Whalley, 1992) of production function calibration, i.e. we assume that production is carried out by a profit maximizing firm under perfect competition. Given the CES specification, all parameters of the production functions (a^1_i, a^2_i and ϑ_i), except for the elasticities τ_i are uniquely determined from the first order conditions for profit maximization and the income

KEY DATA FOR CALIBRATION		
Data (Base Year 1998)	North	South
Labour Income (trillion $(1995))	16.780	3.011
Capital Income (trillion $(1995))	7.193	1.291
Energy Expenditures (trillion $(1995))	1.262	0.731
Carbon emission ($GtCO_2$)	11.406	7.955
Population (billion)	1.005	3.746
Annual population growth rate (2000 – 2015)	.015	.025
Exogenous decarbonization of energy ('NTP') (2000 – 2015)	0	0
Exogenous decarbonization of energy ('TP') (2000 – 2015)	.02	*
Parameters		
Capital survival rate δ	0.95	0.95
Investment technology ω	0.2	0.2
Elasticity of substitution τ_i	-0.5	-0.5
Discount rate β	.975	.975
Climate damage at 560 ppmv in % output loss	2	5
Climate system parameter ϕ_1	0.302	
Climate system parameter ϕ_2	0.99	

Table 3: Key benchmark data. 'NTP' indicates the control scenario with no technological progress and 'TP' indicates the technological progress and diffusion of technology scenario, in which decarbonization of energy in South is endogenous, see below. For data sources see the appendix. `ppmv` is parts per million (volume).

data in Table 3. This table also contains all other required parameter values and exogenous data (like population). The two regions North and South are composed of the 107 countries given in Table 4. North is comprising all countries that were OECD members in 1990 and South contains the remaining countries. The calibration of regional production functions, f_i, yields several regional specific technical parameters. These differences in technology, however, are not necessarily constant over time. Technology in an integrated world economy diffuses globally. It is hence reasonable to assume, at least to a certain extent, convergence of South's energy supply technology towards the more elaborated technology in North.[10] This technology catching–up effect is assumed with respect to the carbon content of energy η_{it}. A specific form of technological progress and diffusion is assumed in the baseline scenario ('TP'). In this scenario we assume a rate of technological progress for North of 2% per year and a complete catching-up South within 14 years. This determines the rate of technological progress in South uniquely as a function of the initial technological gap. The control scenario ('NTP')

[10]For simplicity of the argument we ignore here issues of regional specialization in certain production processes and only look at aggregate technology. Non-convergence of technology due to country specialization, as feasible in e.g. a Heckscher-Ohlin type world is of course an important issue.

assumes no technological progress in both North and South and thus in this scenario the initial technological differences persist entirely.

The results of the small computational experiment are shown in Figure 2, where we depict the GDP–emission relationships for both scenarios and the quadratic CKCs fitted to the 'TP' scenario. The left picture in the figure shows the results for North and the right for South. The results for scenario 'NTP' are displayed in dotted lines and for scenario 'TP' in circled lines. In 'NTP' the GDP–emission relationship is almost linear in both regions. This follows immediately from the constant carbon content of energy and increasing GDP. On the contrary, both regions exhibit in scenario 'TP' an inverse U–pattern due to the exogenous decarbonization of energy. Due to the low per capita incomes in South the quadratic relationship appears to be almost linear in the right picture. In the model, this effect is solely driven by technology induced decarbonization and not by income growth.

As a computational experiment we perform panel estimation of a quadratic CKC in level and log-level terms for the scenario 'TP' . This gives the following results:[11]

$$e_{it} = \hat{\alpha}_i + \underset{(0.747)}{1.786 y_{it}} - \underset{(0.013)}{0.030 y_{it}^2} + \hat{u}_{it} \tag{9}$$

with $\hat{\alpha}_N = -14.220$ and $\hat{\alpha}_S = -0.620$ and 'standard errors' in brackets. Thus, estimation in levels generates an inverse–U shape, however one with 'insignificant' coefficients. Estimation in log levels results in a U–shape with 'significant' coefficients:

$$\ln(e_{it}) = \hat{\alpha}_i - \underset{(0.245)}{0.749 \ln(y_{it})} + \underset{(0.048)}{0.132(\ln(y_{it}))^2} + \hat{u}_{it} \tag{10}$$

with $\hat{\alpha}_N = 3.546$ and $\hat{\alpha}_S = 1.062$ and 'standard errors' in brackets. Thus, despite the clear evidence for an inverse U–shape in the 'TP' scenario, pooled estimation of a homogenous CKC fails to recover this link. However, the inclusion of time effects θ_t leads to 'significant' coefficients with proper signs ($\beta_1 > 0$, $\beta_2 < 0$) in *both* the level specification and the logarithm specification. Thus, the 'econometric' results are very sensitive to the specification, despite the clear graphical evidence displayed in Figure 2.

As our example has illustrated, dynamic CGE modelling requires a significant amount of calibration. The calibration approach consists of using input-output data, some substitution

[11] Obviously this is just intended for illustrative purposes, as the data used for estimation are in fact deterministically generated from the calibrated model. The mis-specification of the equation would be immediately visible from looking at the residuals $\hat{u}_{it}$ (which exhibit quadratic shape over time). From the deterministic behavior of the data it is also clear that the meaning of significance is nothing but a mere statement that standard t-values suggest significance. Of course, they are conceptually wrong.

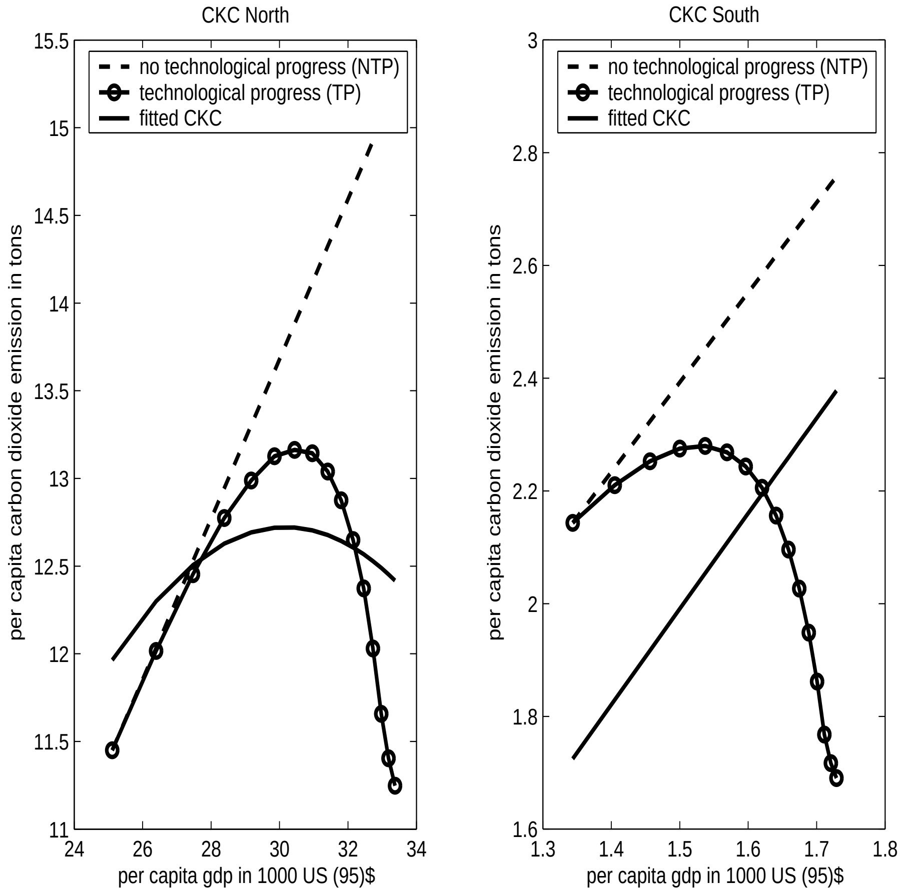

Figure 2: Simulation results for the GDP–CO_2 relation. The dotted line refers to the control scenario where no technological progress occurs. The line with circles shows the results under the technology improvement–diffusion assumption. The solid line gives the fitted CKC, based on a panel with data from the 'technological progress' scenario. The turning point occurs at 30,000$ at 1995 prices.

elasticities and 'educated guesses'. Alternatively, it may be possible to estimate the model parameters by econometric analysis. In practice these two approaches are rarely combined, despite the fruitful potential for doing so, e.g. our CGE model has demonstrated the key role of technological progress in shaping the GDP–emission relationship. This knowledge could be incorporated in econometric analysis of the Carbon Kuznets hypothesis, which was performed using only GDP and emissions data. The other way round, the econometric analysis in Section 2 delivers at best weak evidence for inverse U–shaped GDP–emission relationships, whereas they unambiguously result in the scenario 'TP'. For our example the inconsistency between the econometric findings on the one hand and the findings from the CGE model on the other suggest a reinvestigation of the CGE model specification. Thus, one could by means of a so–called 'dynamic replica check' study the properties of CGE model solutions along this dimension. Replica checks are control runs of CGE model to verify whether the optimization solution does indeed coincide with the benchmark data used in calibration. A dynamic replica check does not only focus on a given base year but also checks how well the model reproduces certain dynamic features of key variables. We thus conclude that there are potentially significant gains from combining econometric analysis and calibration based CGE modelling for climate change economics.

In the model economy, climate policy could be performed by policies altering the (up to now) exogenous decarbonization rate or by output targets. Varying the technology parameter changes the GDP–emission relationship. A faster rate of decarbonization allows for a larger output growth rate without changing the GDP–emission relationship. When basing policy only on a reduced form relationship between GDP and emissions (thereby effectively assuming an unchanged decarbonization rate), the effect of the third important variable, the carbon content of energy, is ignored. Thus, the example illustrates the potential pitfalls of basing policy upon reduced form relationships.

4 Summary and Conclusions

In this paper we have discussed some econometric pitfalls in estimating Carbon Kuznets curves and have also discussed by means of a small CGE model that reduced form relationships between emissions and GDP have to be interpreted carefully.

In particular we have discussed three econometric problems with non–stationary panel analyses of the EKC or CKC: (i) potential cross-sectional correlation, (ii) use of non-linear transformations of integrated variables and (iii) the small sample properties of panel unit root and cointegration techniques. Problems (i) and (ii) are fundamental and the subject of ongoing research. The third problem has been assessed by resorting to bootstrap techniques for a panel of 107 countries over the period 1986–1998. A further problem, not investigated in this paper is, (iv), the usual restriction to homogenous parametric specifications. All these issues need to be analyzed carefully in econometric analyses of the Environmental Kuznets curve hypothesis. One major conclusion is that such time series or panel based analyses presuppose the application of new techniques, such as the recently developed theory of regression with non–linear transformation of integrated variables.

In the penultimate section we addressed the well-known but often not sufficiently acknowledged issue of reduced form versus structural relationships. We have shown with a small CGE model that it is possible to estimate a highly 'significant' Carbon Kuznets curve, which is not driven by income but by exogenous decarbonization and technological spill–overs. From this we conclude – and this holds of course true in general – that it is often inappropriate and misleading to use reduced form relationships for structural or policy analysis. Structural econometric analysis of the CKC hypothesis is therefore an important area for future research.

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Albania	Ecuador	Liberia	Seychelles
Algeria	Egypt	**Luxembourg**	Singapore
Antigua Barbuda	El Salvador	Macao	Solomon Islands
Argentina	Fiji	Malaysia	South Africa
Australia	**Finland**	Malta	**Spain**
Austria	**France**	Mauritania	Sri Lanka
Bahamas	French Guiana	Mauritius	St. Lucia
Bahrain	Gabon	**Mexico**	St. Vincent and Grenadines
Barbados	**Germany**	Mongolia	Suriname
Belgium	**Greece**	Morocco	Swaziland
Belize	Grenada	**Netherlands**	**Sweden**
Bolivia	Guatemala	New Caledonia	**Switzerland**
Botswana	Guyana	**New Zealand**	Syrian Arab. Rep.
Brazil	Honduras	Nicaragua	Thailand
Brunei	Hong Kong	Nigeria	Tonga
Bulgaria	Hungary	**Norway**	Trinidad and Tobago
Cameroon	**Iceland**	Oman	Tunisia
Canada	India	Pakistan	**Turkey**
Chile	Indonesia	Panama	United Arab. Emirates
China	Iran	Papua New Guinea	**United Kingdom**
Colombia	**Ireland**	Paraguay	**United States**
Costa Rica	Israel	Peru	Uruguay
Cyprus	**Italy**	Philippines	Venezuela
Denmark	Jamaica	**Portugal**	Vietnam
Djibouti	**Japan**	Puerto Rico	Zambia
Dominica	Jordan	Romania	Zimbabwe
Dominican Rep.	Korea Rep	Saudi Arabia	

Table 4: Country list. Members of the OECD in 1990 in bold face.

Appendix: Data and Sources

Our analysis is based on balanced panel data for 107 countries for the period 1986–1998. The list of countries is given in Table 4. The former Soviet Union and some eastern European countries are omitted from the sample because of a lack of data. Other countries like Kuwait are omitted because of large jumps in the emissions data. Member countries of the OECD in 1990 are in bold.

Per-capita CO_2 emissions are taken from the Carbon Dioxide Information Analysis Center (CDIAC) data set (see `http://cidia.eds.ornl.gov/trends/emis/emcont.html`). They are measured in metric tons of CO_2. Per capita GDP is measured in constant 1995 US$ and taken from the World Bank Development Indicators 2003.